Say NO to Sunnica

SUNNICA ENERGY FARM
DCO EXAMINATION

COMMENTS ON ANSWERS TO EXA FIRST QUESTIONS

SAY NO TO SUNNICA ACTION GROUP LTD

28 NOVEMBER 2022

Introduction

1. The Say No to Sunnica Action Group Limited (SNTS) is an interested party (ID No 20031080) in the DCO examination.

2. In this document SNTS provides comments on the Applicant's answers to the ExAQs **[REP2-037]**, the appendixes to those answers **[REP2-038]**, and the other responses provided by parties involved in this examination **[REP2-073] to [REP2-079]**. SNTS only includes comments in this document if it usefully advances understanding of the question in issue; where an answer conflicts with our WRs we do not repeat our disagreement.

Q1.0.1

3. The Applicant describes its identification of the majority of the land being low grade, non-BMV agricultural land as an '*opportunity*' in response to this question. The ExA will appreciate that SNTS disagree with the factual basis for that view, as we say that the Applicant has significantly underestimated the amount of BMV land. However, more importantly for this comment, we disagree that this is an '*opportunity*' even if the majority of the land were non-BMV.

4. On the Applicant's own assessment, the majority of the land is still grade 3b or above. This is still good quality agricultural, and which is defined as '*moderate quality agricultural land*'. In addition, it produces significant yields of valuable crops (both with and without the benefit of significant investment into farming infrastructure). Considering Government policy on agricultural land and food production, grade 3b land is still valuable. Indeed, because of the quality of this land, the crops it produces, and the yields it produces, that value is apparent. Thus, SNTS is of the view this falls into the category of both a negative and a constraint. The ExA is still required to weigh negatively in the planning balance the value of this agricultural land that will be lost.

5. We also do not understand why residential receptors being within 500m of the sites is classified as '*both*'. This is clearly a constraint for the site as a whole. Indeed, the proximity of some locations (e.g. the permanent Traveller Site at Red Lodge to the PV cells and the BESS and substation compound) is, we submit, a significant negative and a constraint.

Q1.0.3

6. The answer to this question (and also Q1.0.4 to Q1.0.6 including applicable appendixes) is commented on by our landscape experts in the briefing note appended to this set of comments [**Appendix A**].

Q1.0.4

7. There are various aspects of this answer that SNTS does not respond to as it will merely repeat the content of its WRs. As with Q1.0.3., SNTS disagrees that the scheme is one that has good design. The reasons for this are all those flaws that have been identified through the WRs.

8. However, part of Q1.0.4 comments on public support for solar generation. SNTS does not disagree with the proposition that there is majority public support for solar. The difficulty with the Applicant's position is the view that this scheme responds to what society wants; as designed, the Sunnica scheme is poorly conceived and poorly designed. It is one of the

largest solar schemes in Europe, which is strewn across the landscape in multiple segments. It will have the effect of changing the local setting from a rural agricultural and horseracing one to an industrialised one. As a result of all the flaws identified in the scheme by SNTS in our WRs, it is inappropriate to take an abstract position expressed in polling and advance it as a justification for this specific scheme.

Q1.0.5

9. SNTS note both the view of the Applicant and of the Councils in response to this question. We agree with the Councils that there is value in having some oversight of design in accordance with the National Infrastructure Strategy. Thus SNTS supports the position of the Councils that a design champion and/or design panel is necessary.

10. The Applicant has advanced this scheme making considerable use of the *Rochdale* envelope. However, that the scheme has been assessed on a reasonable worst case basis does not remove the obligation to secure good design. It is still desirable to avoid or mitigate planning harm by securing good design, even if the ExA conclude that assessed on a reasonable worst case the scheme is acceptable in planning terms. Applying policy in favour of good design, the detailed design stage of the scheme should still seek to minimise harm and maximise benefit for the communities which will live with this scheme (many of whom will live with the scheme for the rest of their lives if built). Thus a design champion and/or design panel is necessary.

Q1.0.9 and Q1.0.10

11. Appendix B concerns the issue of associated development. SNTS has addressed this matter in its WRs and in the paper appended to those representations from our expert Alex Dickinson [**REP2-240i**]. The ExA can consider both (and those matters explored at **ISH1** on the dDCO on 1 November 2022) as the positions of the parties on these issues; we do not repeat all of that content here. It must be borne in mind that the question of whether the BESS is associated development goes to the power of the Secretary of State to make the DCO; if the DCO permits works which are not associated development (due to their nature or scope) then the DCO is unlawful. There is, separately, the question of how the BESS sits in the planning balance. That is not commented upon here. While SNTS does not repeat its position set out in the WRs, it does make a few short points.

12. First, the paper considers a 500 MW four-hour (C4) BESS; the capacity of such a BESS would be 2,000MWh. It is then explained that, as average between April to September will exceed this, the BESS is proportionate[1]. However, the Applicant also recognises that at '*times when solar generation is high, the solar development will be using a significant proportion of the available grid export capacity*' (para 17). Thus, on the Applicant's own view, the standard position is the PV cells at times of high generation will export to the grid.

13. This is an intuitive position; such export avoids the losses incurred in rectification and storage and makes best use of the grid connection[2]. The Applicant's position appears to be that, because it could theoretically fill the capacity itself, that is sufficient to make a 2,000MWh BESS associated development. SNTS disagree; the question instead is the approach called for in normal operation. In assessing this, the ExA might consider how often

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[1] This does not take in the Applicant's accepted degradation of generating capacity of 0.55% a year. SNTS doubt the generating capacity of the scheme for the reasons expressed in the Cranfield Report.

[2] Indeed, making best use of the grid connection appears to be the position expressed in all of para 17.

the export capacity will be saturated by PV generation, and how often the PV generation will be constrained by National Grid. No such evidence is available; indeed, that the scheme is being constructed in this location with this National Grid capacity and this connection agreement would tend to indicate that these threats are low.

14. Secondly, the paper omits to consider the inefficiency of the scheme as designed. The BESS is AC linked rather than DC linked; this means that energy produced by the PV cells will need to be inverted from DC to AC for transmission to the BESS, before being rectified from AC to DC for storage. The losses will be considerable[3]. If the BESS were DC linked, the batteries essentially could have been charged directly without any efficiency losses in rectification and inversion. Indeed, it would be difficult to convincingly justify the Applicant having chosen AC linking if its intention was to use the majority of the PV generation to charge the BESS; to do so would be to intentionally accept significant losses to inefficiency. Unusually, because the batteries are AC linked, electricity from the Grid will only need to be rectified before storage. Thus, the design is optimised for charging from the Grid rather than charging from the PV cells.

15. Thirdly, while ancillary services are services required by National Grid, this is merely a justification for grid-connected storage. It provides meagre justification for co-location. Indeed, as these are services that can be provided by any grid-connected storage, this illuminates the complete lack of connection to the PV generating part of the scheme. For example, ancillary services can equally be provided by the freestanding BESS being constructed at Burwell. As to the PV cells, and particularly the attached inverters, they can provide some ancillary services without BESS connection in any event.

16. Fourthly, separate to ancillary services is trading which the scheme also provides for[4]. This is not connected to the needs of the PV generation nor to the services required by National Grid to make the Grid as a whole functional. This is simply a service that provides the Applicant the opportunity to purchase cheap electricity and sell it when it is more expensive. Such uses have no connection at all to the PV generation and cannot be said to be associated development.

17. The ExA must be satisfied that the DCO permits associated development and only associated development. It cannot permit a development which might be associated development. The correct way to assess this is to consider the maximum of what the DCO permits on a reasonable worst-case basis. SNTS remains of the view that, without appropriate constraints, the DCO permits a BESS of such capacity as to be mainly for its own purposes and to saturate the grid connection when it is not being used by the PV generation. Any charging provided to the scheme is of a secondary nature.

Q1.0.11

18. This answer primarily concerns capacity to generate. SNTS does not repeat its position as set out in its WRs and the report of Cranfield University. As to the matter of the BESS, see the preceding comments. Note that relying on the power of the BESS is misleading; what matters in understanding the nature of the storage is its overall capacity in MWh.

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[3] The advice SNTS has received is that such losses for inversion and rectification can each be up to 20% **[REP2-240i]**

[4] [**APP-260]** at p.103.

Q1.0.13

19. SNTS welcomes the Applicant's decision to undertake an Equality Impact Assessment. SNTS suggests that such an assessment be secured by a provision in the draft Development Consent Order.

Q1.0.17

20. The answer to this question is commented on by our landscape experts in the briefing note appended to this set of comments [**Appendix A**].

Q1.0.18

21. The answer to this question is commented on by our ecology experts in the note appended to these comments [**Appendix B**].

Topic 1.1 Generally

22. As was explained in the letter submitted by SNTS at the same time as these comments on the answers to the ExAQs, our expert on matters of battery safety (Prof Paul Christensen) has been unable in the short timescales available to review these questions and the updated outline battery fire safety management plan. However, he has been instructed to undertake such a review, and that will be provided as soon as possible. Here SNTS identify some specific matters that are important to draw to the attention of the ExA at this stage.

23. To assist the ExA at this stage, SNTS has produced a short briefing note commenting on a number of issues arising under this section. This includes references to the comments of Prof Christensen in his original report attached to our WRs. This paper is appended [**Appendix C**]. While primarily directed to Q1.1.6 and 1.1.9, it appends various reports which will assist the ExA in understanding various BESS events across the globe and the safety and environmental impacts involved.

24. SNTS remain concerned about the quality of the information on BESS safety and fire. Lack of information is a factor which makes assessing, preventing risk, and managing events which eventuate difficult.

Q1.1.5

25. SNTS note the Councils' position in respect of fire management and the outline battery fire safety management plan. SNTS agree that there is a significant lack of detail which makes it difficult (indeed impossible) for concerns to be entirely addresses. SNTS also agree that it is necessary for the OBSFMP (and Unplanned Emissions analysis) to be robust so as to manage this difficulty. However, SNTS take the position that the plan is not robust, and indeed the distinct lack of information may be so severe that it is currently not possible for it to be sufficiently robust. Among other things, SNTS consider that chemistry (or, at least, considering the differences between the chemistries) an important aspect of ensuring such safety.

Q1.1.7

26. The problematic nature of AC coupling for charging the BESS from the PV cells is already explored above. Dismissal of DC coupling prior to the PEIR assessment of the scheme is

surprising when an assessment of visual impact at that time could not properly be made. In contrast, the efficiency negatives of AC coupling will have been immediately apparent prior to the PEIR stage. It is noted that there is not a single centralised location for all BESS; there is one available on each site.

Q1.1.9

27. The Applicant is resistant to the idea of setting limits on certain parameters in the DCO in respect of the BESS. There are various justifications for limiting the power (MW) and capacity (MWh) of the BESS. One such reason is to ensure that the BESS actually qualifies as associated development. Setting a limit on capacity or power would not be difficult for the reasons SNTS has explored in its WRs and summary submissions on the draft DCO [REFERENCE]. This matter is addressed further in the submissions made on the current draft of the DCO (submitted at the same time as this document). As to safety matters, this is considered in the short briefing note mentioned above.

Q1.1.14

28. SNTS notes the statement '*fire / explosion risk is directly related to MWh energy contained in each BESS container and the volume of free air*'. SNTS agrees and note this is a factor countervailing against the DCO allowing for an unlimited capacity for the BESS (or, at least, for control over the capacity of each BESS container). Both propensity and severity are increased as the site is more densely packed with capacity.

Q1.1.17

29. The Applicant notes that two water tanks will be located with each of the BESS such as to increase '*resiliency*'. For the reasons expressed by SNTS in its WRs, and the Councils in the LIR, we are of the view that the water storage currently proposed is insufficient considering the difficulty of suppressing a thermal runaway event. Thus, two tanks cannot offer resilience if both (and more) are required in any event. In addition, further water provision increases the risk of breach of the bunding as proposed and consequential wider environmental pollution.

Topic 1.4

30. SNTS broadly supports the approach of the Councils set out in their responses to the ExA's questions. For the reasons expressed by the Councils SNTS supports the requirement for a historic environment management plan. SNTS do not repeat the comments of our heritage expert which can be found appended to our WRs.

Q1.5.8

31. The definition of '*maintain*' was a matter that arose at the ISH on the draft DCO. The definition is very broad, and extends virtually to a permission to do anything in respect of the scheme. Indeed, considering that removing and replacing all of the above ground features of the scheme would not be works done on the '*whole*' of the development, this means that the entire above ground portion of the scheme could change multiple times over its lifetime. This could include wholesale replacement of BESS and PV cells.

32. This matter is explored more in SNTS's comments on the updated draft of the DCO submitted at deadline 3A. SNTS associates itself with the answer provided to this question by the Councils.

Q1.5.78

33. It is noted that the Applicant does not regard it as necessary to undertake operational noise monitoring. In circumstances where article 7 of the draft DCO provides a complete defence to proceedings brought in respect of a nuisance under section 79(1)(g) of the Environmental Protection Act 1990 (noise emitted from premises so as to be prejudicial to health or a nuisance) such an approach is inappropriate. A mechanism must be available to protect sensitive receptors from such harmful noise.

Q1.5.80

34. SNTS notes the codes of practice or guidance cited in answer to this question. We are of the view that the DEFRA Code of Practice for the Sustainable Use of Soils on Construction Sites 2009 should be added (particularly in respect of handling to minimise damage to soils). The code of practice is appended [ATTACH]. Our experts advise us that this is the generally accepted primary guidance on handling to minimise damage to soils.

Q1.6.1

35. In its WRs SNTS has provided a report from Cranfield University which undertakes a whole lifecycle assessment of greenhouse gas emissions for the scheme [CITATION]. This is not repeated here and SNTS does not go through the answer provided by the Applicant to this question. SNTS's position that the scheme produces more greenhouse gas emissions than it saves over its lifetime is set out in that report. A significant factor in this is the omission from Sunnica's assessment of the need to replace BESS lithium-ion cells at regular intervals to maintain their utility. We invite the Applicant to provide an assessment, on a reasonable worst case basis (from a greenhouse gas perspective), of the capacity of the BESS, number of replacements required in its lifetime, and the greenhouse gas emissions this entails for each potential chemistry[5].

36. In the Applicant's answer to the ExA's question does not explore human rights in detail, noting that such a full assessment would require knowledge about manufacturer and country of production. SNTS notes this is the case, although the majority of PV cells are currently produced in China. The ExA may be assisted by the report of the Helena Kennedy Centre for International Justice on the use of forced labour in the global solar supply chain: *In Broad Daylight* (2021) [**Appendix E**].

Q1.6.5

37. We note the suggestion of the removal of piles down to 1 meter by the Applicant. Setting aside the issue of harm in principle, SNTS suggest that such a requirement be a minimum figure and thus removal to a greater depth be implemented if drainage and irrigation requires it.

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[5] Indeed, as is also set out in the Cranfield Report, the generating capacity of the scheme is also problematic. The Applicant should disclose the details of its calculation on generating capacity, including the proposed installed capacity to reach their figure for energy generation over a year.

Q1.6.7, and 1.6.11-12

38. Our ecology expert has produced a briefing note with comments on these answers. This is appended [**Appendix B**] and not repeated here.

Topic 1.7

39. Our landscape experts have produced a briefing note with comments on these answers. This is appended [**Appendix A**] and not repeated here.

Q1.9.2

40. Our agricultural expert has produced a briefing note with comments on these answers. This is appended [**Appendix D**] and not repeated here.

Q1.9.6 to Q1.9.8

41. Our agricultural expert have produced a briefing note with comments on these answers. This is appended [**Appendix D**] and not repeated here.

Topic 1.10

42. SNTS notes that a new construction traffic management plan has been produced on 23 November 2022. This will be reviewed separately when time permits; the comments here deal with matters not appearing to be covered in that review.

Q1.10.4

43. The Applicant's answer does not address additional impacts on junction capacity that result from the proposal as a result of known traffic diversions.

Q1.10.37

44. SNTS note that, in respect of this answer, no reference is made to the cable route connection from the A142 as being a potential access to West B. We maintain the position that routing through Snailwell to access West B is unnecessary and access can be obtained via the cable route.

Q1.10.63

45. SNTS note the restrictions on staff vehicles expressed in this answer. It is unclear, but SNTS suggest that the embargo should include (if it does not already) inter-site traffic at those peak periods.

Q1.10.65

46. SNTS note the proposal that updates to the CTMP and TP will be considered if there is a risk of repeated breaches. SNTS note that any such update should not be merely to excuse breaches, but to instead manage the conduct that poses the risk appropriately to avoid the harm through alternative manageable routes.

Appendix A

Landscape Briefing Note 7

Project:	1186 Sunnica PVD
Date:	25th November 2022
Purpose:	Review and comment on responses to ExQ1
Reference:	1186 BN07 Sunnica PVD Comments on responses to ExQ1.docx
Author:	John Jeffcock CMLI

Introduction

1. This note provides our comments on responses to the Examining Authority's (ExA's) written questions and requests for information (ExQ1). It addresses responses from Sunnica and the Councils to questions on landscape and visual matters, primarily from ExQ1 *Topic 1.7 Landscape and Visual Effects*. Table 1 on the following page provides our comments in relation to each response in turn. Key points from Table 1 are summarised below.

   - We disagree with points made by Sunnica in answers to questions on site selection / design. We consider that as a result of the flawed selection process, sites such as Sunnica West Site A were chosen where significant adverse landscape and visual effects cannot be adequately mitigated through good design or design principles (Q1.0.3 – Q1.0.6).
   - We agree with Sunnica that the only way to reduce the significant adverse cumulative landscape and visual effects identified in the LVIA (and our report[1]) is to significantly reduce the scale of the proposed development (Q1.0.17). However, we consider the extent of cumulative landscape and visual effects generated by the proposals would be greater than identified by Sunnica, and this issue is addressed in more detail in the conclusion at the end of this note.
   - We agree with Sunnica's response in relation to the impacts on views from Ely Cathedral (West Tower) but consider that the more relevant point is the impact on views towards the Cathedral from the Limekilns, which hasn't been addressed (this point wasn't the subject of a question in ExQ1) (Q1.7.1).
   - We have not undertaken a glint and glare assessment and therefore have no comments on Sunnica's conclusions in relation to possible glint and glare effects. However, we do dispute their conclusion on the level of visibility of the scheme from

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[1] Landscape and Visual Issues Relating to the Sunnica Energy Farm, 8th November 2022

Snailwell Gallops, where Sunnica accepts solar reflections could occur (Q1.7.2).

- We support the Councils' request for Sunnica to provide complete surveys of trees and hedgerows, and for the proposed loss of vegetation to be quantified at this stage (Q1.7.3).
- The number of photomontages submitted by Sunnica (12) is disproportionally low compared with the scale of the proposals (nearly 1,000ha). In addition, key viewpoints (e.g., PRoW 204/1 and Chippenham Road) have been omitted without adequate explanation (Q1.7.5).
- We agree with the Councils that the proposals are at a scale and duration which would result in long term changes at a landscape scale, however we consider that the Councils' placemaking recommendations would not overcome the fundamental landscape and visual harm which would occur as a result of the scale and location of the development (Q1.7.7).
- We disagree with Sunnica's response to Q1.7.10. We consider that if the duration of a construction phase is significantly prolonged beyond the assumed timeframe the *duration* of a construction project alone could increase the overall level of construction effects on the landscape, even if progress towards completion continues.
- We disagree with Sunnica's response to Q1.7.10. We consider that an extension of the construction phase beyond 24 months could extend the duration of visual impacts for visual receptors who would see more than one area of the Order Limits as part of a sequential experience, and this may result in a greater overall cumulative visual effect.

Table 1 Review of Sunnica's Responses to ExQ1 Topic 1.7 Landscape and Visual Effects

ExQ1	Question	Comments on Response
Q1.0.3 – Q1.0.6 Sunnica	Questions relating to good design & design principles (due to length, these questions are not repeated in our table).	Section 8 of our report sets out concerns regarding the applicant's site selection process. We consider that as a result of the flawed selection process, sites such as Sunnica West Site A were chosen where significant adverse landscape and visual effects cannot be adequately mitigated through good design or design principles. We disagree that the location of the substation at Sunnica East Site B is sited to minimise its impact on its surroundings. Due to the location of E18 the substation could be located immediately alongside Elms Rd where it would have a significant adverse impact on the character of the road and the visual amenity of people using the road. Refer sections 9 & 10 of our report for more information. We disagree with Sunnica where they consider that co-locating the substations at Sunnica West Site A and East Site A alongside other buildings, would help '*the massing and land use be perceived in the context of existing infrastructure and built structures*'. In both cases the neighbouring built development consists of agricultural buildings which are in keeping with their rural context (a barn next to W17 and a farm complex next to E33). These buildings will not lessen the impact of the BESS developments as they would be dwarfed by them. The BESS developments would not be

ExQ1	Question	Comments on Response
		seen in the context of any significant urbanising features but would be located and visible at locations which are otherwise free from urbanising features, and which have a prevailing rural character. The lack of any significant infrastructure and built structures for co-location purposes reflects the inherently rural location of the BESS sites, especially E33. Significant cumulative effects have not been mitigated by the measures outlined in Sunnica's Appendix A Settlement design iteration. Settlements referenced in Appendix A would be dwarfed by the solar PV and BESS developments, and people travelling between some of these settlements e.g., between Badlingham and Worlington on PRoW U6006 would have a sense of being surrounded by electrical development.
Q1.0.17 Sunnica	Cumulative Effects Assessment (due to its length, this question is not repeated in our table).	Sunnica consider that the significant adverse cumulative effects identified in their LVIA cannot be mitigated by additional planting or design changes without seriously reducing the scale of renewable energy proposed or the build schedule. They suggest that the type of mitigation required would involve removing large areas of the solar PV development and replacing it with woodland. We agree that the only way to reduce the significant adverse cumulative landscape and visual effects of the proposals is to significantly reduce the scale of the

ExQ1	Question	Comments on Response
		proposed development. However, we consider that in some locations woodland planting would be harmful to landscape character. Furthermore, we consider that the current proposals will result in greater cumulative landscape and visual effects than reported in Sunnica's response. More information on this aspect is provided in our report, and in the conclusion to this Note.
Q1.7.1 Sunnica	Visual impact Given that Figure 10-11F [APP-206] shows that there would be visibility of the site from the city of Ely, why has Ely Cathedral been excluded from the Visual Impact Assessment?	Sunnica have provided photography (Appendix I) and a description of the views from the top of the West Tower of Ely Cathedral. Their description corresponds with our experience of visiting the top of the West Tower, albeit in relation to a different project. Their assessment of the impact on this receptor (visitors to the Tower) is comprehensive, and we agree with their conclusion that the overall effect is expected to be negligible. Also of relevance is the fact that the proposals will adversely impact on the character of views towards Ely Cathedral from the Limekilns Gallops (para 9.26 in our report). This point wasn't raised in the question and therefore isn't addressed in Sunnica's response.
Q1.7.2 Sunnica	Glint and glare The Glint and Glare Assessment [APP-121] refers to selected locations rather than	Sunnica's response in relation to the Limekilns is that it is not geometrically possible for the Limekilns Gallops to be affected by glint and glare effects. We have not undertaken a glint and glare assessment

ExQ1	Question	Comments on Response
	general areas of visibility such as are set out in the figures relating to zones of theoretical visibility [APP-201 to APP-206]. Why have areas with potentially high levels of visibility, such as the Limekiln Gallops, been omitted from the Glint and Glare Assessment?	and therefore have no comments on this conclusion. For the same reasons we have not commented on Appendix J to Sunnica's response. Sunnica state that it is possible for solar reflections to effect Snailwell Gallops, but they consider that existing vegetation would screen these impacts. Our assessment finds that there would be visibility of the solar panels, particularly during winter months, from Snailwell Gallops & PRoW 204/5 alongside the gallops. Existing and proposed planting is unlikely to screen the panels entirely, with filtered views expected. We are not in a position to assess whether this level of visibility would result in glint and glare effects or not.
Q1.7.3 East Cambridgeshire District Council (ECDC)	ECDC Relevant Representation [RR-0998] Section 6.15 states that "There continues to be a lack of relevant details in the submitted application, this does not promote the full and clear understanding of the landscape and visual effects of the proposal. This may substantially limit the ability to provide precise	We support the Councils' request for Sunnica to provide complete surveys of trees and hedgerows, and for the proposed loss of vegetation to be quantified at this stage. We also support their request for a detailed landscape masterplan to be prepared. This would provide further information on the planting which is relied upon for mitigation in the applicant's assessment of landscape and visual effects. We note in response to Q1.7.11, Sunnica intend to provide an Arboricultural impact assessment at a future deadline. In the draft statement of common ground between the Councils and Sunnica, Sunnica also propose to provide a detailed

ExQ1	Question	Comments on Response
	comments within the LIR". Please provide further details on what information they consider to be absent, in order for the Applicant and other Interested Parties to be able to comment.	environmental masterplan. In their response to Q1.7.1 Sunnica have addressed the omission of a visual assessment from Ely Cathedral.
Q1.7.4 Suffolk County Council (SCC)	SCC Relevant Representation [RR-1340] Section 7.22 states that "The continued lack of relevant detail (for example, with regards to the spatial arrangement of various components of infrastructure in each parcel; the quantification of vegetation losses; the consideration of required visibility splays for access points and their impact on roadside trees and hedges; the design of access points; etc.) does not promote the full and clear understanding of the landscape and visual effects of the	SCC do not provide a specific response to this question but instead refer to their response to Q1.7.3.

ExQ1	Question	Comments on Response
	proposals.”. Please provide a full list of the details which it considers are absent, so that the Applicant and other Interested Parties are able to comment.	
Q1.7.5 Sunnica	Landscape and visual assessment ES chapter 10 [APP-042], Table 10-2, provides a response to a number of comments within the Scoping Opinion and from other consultation bodies. Some of these are not fully responded to or are not included within the relevant section of the ES chapter. Please provide the methodologies for the Type 2 photomontages (as the Type 4 methodology is detailed in the relevant appendix but Type 2 is not), including an explanation as to why only selected viewpoints have the	Sunnica acknowledge that reference to Type 2 photomontages was in error, and they should have described these as Type 1 images (annotated photographs). Sunnica’s explanation of why only some viewpoints have Type 4 photomontages is that only key viewpoints selected through consultation with Suffolk CC and West Suffolk CC were included. In their response, Sunnica refer to a new technical note attached as Appendix L which includes a section on viewpoint selection in which Sunnica states that ‘photomontages were provided for a selection of key viewpoints’. As per our report (para 11.18 onwards) we consider there are too few photomontages, and that key viewpoints have been omitted without adequate explanation. While the inclusion of 12 photomontages might seem appropriate for a single development application, the order limits cover almost 1,000ha, and consist of several substantial dispersed developments. There is only 1 photomontage for the entirety of Sunnica West Site B (66ha), which will have impacts

ExQ1	Question	Comments on Response
	photographs and wireframe montages, and why this section uses the terminology Type 2 or 4 whereas the rest of the document refers to Type 1 and 4.	at more than one location, e.g., PRoW 204/1 and Chippenham Road. New photomontages have been submitted which show the mitigation planting at Year 5 for Vps 5, 15A, 32 & 46 (Appendix M). These images show that the proposed planting would do very little to mitigate the visual impact of the proposals at Year 5.
Q1.7.6 Suffolk County Council (SCC)	SCC Relevant Representation [RR-1340] Section 7.18 states that “However, a key component in the success or otherwise, of the project’s Green Infrastructure (GI) will be effective management, in the short and long term, and this should be part of the LEMP vision. Inconsistencies within the Environmental Statement (ES) with regard to the retention of the gained Green Infrastructure post-decommission create uncertainty. If the intention is for the proposed GI to reflect the surrounding landscape character and	We do not have any comments on the Councils’ response to Q1.7.6, which primarily concerns responsibility for GI and land ownership post decommissioning.

ExQ1	Question	Comments on Response
	context, this should be part of the overall LEMP vision". Please provide further details on these inconsistencies, in order for the Applicant and other Interested Parties to be able to comment.	
Q1.7.7 Relevant Authorities	Landscape mitigation The local authorities' Relevant Representations refer to the need for "positive place making" or "innovative design solutions" in order to ensure that appropriate mitigation is provided. Could the local authorities please explain in more detail what they mean by this and what they would like the Applicant to submit in order to demonstrate that appropriate mitigation will be provided.	We agree with the Councils that the proposals are at a scale and duration which would result in long term changes at a landscape scale. The Councils have offered a number of specific recommendations concerning detailed design and place-making initiatives. Whilst these recommendations are positive in place making terms, we consider that even if implemented they would not overcome the fundamental landscape and visual harm which would occur as a result of the scale and location of the proposals.
Q1.7.8 East Cambridgeshire District Council	ECDC Relevant Representation [RR-0998] section 6.13 states that "Current inconsistences within	ECDC refer to the Councils' response to Q1.7.6. As above, we do not have any comments on the Councils' response to Q1.7.6.

ExQ1	Question	Comments on Response
(ECDC)	the Environmental Statement with regards to the retention of the gained Green Infrastructure create uncertainty. If the intention is for the Green Infrastructure to reflect the surrounding landscape character/ context this should again form part of the LEMP". Please provide further details on these inconsistencies, in order for the applicant and other interested parties to be able to comment.	
Q1.7.9 Sunnica	Landscape mitigation Please confirm whether a hedgerow is proposed between plots E12 and ECO3.	Sunnica have confirmed that a hedgerow is proposed in this location.
Q1.7.10 Sunnica	Construction impacts on landscape ES chapter 10 [APP-042], paragraphs 10.1.2 and 10.3.9 states that effects of a short construction period extension beyond 24 months are	Sunnica appear to suggest that an increase in the duration of the works wouldn't alter the magnitude of change, because it is only one of several considerations. There are four considerations (size, scale, duration, and reversibility), and we consider that an increase or change in any one of these factors can increase the overall judgement on magnitude.

ExQ1	Question	Comments on Response
	not noted to be enough to change the assessment. Please confirm: i) Why this is considered to be the case, as limited evidence has been provided. ii) At what point in time additional assessment would be required as the location, duration, magnitude or significance of effects has changed.	We disagree with Sunnica's response where they state that *'Should the overall construction programme become longer than the assumed 24 months, which might be the case if it is phased sequentially field by field for example, it would not extend the duration of impact for a specific visual receptor. The visual receptors that have been assessed do not have views over large swathes of the Order limits; their views are limited to relatively small areas of the Order limits'.* Sunnica's response above does not reflect the fact that visual receptors are people and are not static. Visual receptors using the local rights of way network and roads would see more than one area of the Order Limits as part of a sequential experience. In relation to these receptors in particular, we consider that an extension of the construction phase beyond 24 months would extend the duration of visual impacts, and this may result in a greater overall cumulative visual effect.
Q1.7.11 Sunnica	Trees & woodland With reference to ES Chapter 10, Landscape and Visual Amenity [APP-042] paragraph 10.3.4, please explain why you consider it appropriate not to	Sunnica intend to submit an Arboricultural impact assessment at a '*future deadline*'.

ExQ1	Question	Comments on Response
	have undertaken a detailed Arboricultural assessment at the application stage?	
Q1.7.12 Sunnica	Trees & woodland [APP-264] paragraph 2.2.70 states that there are “no ancient woodland or veteran trees within the order limits”; however para 5.1.7 of the Tree Constraints Report [APP-101] states that several trees with veteran characteristics were identified during survey work.	Sunnica state that there is a drafting error in para 2.2.70 and that there are ‘*a number of trees considered to qualify as veteran*’. Sunnica will add to the OLEMP proposed mitigation measures to avoid loss/impact to these trees ‘*in due course*’.

2. Although not a response to ExQ1, Document Ref EN010106/APP/8.11 was also submitted at Deadline 2. This is Sunnica’s response to comments made by Say No to Sunnica (SNTS) concerning the change application. Sunnica’s response does not include revised drawings to correct the presentational issues identified by SNTS, and therefore we consider that the concerns raised in SNTS’s comments remain valid.

Conclusion

3. We consider that as a result of the flawed selection process, sites such as Sunnica West Site A were chosen where significant adverse landscape and visual effects cannot be adequately mitigated through good design, design principles, or the Councils’ recommendations relating to place-making (Q1.0.3 – Q1.0.6 and Q1.7.7).

4. We agree with Sunnica that the only way to reduce the significant adverse cumulative landscape and visual effects identified in the LVIA (and our report[2]) is to significantly reduce the scale of the proposed development. However, we consider that the proposed development will result in greater cumulative landscape and visual effects than reported in Sunnica's response to Q1.0.17 or their report attached as Appendix K.

5. Factors not considered in Sunnica's response, which may have led to their underestimation of cumulative effects, include:

   - The high number and dispersal of development sites across the landscape. Although Sunnica refer to 4 development sites[3], these sites are fragmented and several of the development areas are physically detached and separated by substantial distances or by the A11 e.g., W15. This means that the overall number of development sites, which are considered to be separate, should be 7.
   - The scale of the development. At 652.1 hectares, the combined development footprint of the solar PV developments and the BESS developments would dwarf surrounding settlements. Most are rural villages whose identities are intrinsically linked to the productive countryside.
   - The repeated awareness of the development for people travelling between different settlements including Worlington, Freckenham, Isleham, Badlingham, and Chippenham as the wider landscape surrounding these villages would be dominated by electrical development.
   - The conversion of more than 450ha of land within the Rolling Estate Chalklands LCTs from farmland to electrical development, resulting in a fundamental change to its otherwise largely rural landscape character.
   - The short timeframe in which these fundamental changes to landscape character would occur. The changes would not be gradual or incremental over time, but instead would be perceived to happen all at once.
   - Difficulties in successfully integrating the proposed development in those parts of the order limits that are inherently open in character (e.g. Sunnica East B) or are overlooked due to changes in landform and where there are also historically important views (e.g. Sunnica West Site A).

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[2] Landscape and Visual Issues Relating to the Sunnica Energy Farm, 8th November 2022

[3] Sunnica West Site A, Sunnica West Site B, Sunnica East Site A, Sunnica East Site B.

6. In response to Q1.0.17, Sunnica consider that the type of mitigation required to mitigate the significant adverse cumulative effects that they have identified, would involve removing large areas of the solar PV development and replacing it with woodland. While we agree that the only way to reduce the significant adverse cumulative landscape and visual effects of the proposals is to significantly reduce the scale of the proposed development, we disagree with the assumption that woodland planting would be appropriate. Attempting to mitigate the impact on the Rolling Estate Chalklands LCT[4], especially south and east of Isleham (Sunnica East B) with woodland or other types of screen planting, would harm the openness of this landscape, which is an intrinsic characteristic and fundamental to local identity. The inability to successfully integrate the development and adequality mitigate its impacts without exacerbating adverse impacts on the landscape is a key issue, and one which relates fundamentally to the location of the proposed development.

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[4] In Appendix K, Sunnica conclude there would be a significant cumulative effect on this LCT. In their response to Q1.0.17 they refer to the LCT affected as the Lowland Village Chalklands Landscape Character Type. These LCTs cover similar areas but are from different assessments. The former is from the Suffolk Landscape Character Assessment, 2008. The latter is from the East of England Framework, 2011.

Appendix B

Planning Act (2008)
PROPOSED SUNNICA ENERGY FARM
EN010106

Deadline 3 submission 28 November 2022

1. Comments on Sunnica Ltd's responses to First Written Questions
2. Comments on draft Statements of Common Ground
3. Comments on Framework Construction, Operational and Decommissioning Management Plans

Bioscan UK Ltd
for
Say No To Sunnica

E2132R3

COMMISSIONED BY

Say No to Sunnica

PROPOSED SUNNICA ENERGY FARM

Submissions on Ecology Matters:

1. Comments on Sunnica Ltd’s responses to First Written Questions
2. Comments on draft Statements of Common Ground
3. Comments on Framework Construction, Operational and Decommissioning Management Plans

Examination Deadline 3
28 November 2022

Bioscan Report No.
E2132R3

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CONTENTS

1 INTRODUCTION

1.1.1 This document contains comment, observations, matters of concern and (where applicable) rebuttal or corrective responses from Bioscan on behalf of Say No To Sunnica (SNTS), on the following:

1) The responses from Sunnica Ltd to the Examining Authority's First Written Questions (FWQs), as submitted at Deadline 2 [REP2-037 and REP2-038];

2) The initial (draft) Statements of Common Ground of the Local Authorities [REP2-044], the Environment Agency [REP2-045], Natural England [REP2-046] and the Suffolk Wildlife Trust [REP2-049];

3) The latest versions of the Framework Construction Environmental Management Plan [REP3-015 and REP3-016], the Framework Operation Environmental Management Plan [REP2-030 and REP2-031] and the Framework Decommissioning Environmental Management Plan [REP2-028 and REP2-029].

1.1.2 The following sections deal with each of the above in turn.

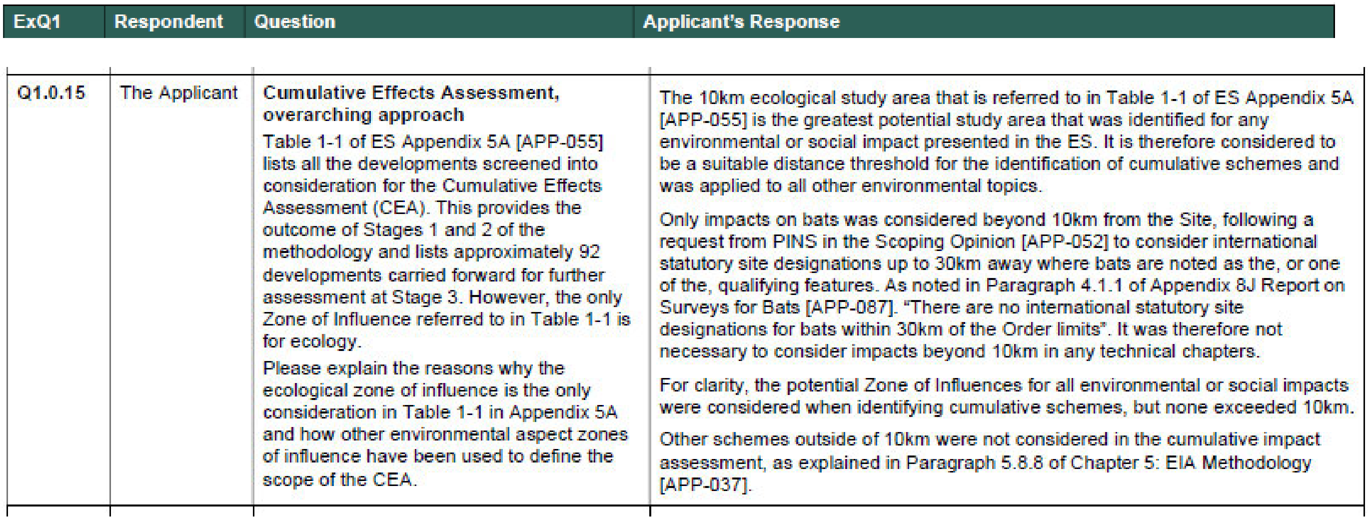
2 COMMENT ON THE RESPONSES FROM THE APPLICANT (SUNNICA LTD) TO THE EXAMINING AUTHORITY'S FIRST WRITTEN QUESTIONS (FWQs)

2.1 Format of comments

2.1.1 In places below we have extracted, via screengrabs or quoted text, extracts from the table presented in section 2 of Sunnica Ltd's response document [REP2-037], relating to specific questions upon which we wish to make comment. Where we have done this, we provide our commentary below each in turn below. Elsewhere, for brevity, we simply reference the question number and the subject it addresses by way of heading. Reference should be made to REP2-037 for the precise wording of the question and Sunnica Limited's response in those cases.

2.2 Comments on Sunnica Ltd's Responses to the FWQs.

Q1.0.15: Cumulative Effects Assessment - Methodology



ExQ1	Respondent	Question	Applicant's Response
Q1.0.15	The Applicant	**Cumulative Effects Assessment, overarching approach** Table 1-1 of ES Appendix 5A [APP-055] lists all the developments screened into consideration for the Cumulative Effects Assessment (CEA). This provides the outcome of Stages 1 and 2 of the methodology and lists approximately 92 developments carried forward for further assessment at Stage 3. However, the only Zone of Influence referred to in Table 1-1 is for ecology. Please explain the reasons why the ecological zone of influence is the only consideration in Table 1-1 in Appendix 5A and how other environmental aspect zones of influence have been used to define the scope of the CEA.	The 10km ecological study area that is referred to in Table 1-1 of ES Appendix 5A [APP-055] is the greatest potential study area that was identified for any environmental or social impact presented in the ES. It is therefore considered to be a suitable distance threshold for the identification of cumulative schemes and was applied to all other environmental topics. Only impacts on bats was considered beyond 10km from the Site, following a request from PINS in the Scoping Opinion [APP-052] to consider international statutory site designations up to 30km away where bats are noted as the, or one of the, qualifying features. As noted in Paragraph 4.1.1 of Appendix 8J Report on Surveys for Bats [APP-087]. "There are no international statutory site designations for bats within 30km of the Order limits". It was therefore not necessary to consider impacts beyond 10km in any technical chapters. For clarity, the potential Zone of Influences for all environmental or social impacts were considered when identifying cumulative schemes, but none exceeded 10km. Other schemes outside of 10km were not considered in the cumulative impact assessment, as explained in Paragraph 5.8.8 of Chapter 5: EIA Methodology [APP-037].

2.2.1 Sunnica Ltd's statement above, which echoes the wording at 6.6.4 of the ES [APP-040], that "*There are no international statutory site designations for bats within 30km of the Order limits*" is factually incorrect.

2.2.2 Eversden and Wimpole Woods Special Area of Conservation (SAC) is approximately 26.7km from the Burwell substation which lies within the Order limits. This site is designated for the presence of the rare Annex II bat species barbastelle *Barbastella barbastellus.*

2.2.3 This omission or oversight is particularly relevant to both the EIA and HRA processes as this rare bat species disperses significant distances from roosts for foraging purposes. Indeed it was found within the Order limits, including grid connection areas, by the applicant [see ES Appendix 8J – APP-087]. There is the potential, therefore, for a functional linkage between the land covered by the Order limits and the Wimpole Woods Special Area of Conservation that has not been identified or assessed.

Q1.2.1: Ecological Assessment Methodology

2.2.4 The first part of this question relates to the methodology and terminology employed by the applicant to characterise the magnitude and significance of effects on ecological receptors.

2.2.5 The applicant's departure from the CIEEM approach (for reasons it would seem of no more than consistency with other ES chapters), which lies at the root of the ExA's question, has the effect of masking effects that are significant at Local (e.g. Parish) level. The reason the CIEEM industry standard advocates against the matrix-based approach is precisely because effects at this level have the potential to fail to comply with national and local policy (e.g. to avoid net loss of biodiversity) and thus the matrix approach can result in artificially restricted considerations of cumulative effects, as impacts below EIA significance thresholds are 'screened out'. In short, the threshold for significance in EIA terms is above the level at which significant effects on ecology, that have the potential to engage with policy, might, or will, actually occur. Fixation on a traditional EIA approach, eschewing the more up to date and relevant methodology set out in the CIEEM Guidelines, can and does result in impacts which may be major in magnitude at local (e.g. Parish) geographical frames of reference being disregarded as 'not significant'. When such impacts are considered cumulatively, there is a logical shift in amplitude upwards to District or higher geographical levels which the applicant's approach risks missing, inadequately documenting, or downplaying. A relevant example in this case would be the cumulative effects of loss of arable land of value to a range of scarce, arable-adapted, flora and fauna being inadequately accounted for in the impact assessment.

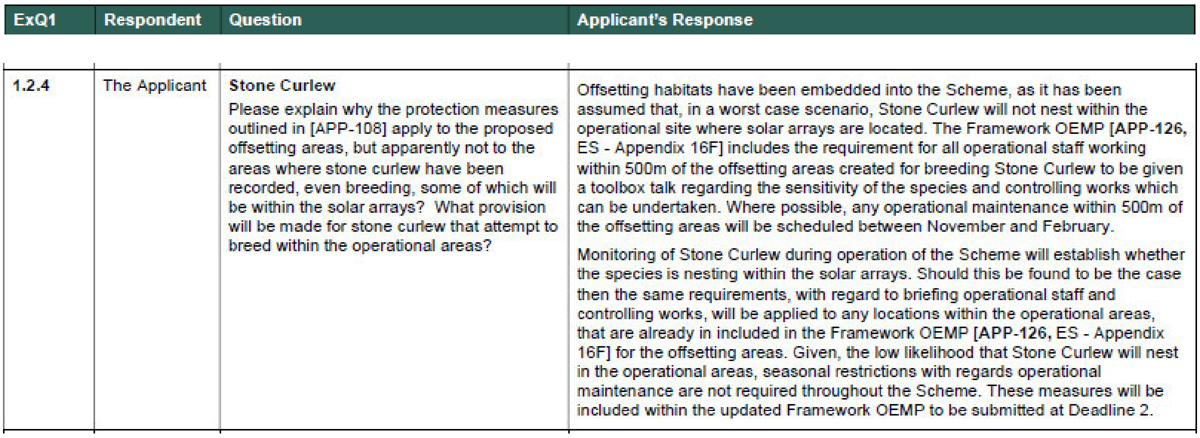
2.2.6 We therefore comment that the applicant's statement in response to this question – that "*the assessment approach follows the good practice guidelines for ecological impact assessment (EcIA) described in CIEEM (2018)*" - is not strictly correct. The applicant has departed from the recommended methodology set out in CIEEM (2018 and as subsequently revised) and, for the reasons set out above, the EIA is rendered less comprehensive and robust because of this. We would further remark that it is notable that the applicant does **not** claim that the 264m of hedgerow removal it uses as the basis of its assessment of loss for this receptor is the worst-case scenario. Nor whether this is consistent with the figures arising from the recently submitted Arboricultural Impact Assessment discussed later in this submission.

2.2.7 On the second part of the ExAs question, we comment in section 4 of this submission on how the 'design controls' to avoid and minimise impacts on biodiversity as set out in the framework CEMP, OEMP and DEMP are high level and nebulous, and subject to significant questions over the resourcing capability applied to the essential clerk of works personnel that will ensure they are adhered to and/or enforced. In essence, we do not consider that the applicant, in seeking the degree of flexibility that it does, has fully engaged with the mitigation hierarchy nor that it has fully committed to engagement with that hierarchy at the detailed and/or construction stages, and that it is relying on nebulous commitments and failsafes that it provides no evidence as being appropriately committed to or resourced.

Q1.2.3 – Stone Curlew

2.2.8 Given the importance of the area affected by the Order limits for this species, and the actual or potential functional linkages to the Breckland SPA, we consider it a matter of concern that there still remain matters of uncertainty and negotiation over the type, level and significance of impacts on this iconic species and the adequacy of the mitigation and compensation proposed for it. Our comments on the interim SoCG between the applicant and Natural England on this matter are also relevant and are as set out in section 3 of this submission.

Q1.2.4 – Stone Curlew



ExQ1	Respondent	Question	Applicant's Response
1.2.4	The Applicant	**Stone Curlew** Please explain why the protection measures outlined in [APP-108] apply to the proposed offsetting areas, but apparently not to the areas where stone curlew have been recorded, even breeding, some of which will be within the solar arrays? What provision will be made for stone curlew that attempt to breed within the operational areas?	Offsetting habitats have been embedded into the Scheme, as it has been assumed that, in a worst case scenario, Stone Curlew will not nest within the operational site where solar arrays are located. The Framework OEMP **[APP-126**, ES - Appendix 16F] includes the requirement for all operational staff working within 500m of the offsetting areas created for breeding Stone Curlew to be given a toolbox talk regarding the sensitivity of the species and controlling works which can be undertaken. Where possible, any operational maintenance within 500m of the offsetting areas will be scheduled between November and February. Monitoring of Stone Curlew during operation of the Scheme will establish whether the species is nesting within the solar arrays. Should this be found to be the case then the same requirements, with regard to briefing operational staff and controlling works, will be applied to any locations within the operational areas, that are already in included in the Framework OEMP [**APP-126**, ES - Appendix 16F] for the offsetting areas. Given, the low likelihood that Stone Curlew will nest in the operational areas, seasonal restrictions with regards operational maintenance are not required throughout the Scheme. These measures will be included within the updated Framework OEMP to be submitted at Deadline 2.

2.2.9 We do not agree with the applicant that a scenario where stone curlew refuse to nest amongst the solar arrays or otherwise in the operational site is "worst case". In the absence of any evidence that the species habitually does nest amongst solar arrays or in solar farms, this should instead be considered the likely and realistic case. Indeed, we note that the applicant itself, in its answer to the question above, considers the prospect of this species nesting within solar arrays to be "low likelihood". If the applicant accepts there is only a 'low likelihood' of the species nesting within solar arrays, then the prospect of that low likelihood of nesting being manifested as no nesting, cannot be a 'worst case' scenario.

2.2.10 The applicant's latter position (that there is a low likelihood of stone curlew nesting within solar arrays), is of course the more robust on the available evidence. On this basis, we support the concerns raised by RSPB and others over whether the quantum of compensatory provision for this species is adequate, considering the worst-case magnitude of displacement (i.e. as counted in numbers of pairs or held territories/breeding attempts, and taking into account likely displacement and/or disturbance effects at 500m or more), and also taking a precautionary approach to matters such as the success of habitat creation in compensation areas and their likely take up by the species, having regard to its specific autecological attributes.

Q1.2.5 – Stone Curlew

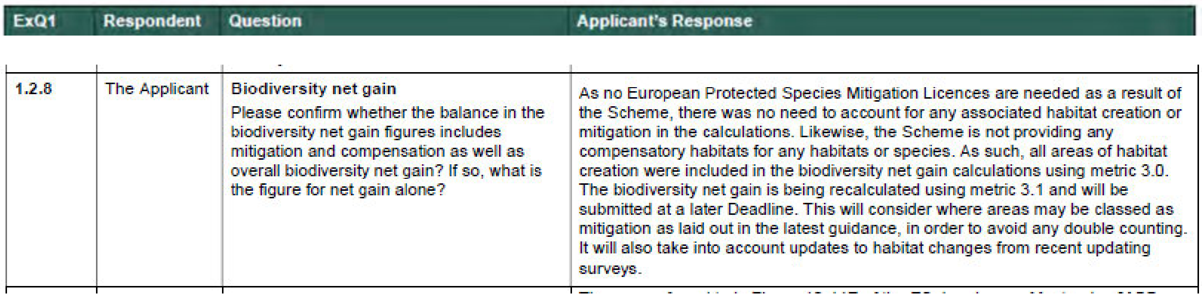
2.2.11 The applicant's answer to this question from the ExA about the 'appropriateness, adequacy and realism'; of the proposed offsetting measures for stone curlew does not in our view provide comfort that any more than a *de minimis* approach has been taken to compensation for this species. Using simple arithmetic of pairs x territory size to determine compensation effort builds in no 'risk multipliers' of the sort now incorporated as standard in compensatory calculations (e.g. under the Biodiversity Metric). The applicant's intention to rely on 'adaptive management prescriptions' appears to be a further recognition as to the huge margins of uncertainty over delivery of appropriate compensatory habitat for this species. In this context the necessary headroom built in to the compensation provision for failure is, in our view, absent or inadequate.

2.2.12 In the baseline state, stone curlew occupy various areas of the Order limits at various times. In this context the net diminution in area available to these birds, not only for breeding but also for post-breeding congregation and foraging at other times, does not appear to have been considered on a precautionary basis. In the absence of supporting evidence as to the efficacy of the measures the applicant proposes by way of compensation, the likely outcome is some degree of diminution in numbers using the Order limits, for breeding or generally. We are not satisfied that the applicant has duly assessed the impact of displacement of a proportion of the local population into surrounding farmland, including whether there is suitable habitat available to absorb displaced birds, nor the potential in-combination effects of this with other future land-use changes predictable locally (including both development and non-development land-use changes).

Q1.2.7 – Stone Curlew

2.2.13 The provisions and failsafes suggested by the applicant in response to this question appear broadly appropriate, but the larger issue with the compensatory habitat provision is as discussed under Q1.2.5 above.

Q1.2.8: Biodiversity Net Gain



ExQ1	Respondent	Question	Applicant's Response
1.2.8	The Applicant	**Biodiversity net gain** Please confirm whether the balance in the biodiversity net gain figures includes mitigation and compensation as well as overall biodiversity net gain? If so, what is the figure for net gain alone?	As no European Protected Species Mitigation Licences are needed as a result of the Scheme, there was no need to account for any associated habitat creation or mitigation in the calculations. Likewise, the Scheme is not providing any compensatory habitats for any habitats or species. As such, all areas of habitat creation were included in the biodiversity net gain calculations using metric 3.0. The biodiversity net gain is being recalculated using metric 3.1 and will be submitted at a later Deadline. This will consider where areas may be classed as mitigation as laid out in the latest guidance, in order to avoid any double counting. It will also take into account updates to habitat changes from recent updating surveys.

2.2.14 Bioscan, on behalf of SNTS, have a number of comments to make with regard to the applicant's answer to this question, per the screengrab above.

2.2.15 In the first instance, the applicant's reference to European Protected Species licences, despite being beside the point, highlights that we remain to be convinced that no European Protected Species mitigation licences are needed as a result of the Scheme, and we consider that the Examining Authority is, at least currently, bereft of sufficient information to agree with the applicant's position.

2.2.16 We have highlighted, for example, omitted records for great crested newts from Chippenham Fen, in locations where terrestrial phase animals could range into the proposed development areas within the Order limits. There are questions over the veracity of the omitted GCN record (which originates from a licence return on 'Magic', as detailed in our reports included in SNTS's Written Representation), but until this is resolved the applicant is not in a position to state that this species could not be impacted and that no licensing provisions can apply, and should not be doing so. Similarly, the flexibility the applicant seeks in respect of road crossings, hedgerow removal and the risk of impacting trees with potential for bat roosting, means that the suggestion that there is no scope for licensing for bats to be required during implementation is similarly non-precautionary. It appears to be flatly contradicted by the Arboricultural Impact Assessment submitted at Deadline 3.

2.2.17 Notwithstanding the above, the Examining Authority's question was about Biodiversity Net Gain (BNG) which is a matter on which we have made detailed submissions via the Bioscan reports contained in SNTSs Written Representation. In light of the applicant's statements that they intend to submit more information on BNG, it is enough for us to ask the Examining Authority to note that the comments and concerns we raised in STNSs written representation are not answered in the applicant's response above. We note the applicant confirms its intention to recalculate its BNG figures using Metric 3.1 and to submit these "at a later deadline". It remains to be seen whether the habitat classification and other errors we have brought first to the applicant's attention and latterly to the Examining Authority's attention will be duly and properly corrected as part of this process.

Q1.2.9: Ecological Mitigation (proposed wet grassland adj. River Snail)

2.2.18 We note that the applicant recognises that the area proposed for compensatory habitat creation/mitigation south-west of Chippenham Fen is "*influenced by the River Snail*", but there does not appear to have been any hydrological modelling demonstrating how inundation frequency for the proposed wet grassland will be optimised, without either topographical changes to reduce land levels, or changes to the physical form and character of the river channel itself – neither of which appear to be being proposed. In the absence of such interventions, there can be little confidence in the development of any wetter a grassland than at present, and in this context the contribution towards mitigation, compensation and BNG scores from this element of the proposals has to be treated with caution. Surface scarification and re-seeding is proposed but in the absence of hydrological change, and without interventions to influence soil chemistry, this is highly unlikely to deliver a significant uplift in habitat quality and, in stating that the proposals "*will utilise the existing soil conditions and topography*" the applicant appears to be confirming that no more than localised scarification and seeding is actually proposed. It is noted that the applicant is "*currently working with stakeholders to agree an appropriate management regime for this area*". We suggest such discussions should also include the practical detail of how the objectives will be physically achieved, rather than be restricted to discussions about management, to ensure this habitat creation is meaningful and not tokenistic.

Q1.2.10: Grassland Re-establishment

2.2.19 We note that the Examining Authority has picked up on the confused picture as regards the grassland creation objectives set out in the ES, and we note that the applicant is moving to provide clarity on the area-by-area objectives. This is welcomed, and we note that the applicant's BNG calculations will need to change to reflect this rationalisation of objectives and their improved alignment with what is achievable in practice.

2.2.20 However, we note, as a point of concern, that in listing the factors influencing decision on species-composition for sown grasslands, no consideration is given in the applicant's response to the availability of suitable native seed. This may well provide to be the single most important driver in success in achieving variation and/or target condition. If insufficient seed is available, (and the quantity required for this project appears to far outstrip the resources of commercial suppliers in any given year), the likely result across large areas of the proposed Order limits will be much more mundane and uniform grassland types derived from a relaxation of cultivation – comprising a flush of ruderal species and ubiquitous grasses tolerant of latent high-fertility levels. We make further comment on this important matter under Q1.2.11 below.

Q1.2.11: Grassland Re-establishment (2)

2.2.21 The applicant's response to this question is wholly unsatisfactory. It reveals that there has been next to no thinking about this significant logistical challenge to date, and suggests that the applicant did not consider it in any meaningful way until it was raised as a practical concern by several objectors and other stakeholders (including ourselves).

2.2.22 In essence, the answer confirms that the Examining Authority is in no position to have confidence in the habitat creation targets and objectives the applicant seeks to rely upon to support its claims of no net loss of biodiversity and net benefits/enhancement. Nor its claim of serviceable compensation provision for receptors such as stone curlew, and its inflated and exaggerated calculation outputs for BNG. The reference to discussions about 'scope' and possible seed sources that will be subject to a whole suite of agreements and (potentially) consents is to matters that should have been concluded, or at least significantly further advanced, before submission if the applicant wished the Examining Authority and others to place weight on its habitat creation and enhancement proposals. It is all too easy to say that a seed mix will be used to create habitat 'X', but in real life there are a whole suite of practical and ecological challenges for that objective to be successfully attained. It is not acceptable for the applicant to seek to leave such matters to deep into the Examination later, while at the same time asking the Examining Authority, consultees and stakeholders to accept that the picture it seeks to paint of the post-development scenario is reliable or accurate.

Q1.2.13: Glint and Glare Assessment

2.2.23 We note that the applicant confirms that it made no meaningful efforts to look into this potential impact source prior to submission of the DCO application. Bioscan recognise that this is an area of significant uncertainty and where scientific research is relatively lacking, but given that it is a concern that has been expressed internationally (even if less so to date in the UK), and given the site's proximity to internationally important sites for both birds and invertebrates, this has to be seen as less than best practice and a matter of concern.

2.2.24 The brief comments that the applicant now offers in justification for its decision to scope out any risk to bird species from this potential impact source are concerning. The scope for impact appears to have been limited almost exclusively to a theoretical impact arising from 'significant numbers of waterbirds' becoming confused by the panels, mistaking them for a waterbody and seeking to land on them.

2.2.25 This is a highly simplistic approach that conveys a worrying lack of application of ornithological expertise. The suite of bird species that could mistake the panel arrays for bodies of water is not limited to species of waterfowl that aggregate in flocks. If that was an ecological truism, then 'new' artificially created inland waterbodies such as at the nearby RSPB Lakenheath Fen reserve would never attract the wider suite of wetland species that it has.

2.2.26 Bioscan and SNTS believe that a more robust assessment, supported by empirical data and/or a thorough research review, is needed before the Examining Authority can have any confidence that this potential impact source (glint and glare impacts on birds) can be screened out of further consideration.

2.2.27 Similarly, and as commented upon in our comments on the Local Impact Report ([REP3-026] submitted 22 November 2022), Bioscan and SNTS believe that the assessment the applicant has belatedly carried out of the scope for significant effects on invertebrates (Appendix C of REP-038) is inadequate.

2.2.28 Increasing concerns have been expressed internationally about the potential impact of solar arrays on aquatic invertebrate species attracted to polarised light and there can be little dispute that the evidence of potential impacts from this source is compelling. The panel arrays in Sunnica West Site B (in proximity to the designated Chippenham Fen) therefore pose a credible risk of creating an ecological trap for invertebrate fauna associated with the SAC/Ramsar/SSSI/NNR. This matter should be thoroughly examined in order to define the risk, if any, to the integrity of not only the international designations (in accordance with Appropriate Assessment/HRA requirements), but also the integrity of the SSSI and the site's ecological integrity more generally.

2.2.29 The starting position on this issue, in accordance with the avoid-mitigate-compensate hierarchy, should be to avoid impacts on such high value resources entirely which demands a precautionary approach wherever there is any doubt over whether significant effects could occur.

2.2.30 We note that the applicant's originally submitted HRA [APP-092] gives this matter only cursory attention and appears to rely on the 200m distance between wetland within the international site and the nearest proposed PV positions to suggest that there "are no pathways for significant effects on invertebrates" associated with the SAC and Ramsar (e.g. APP-092 page 8M-60). This assessment is no more than an unevidenced leap of faith. The Examining Authority will note, in any event, that the applicant's position has now changed. Indeed, the conclusions of the applicant's HRA are now flatly contradicted by the applicant's more recent response to the Examining Authority's First Written Questions (FWQs) [REP2-038, Appendix C]. In this appendix, further attention has been given to aquatic invertebrates and the risk posed to them by photovoltaic panels in the form of a desk-based review of available literature and a revised assessment based on little more than guesswork and the use of proxy scenarios. The literature review demonstrates that this is, contrary to the position taken in the HRA, a credible impact risk and it exposes that the complete absence of relevant survey data that would assist in defining the risk more acutely is a significant failing of the application submission. In lieu of empirical data or site-specific evidence to inform this belated impact assessment, the applicant sets up a theoretical scenario using a weak flying taxon (Ephemeroptera) and a set of unproven assumptions about what happens at and around Chippenham Fen.

2.2.31 SNTS/Bioscan consider that baseline invertebrate survey data targeted to the potential impact vector is necessary in order to inform a robust assessment of potential impacts from this source. The approach taken by the applicant and as described in its response to this question is no more than an elaborate exercise in trying to paper over the cracks. Invertebrate surveys could have established whether target species from the SAC/Ramsar populations occur at the locations proposed for panel arrays (rather than guessing whether they do or do not) which could have either lent support to the conclusions the applicant presents that there is no likely significant effects or, in the alternative, could have better defined the magnitude of effects and (where necessary) guided decisions on avoidance, mitigation and compensation. As the applicant has failed to collect such data, it seeks to deal with this potential impact vector to the international site via little more than conjecture and supposition. This is not a robust approach and in the absence of further work, STNS/Bioscan supports the suggestion made by the Councils in their LIR [REP1-024] that the panels should be removed from Sunnica West Site B for precautionary reasons.

Q1.2.14: Biosecurity

2.2.32 Bioscan have no comment to make on this question, albeit SNTS may have commented (or may still comment) separately.

Q1.2.17: Habitats Regulations Assessment (mismatch in area figures)

2.2.33 The applicant's response to this question, that corrections will be forthcoming in a re-submitted HRA, is noted. Bioscan/SNTS may wish to comment on the resubmitted HRA in due course.

Q1.2.18: Habitats Regulations Assessment (cabling within stone curlew areas)

2.2.34 We are unclear from the applicant's answer whether there are implications for the readiness of the stone curlew replacement habitat and/or whether there is a risk (high, low, certain) that cable laying works could disturb the species (if it happens to use the replacement habitat at the time) and if so how that can be avoided if implementation programmes unavoidably clash with the time periods that the species is present. Further clarity on these matters would be appreciated from the applicant.

Q1.2.19: Habitats Regulations Assessment (ExA requested corrections)

Q1.2.20: Habitats Regulations Assessment (piling)

Q1.2.21: Habitats Regulations Assessment (update of matrices)

Q1.2.22: Habitats Regulations Assessment (update of matrices)

Q1.2.23: Habitats Regulations Assessment (update of matrices)

2.2.35 The applicant's proposed corrections and updates to the HRA in response to these questions are noted. Bioscan/SNTS may wish to comment on the resubmitted HRA in due course.

Q.1.2.24: Habitats Regulations Assessment (limits of excavation)

2.2.36 Bioscan/SNTS consider that in referencing the maximum excavation parameters set out at Chapter 3 of the ES, the applicant is indicating that it does not intend to exert tighter controls in proximity to the designated European Site and, furthermore, that it appears to be inviting such controls to be specified in the DCO. We suggest that Natural England should have input into defining suitably precautionary excavation limits within appropriate buffer distances around Chippenham Fen SAC/Ramsar/SSSI/NNR to ensure adequate protection of groundwater catchment.

Q1.2.25: Habitats Regulations Assessment (agreement on mitigation with SNCB)

2.2.37 The applicant's response is noted. Bioscan's/SNTS's comments on the interim statement of common ground between the applicant and Natural England are provided in section 4 of this submission.

Q1.2.26: Habitats Regulations Assessment (tables 4-1 and 4-2)

2.2.38 The ExA's question about presentational clarity and the applicant's response to it are noted. Bioscan/SNTS may wish to comment on the resubmitted HRA in due course.

Q1.2.27: Habitats Regulations Assessment (stone curlew, mitigation hierarchy)

2.2.39 The applicant's proposed corrections and updates to the HRA in response to these questions are noted. Bioscan/SNTS may wish to comment on the resubmitted HRA in due course.

Q1.2.28: Habitats Regulations Assessment (Condition Assessment)
Q1.2.30: Habitats Regulations Assessment (Updates on SPA bird impacts)
Q1.2.31: Habitats Regulations Assessment (Updated matrices)
Q1.2.32: Habitats Regulations Assessment (Updated matrices)

2.2.40 The applicant's proposed corrections and updates to the HRA in response to these questions are noted. Bioscan/SNTS may wish to comment on the resubmitted HRA in due course.

Q1.2.33: Habitats Regulations Assessment (GCN and Fenland SAC)

2.2.41 We note that the applicant does not consider there to be any scope for impact on great crested newt (GCN) populations functionally linked to the Fenland SAC. However, and as set out in Bioscan's reports submitted with SNTS's written representation [REP2-240], this disregards (due to oversight) a past record of GCN from Chippenham Fen which we have since brought to the applicant's attention.

Q1.6.7: Long-term management of ecological mitigation land

2.2.42 The applicant's response to this question provides useful but alarming clarity on the rather tokenistic nature of the proposed mitigation, compensation and enhancements and related commitments. It confirms that even if it were to be accepted that the scheme could deliver net beneficial change in land-uses, there would be nothing in place to prevent any such benefits being reversed in (what is in ecological terms) a very short timescale.

Q1.6.8: Construction Environmental Management Plan
Q1.6.9: Construction Environmental Management Plan

2.2.43 The applicant's responses to these questions are noted. Comments on the framework CEMP are provided at section 4 of this submission.

Q1.6.10: Construction Environmental Management Plan
Q1.6.11 Construction Environmental Management Plan
Q1.6.12: Construction Environmental Management Plan

2.2.44 The applicant’s responses to these questions are noted. The Examining Authority is asked to note the nebulous wording used in order to seek to retain operational and construction flexibility to carry out works at suboptimal times of year (e.g. in respect of bird breeding) and the fact that worst case assumptions underpinning the ES and HRA do not appear to be consistent with this.

Q1.7.11: Absence of Arboricultural Impact Assessment

2.2.45 We note that the applicant has belatedly submitted an AIA at Deadline 3 on which we have yet to comment in detail. However, Bioscan/SNTS note how this illuminates how the original position of the applicant on tree and woodland loss, as set out in the ES, is incorrect, and that this has necessitated revisions to ancillary documents such as the CEMP (see section 4 of this submission), vindicating the ExAs question.

2.2.46 Bioscan/SNTS wish to seek clarity as to whether the Environmental Statement is now similarly going to be revised in order to better reflect the factual position as regards impacts to trees and linear features, and how this may impinge on the previous conclusions drawn, for example about bats, which now quite clearly need to be revisited.

2.2.47 For example, the AIA confirms that “*Two individual trees* [one subject to TPO]*, two tree groups* [also subject to TPO]*, part of four woodland groups, part of 13 tree groups and part of four hedgerow features are to be removed to facilitate the Scheme. This would include four part woodland groups of high quality (Category A), one tree group, part of seven tree groups and part of two hedgerows of moderate quality (Category B), two individual trees, part of six tree groups and part of two hedgerows of low quality (Category C) and one individual tree and one tree group which are unsuitable for retention for more than 10 years (Category U).*”

2.2.48 It is further noted that the AIA states that “*as a reasonable worst case the Scheme would require the removal of up to 150m2 of likely high quality tree cover, 5300m2 of likely moderate quality tree cover and 2850m2 of likely low quality tree cover (8300m2 in total)*.”

2.2.49 The Examining Authority is asked to note the difference between the position as now assessed via the AIA and the statements made in the original ES Chapter such as:

- “*Woodland habitats across the Order limits will be retained*” (ES Chapter 8: Table 8-10, page 8-108)
- “*The construction of the Scheme will avoid features used by roosting and foraging / commuting bats, based on the current baseline conditions. There will be no loss of habitats identified as being important for bats anywhere within the Order limits*.” (ES Chapter 8: Table 8-10, page 8-122)
- “*The construction of the Scheme will not impact upon mature, species-rich hedgerows and other boundary features, which will retain connectivity across the Order limits for commuting and foraging bats. Therefore, there will be no fragmentation of habitats used by bats*” (ES Chapter 8: Table 8-10, page 8-122).

- “*Therefore, there are no impact pathways, either directly or indirectly, that would impact upon bats*”.

2.2.50 In addition, it is noted that based on erroneous assumptions about avoiding tree loss, the ‘Report on Surveys for Bats’ [APP-087: ES Appendix 8J] did not adequately consider impacts on bats arising from loss of foraging or roosting habitat (see para 5.5.5 of that document). It went on to recommend that “*further more detailed bat roost surveys will be required at specific features (i.e. structures with low to high roost suitability and trees with moderate to high roost suitability) to inform mitigation and potential licence application in accordance with best practice guidance*”. In light of the results of the AIA, that position would appear to have been reached. Bioscan/SNTS therefore wish to seek clarity from the applicant as to whether and when it is now duly carrying out this additional work, and whether it intends the results to be available before the close of the Examination.

Q1.7.12: Inconsistency regarding veteran trees

2.2.51 We note that the applicant has recognised the inconsistency highlighted in the ExA’s question as regards veteran trees within the proposed Order limits and that this may necessitate design changes. We ask the ExA to note how this is consistent with other errors and omissions noted on the baseline habitat surveys and as set out in Bioscan’s reports appended to SNTS’s written representation. We await the applicant’s update surveys (promised at Deadline 1) to see whether similar design and mitigation implications are triggered in other areas due to deficiencies in the baseline and reliance on assumptions that later prove to be incorrect. We will offer further comment on this, and its implications, in due course.

2.3 Overall conclusions on applicant’s responses to FWQs

2.3.1 Bioscan and SNTS consider that the applicant’s responses to the Examining Authorities First Written Questions (and indeed the volume of those questions), illuminate the lack of thoroughness in the applicant’s submitted ES and HRA, and related submission material. We await several further revised submissions on matters that should have been available to the Examining Authority, and stakeholders, at the outset, including on crucial factors such as compliance with the Conservation of Habitats and Species Regulations, the mitigation hierarchy and crucial details that directly influence the weight that can or cannot be attached to the applicant’s claims on enhancement, compensation and biodiversity net gain. The Examining Authority is asked to note the additional burden that responding to this material in such a piecemeal way places on stakeholder groups with limited resources, such as SNTS. We also note the applicant’s revealing answer to Q1.6.7 which confirms beyond any residual doubt that any compensatory or enhancement benefits secured via the DCO would likely be temporary, with no residual control over land beyond the *maximum* 40-year life of the proposed solar facility.

3 COMMENTS ON DRAFT STATEMENTS OF COMMON GROUND

3.1.1 On behalf of SNTS, Bioscan's comments on the draft/interim statements of common ground of the Local Authorities, Natural England, Suffolk Wildlife Trust and the Environment Agency are set out in turn below:

3.2 Local Authorities

3.2.1 Bioscan note and agree with the position implied by the lack of agreement between the applicant and the Local Authorities on 'application of expert/professional judgments' – i.e. that the Local Authorities are not satisfied that the judgments reached by the applicant on ecological matters are robust. The catalogue of habitat classification errors, assessment omissions and unevidenced leaps of faith about the future position support the LPAs position of non-agreement at this stage. Indeed, it might be argued that they are added to or confirmed at each Examination deadline.

3.2.2 We note under 'matters under discussion' that the applicant intends to submit the delayed additional surveys responding to omissions identified by ourselves and others at Deadline 3, not Deadline 1 as originally advised. The ExA is reminded of our comments at 2.3.1 above about how these shifting deadlines for receipt of new information bears upon the satisfactory (or otherwise) running of the examination in respect of SNTSs limited time and resources (and not least those of PINS).

3.2.3 We note that the applicant states that it is intending to submit a revised Metric 3.1 calculation to the Examination "*at the earliest convenience*". If this material is not forthcoming at Deadline 3, then we consider that greater clarity on this submission timescale should be sought by the ExA.

3.3 Natural England

3.3.1 Bioscan and SNTS disagree that the study areas adopted by Sunnica within the ecology and nature conservation assessments "*reflects current best practice and standards*" and we question why this has been agreed by Natural England.

3.3.2 As set out in our response to FWQ 1.0.15 above, the applicant's claims that there are no international sites designated for their bat interest within 30 km of the proposed Order limits appears to be factually incorrect. Specifically, Eversden and Wimpole Woods Special Area of Conservation (SAC) is approximately 26.7km from the Order limits at Burwell substation. This SAC is designated for the presence of the rare Annex II bat species barbastelle *Barbastella barbastellus*. This omission or oversight is particularly relevant to the EIA (and HRA) processes as this rare bat species disperses significant distances from roosts for foraging purposes and has been recorded within the Order limits. This oversight also calls into question the statement, presented as an agreed matter, that "*The parties agree that the Stage 1 – Screening has identified all relevant sites, potential impact pathways and has taken into consideration all potential Likely Significant Effects*."

3.3.3 We note that there is a divergence of opinion between NE and the Local Authorities on whether the application of professional judgement by specialists in respect of ecological impacts is appropriate and robust. Bioscan and SNTS agree with the Local Authorities that there are clear grounds (as set out in SNTS's written representation, and in the comments earlier in this document) to question that view. We have also highlighted in our comments on the applicant's response to FWQ 1.2.1 how the impact matrix approach deviates from accepted best practice standards and how it can result in relevant impacts being disregarded.

3.3.4 Bioscan/SNTS question how in a situation where the applicant is being compelled to submit addendum information to address deficiencies in the baseline data, there can be an agreed position between the applicant and NE on the adequacy of the submitted survey data at this stage. We question whether the reality is that Natural England has confined its considerations to matters of a statutory nature, as per its normal remit in engaging with the planning process, and has thus not given detailed consideration to the adequacy of matters such as accurate habitat classification outside of the designation boundaries and impact buffers around statutory sites, except where concerning statutory protected species. We suggest the Examining Authority should seek clarity from Natural England as to precisely where it positions its involvement in the Examination on non-statutory matters, in order that it can adjust the weight to be attached to a lack of comment from the statutory authority (or agreement on statements proffered by the applicant) accordingly.

3.3.5 Bioscan/SNTS note the inconsistency between NE having been portrayed as agreeing that "*the application of professional judgement by specialists within the following assessments is considered to be appropriate and robust: … air quality*" and the later statement that "*It is considered by the parties that the outcomes of the cumulative effects assessment in relation to development interactions are accurate with the exception of air quality, where Natural England has requested an in-combination assessment be carried out*.". This inconsistency is reflected elsewhere in the comparison of statements suggesting that matters such as potential effects on Chippenham Fen are agreed, which is flatly contradicted by later statements that impacts on aquatic invertebrates associated with Chippenham Fen Ramsar site and Fenland SAC are a matter of ongoing data exchange and discussion.

3.3.6 Bioscan note that the record of GCN from Chippenham Fen drawn to the applicant's attention some months back, and referenced again in SNTS's written representation, is not mentioned in the statement on GCN. Bioscan wonder whether this matter has been discussed at all between the applicant and NE since it was flagged by ourselves.

3.3.7 Bioscan/SNTS consider that due to deficiencies in the submission material and a lack of detail on critical matters, Natural England are not in an informed enough position on the following matters to agree that the impacts have been appropriately identified and assessed:

- Impacts to and loss of arable flora, including populations of locally and nationally scarce species;

- Displacement impacts on stone curlew and other farmland birds (e.g. skylark);
- Potential impact vectors to the Chippenham Fen SAC/Ramsar/SSSI/NNR, in particular in respect of aquatic invertebrates, the data vacuum around these, and the application of the precautionary principle;
- Whether the scheme delivers a net gain in biodiversity, whether objectively via the metric-based approach or subjectively on the basis of the balance of evidence in relation to both flora and fauna;
- Whether the applicant's claims of habitat enhancement are practical and achievable having regard to matters such as simple logistics, soil fertility and other factors.

3.3.8 Bioscan/SNTS will review future iterations of this Statement of Common Ground with interest, in light of the above.

3.4 Suffolk Wildlife Trust

3.4.1 Somewhat in contrast to the position the applicant sets out in the draft Statements of Common Ground with the Local Authorities and Natural England, Bioscan/SNTS notes that the Suffolk Wildlife Trust has not yet agreed any matters on ecology.

3.4.2 For all of the reasons set out in preceding sections of this document, including data deficiencies, unevidenced claims and assumptions, inconsistencies and simple matters of factual error, Bioscan/SNTS consider this to be very much the more defensible position at this stage of the Examination.

3.5 Environment Agency

3.5.1 Many or most of the comments made above in respect of the draft Statement of Common Ground with Natural England apply equally to the draft Statement of Common Ground with the Environment Agency. We are concerned that statutory agencies are being portrayed by the applicant as being in agreement with them on matters that are subsequently found to either be factually incorrect, or which fall outside of the statutory remit they define in consultation correspondence and which leaves matters such as non-statutory biodiversity matters largely to local authorities and non-statutory agencies such as the Wildlife Trusts.

4 COMMENTS ON LATEST VERSIONS OF CEMP, OEMP AND DEMP

4.1 Framework Construction Environmental Management Plan [REP3-015/16 + appendices]

4.1.1 Bioscan/SNTS note how the (tracked) changes to the CEMP indicates (amongst other things) how additional information fed into the design process via the arboricultural impact assessment (AIA), changes the original position of the applicant that no mature trees will be affected during the construction phase. This has necessitated revisions to ancillary documents such as the CEMP, and Bioscan/SNTS wish to seek clarity as to whether the Environmental Statement is similarly going to be revised in order to better reflect the factual position as regards impacts to trees and linear features, and how this may impinge on the previous conclusions drawn about bats.

4.1.2 For example, having undertaken an initial review of the AIA, Bioscan note that "*Two individual trees* [one subject to TPO]*, two tree groups* [also subject to TPO]*, part of four woodland groups, part of 13 tree groups and part of four hedgerow features are to be removed to facilitate the Scheme. This would include four part woodland groups of high quality (Category A), one tree group, part of seven tree groups and part of two hedgerows of moderate quality (Category B), two individual trees, part of six tree groups and part of two hedgerows of low quality (Category C) and one individual tree and one tree group which are unsuitable for retention for more than 10 years (Category U).*"

4.1.3 It is further noted that "*as a reasonable worst case the Scheme would require the removal of up to 150m2 of likely high quality tree cover, 5300m2 of likely moderate quality tree cover and 2850m2 of likely low quality tree cover (8300m2 in total).*"

4.1.4 The Examining Authority is asked to note the difference between the position as now assessed via the AIA and the statements made in the original ES Chapter such as:

- "*Woodland habitats across the Order limits will be retained*" (ES Chapter 8: Table 8-10, page 8-108)
- "*The construction of the Scheme will avoid features used by roosting and foraging / commuting bats, based on the current baseline conditions. There will be no loss of habitats identified as being important for bats anywhere within the Order limits.*" (ES Chapter 8: Table 8-10, page 8-122)
- "*The construction of the Scheme will not impact upon mature, species-rich hedgerows and other boundary features, which will retain connectivity across the Order limits for commuting and foraging bats. Therefore, there will be no fragmentation of habitats used by bats*" (ES Chapter 8: Table 8-10, page 8-122).
- "*Therefore, there are no impact pathways, either directly or indirectly, that would impact upon bats*".

4.2 Ecological Clerk of Works – clarity sought from applicant

4.2.1 In addition to the above, Bioscan/SNTS would request that the applicant defines what is meant by "*a licenced Ecological Clerk of Works*" (page 16C-15) and in particular how it will be ensured that someone with suitable experience of stone curlew, as well as all the other relevant receptors, will be employed.

4.2.2 Bioscan/SNTS would also request that the applicant defines precisely how many ECoW are likely to be required to cover all potential impact fronts/interfaces with ecological receptors that require supervision and monitoring during the construction phase. It is very notable that references to ECoW are made in the singular and appear to be generic, as if lifted from another project. The size of this project means that this would be wholly inadequate to implement the CEMP to the intended efficacy. The Examining Authority is asked to note the outcome of a simple totting up exercise of all the likely and potential daily tasks that may fall to a single ECoW and the impracticality of their being covered without multiple ECoWs being in post.

4.2.3 Bioscan/SNTS consider that this matter requires further detail before any weight can be placed on the CEMP as an effective means to limit construction-phase effects. Confirmation of the skill set, number of employees and an indication of anticipated daily schedule of tasks would assist the ExA and stakeholders in determining whether the applicant has sufficient intention and resource to cover this essential matter.

4.3 Framework Operational Management Plan [REP2-030 and REP2-031]

4.3.1 The text in this document on Biodiversity (table 3-3) is insufficiently precise and evidently subject to change in the light of further information (e.g. on stone curlew) and Bioscan/SNTS therefore reserve the right to comment on it at a later stage of the Examination.

4.3.2 However, the comments made above about the resourcing requirements to ensure the value of an ECoW should be noted also with regard to the operational phase, though they are perhaps less acute as a concern than with the construction phase.

4.4 Framework Decommissioning Management Plan [REP2-028/029]

4.4.1 The comments provided above at 4.1 and 4.2 apply equally to the Framework Decommissioning Management Plan. In addition, the Examining Authority's attention is drawn to Bioscan/SNTS's comments on FWQ 1.6.7 (para 2.2.42 above) concerning the absence of security over the future position beyond the operational life of the solar facility.

5 SUMMARY AND CONCLUSIONS

5.1 Bioscan and SNTS consider that the applicant’s responses to the Examining Authorities First Written Questions illuminate how errors and omissions have infected the Environmental Statement submission (and its supporting surveys), as regards biodiversity impacts. These individually and collectively undermine the robustness of the conclusions the applicant presents, with a further diminution of robustness added in the absence of detail on the long term and future position that is claimed will be delivered.

5.2 Bioscan and SNTS consider that the applicant’s ticker tape submissions in response to these errors and omissions, including additional surveys and submissions, related adjustments and corrections and changes of position do not imply a robust and well thought through scheme. We suspect the Examining Authority shares in our frustration that this rather haphazard approach to designing and assessing a scheme brings, and in the resourcing implications for stakeholders that it gives rise to.

5.3 We await further information on the matters of concern raised in this document and will respond as necessary.

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Appendix C

Summary Report Relating to Topic 1.1. Air Quality and Human Health of the Responses to ExA First Written Questions

1. Grid scale lithium-ion batteries present a well-known and well documented fire hazard. There have been over 40 thermal runaway incidents in such installations, with a large proportion of these in the last 3-4 years.[1-4] It is essential that battery safety measures are thoroughly examined as part of the Sunnica DCO application, including full consultation with the Health and Safety Executive (HSE), as well as local Fire and Rescue services and local authorities.

2. Statistically, the more lithium-ion cells, the higher the probability of an incident occurring. According to Professor Paul Christensen, world-renowned expert in Lithium-ion BESS safety, the estimate of spontaneous cell failure is between 1 in 10 million to 1 in 40 million cell failures.[3]

3. Sunnica Ltd propose to use lithium ion batteries; specifically:

   "The lithium-ion batteries will be either NMC (Nickel Manganese Cobalt) or Lithium Iron Phosphate (LiFePO4) chemistry." (per the Outline Battery Fire Safety Management Plan, OBFSMP. Ref EN010106/APP/Volume 7 7.6 Outline Battery Fire Safety Management Plan. APP-267 and revised REP2-033)

4. In the applicant's response to the Examiners first written question 1.1.6 it is stated that:

   "The various references to Lithium-ion battery chemistry types (NMC or LFP) refers to the cathode materials. This will typically be aluminium foil coated with a metal oxide or phosphate such as Nickel Manganese Cobalt (NMC) or Lithium Iron Phosphate (LFP). It is this cathode material which determines the capacity and voltage of the cell."

5. Sunnica also state in 1.1.6 that:

   "from a fire risk perspective there is relatively little to distinguish between lithium ion battery chemistries as they share common hazard parameters during thermal runaway reactions and chemistry is in fact a very small part.

6. This is a deviation from accepted scientific understanding.

LFP vs NMC mitigation considerations

7. According to Professor Christensen, the precise cell chemistry is an essential factor in developing a suitable Outline Battery Fire Safety Management Plan (OBFSMP). In his review[1] of Sunnica's OBFSMP he states:

   *"The choice of Nickel Manganese Cobalt (NMC) or Lithium Iron Phosphate (LFP) cells and their form factors will have **major implications for the fire sensing and suppression to be employed in the containers**.*

   Thus, draft standards due in 2023 and likely to be employed by UK manufacturers in the absence of UK standards will require venting of LiBESS containers once off-gassing is detected from lithium-ion cells. This, in turn, demands appropriate gas sensors. However, whilst the literature suggests that prismatic and cylindrical cells vent many minutes prior to thermal runaway (depending upon the definition of this), pouch cells simply burst without such warning and there is no evidence that advance warning via venting occurs. In fact, my own research has shown this not to be the case.

   The choice of chemistry can also have a major effect upon the efficacy or otherwise of e.g. sprinkler systems in containers. Thus experiments conducted under the aegis of the National Fire Prevention Association (NFPA) have shown that such systems are essentially ineffective for the suppression of fire in racks of NMC cells, but can be effective against fires involving LFP cells.

   Overall, the above considerations are key to the fire safety aspects of the OBFSMP and hence BFSMP."

8. In further communications[5] on cathode chemistry Professor Christensen states that:

> *"Cathode chemistry has a major effect [on the hazards associated with thermal runaway] eg LFP hazard is more explosion than fire. More energetic chemistries eg NMC, NCA more prone to fire.*
>
> *Higher SoC [State of Charge] favours ignition and hence fire, lower SoC hazard switches to explosion.*
>
> *VCE [Vapour Cloud Explosion] of LFP LiBESS [Lithium ion BESS] in Beijing so far the only fatal LiBESS VCE killing two fire officers.*
>
> *LFP LiBESS on Nathan Campus of Griffith University, LFP cells went into TR [thermal runaway] and vented vapour cloud which collected in ceiling void and exploded."*

9. He also states that:

> *"LFP cells do require higher temperatures for ignition to occur but delayed ignition allows more vapour cloud to be produced increasing explosion risk."*

10. There is clearly a difference in the safety considerations for LFP or NMC batteries. The former enters thermal runaway at higher temperatures (so in one respect may be perceived as "safer" [6]), but this can lead to a build up of vapours, and increased risk of vapour cloud explosion (VCE).

11. The latter (NMC) may enter thermal runaway at lower temperatures, but are more hazardous from a fire perspective. The applicant needs to fully consider both explosion risk and release of toxic emissions as part of their safety assessments.

12. Professor Christensen highlighted his concerns about the applicant's assessments in the initial OBFSMP[1]

> *"The applicants do not appear to have any grasp of the critical difference between immediate and delayed ignition. This is essential to the design of the fire sensing and suppression system.*
>
> *The applicants do not seem to be appear of the current best practice of design for failure in addition to design for safety."*

13. The differences between NMC and LFP cell types are also re-iterated by Dr Fordham (EurIng Dr Edmund Fordham MA PhD CPhys CEng Fellow of the Institute of Physics), who states that[7]

> *"LFP cells fail less aggressively - slower temperature rise, lower maximum temperatures (say 400 deg C approx) and have higher thermal runaway thresholds (say 200 deg C instead of 150 deg C). But that's still 200 degrees difference from a failed cell to the neighbouring one and quite enough to kick off thermal runaway.*
>
> *[That implies higher risk of explosion (after delayed build-up of flammables)].*
>
> *NMC cells are more likely to develop flame immediately, difficult to put out."*

14. The Liverpool lithium ion BESS thermal runaway incident in September 2020 involved a significant explosion as descried in the investigation report[8]:

> *"The internal CCTV shows the vapours (vented gases-droplets of organic solvent from the cells) building up at low level filling the container as to started to reach their flammable limits, before coming into contact with an ignition source, the exact ignition source within the container is not known. The vapours ignited causing a deflagration which blew off both doors and caused the HVACs to come detached from the roof as well as deforming the container."*

Debris from the affected container was blown 23m away.

15. Explosion in one battery container has the potential to damage a neighbouring container so it is essential that the explosion risks of the different cell chemistries are appropriately considered as part of the DCO application. This also poses a risk to first responders, noting that the injuries sustained to the firefighters in the Arizona 2019 incident were as a result of the explosion.[9]

Consideration of Emissions from LFP and NMC cell types

16. In addition to differences in fire and explosion risks, LFP and NMC cell types also differ in the toxic emissions produced during thermal runaway.

17. Per Professor Christensen[1]

    "There can be no valid dispersion modelling without knowing the parameters on which the model was based. The cell chemistry, the energy densities of the cells, the total energy density, the rate of thermal propagation (container type, module type, spacing, cell chemistry), the volume and composition of the gases emitted (cell chemistry)?) all need to be taken into account. On the basis of the information provided by the applicants, no conclusion can be drawn….

    …Further, Hydrogen Fluoride (HF) is not the only toxic or dangerous gas that may be emitted during a LiBESS fire. It is not as persistent compared to some of the other toxic gases produced by immediate or delayed ignition. Other toxic gases include HCN and HCl."

18. NMC cells tend to have lower emissions of Hydrogen Fluoride (HF) and other toxic fluorides when compared to LFP.[6] However, a concerning aspect of NMC cells is the production of Nickel Oxide dust or smokes which are potent carcinogens[6] and are strongly regulated (Named Dangerous Substance under Seveso i.e. in Part 2 "Named Hazardous substances" of the P(HS)Regs 2015 and similarly in Part 2 of the Schedule to the COMAH Regs 2015).

19. In contrast, LFP cells do not have the Nickel, Manganese, Cobalt toxic compounds (oxide smokes), but do have worse emissions of HF in failure.[6]

20. During the BESS thermal runaway incident in Arizona in 2019, nine first responders were contaminated with Hydrogen Cyanide (HCN).[4,9] In the Hill investigation report into this incident[9], it is stated that:

    "a common signature of a suspected battery thermal runaway event is the presence of HCN, HCl, or HF"

    (noting that some of these may be attributed to the plastics and other material present in the batteries).

21. Similarly, in the 2016 Fire Protection Research Foundation (FPRF) report[10] referenced by the applicant it is noted that:

    "toxic compounds such as CO2, NOx, HCN, HCl, CO, and HF can be produced during the fires"

22. A further important consideration is the choice of "reference case" for any plume dispersal modelling. The afore mentioned FPRF report carried out experiments using 100 kWh 'Powerpak' batteries supplied by Tesla. The precise cell chemistry of the Powerpak was not reported in the paper, so it is unclear whether these were NMC or LFP or other types of lithium ion battery.

23. The gases measured in the FPRF study were Carbon Monoxide (CO), chlorine (Cl2), methane (CH4) and HF based on previous experience and information provided by Tesla. That is not to say that other gases were not emitted – only that the experiment focused on these four gases. The authors note in the paper that:

    "a standalone Powerpack was tested in this test program, not a large installation with many Powerpacks installed in an array. As such, the effects, if any, of additional Powerpacks installed within close proximity to one another was not directly assessed during these two tests and may warrant further investigation."

24. The authors also stated that,

    "In addition, this test series only assessed select products of combustion produced during the Powerpack fires, namely HF. Additional testing accounting for other toxic products of combustion may warrant further investigation"

25. Scaling up results from a 100 kWh battery to a sizeable facility such as Sunnica is also considered invalid per Professor Christensen, who notes in his report[1]:

    "Having reviewed Appendix 16D, it appears that this assessment was based on a report using a 100kWh LiBESS. It is well known that scaling-up calculations and models concerning lithium-ion batteries is wholly and completely invalid due, for example, to the volume effect."

26. The 2013 Andersen study[11] referred to in Sunnica's Chapter 16 Unplanned Emissions document is based on LFP cells, so does not provide information on emissions from NMC cell types.

27. Professor Christensen[1] states that

"Hydrogen Fluoride (HF) is not the only toxic or dangerous gas that may be emitted during a LiBESS fire. It is not as persistent compared to some of the other toxic gases produced by immediate or delayed ignition. Other toxic gases include HCN and HCl."

28. Dr Fordham also notes that the HSE for Northern Ireland commissioned a report from consulting engineers Atkins[12] which describes independent modelling of HF plume dispersal from a 5 MWh BESS container. HF concentrations reached the IDLH level (Imminent Danger to Life or Heath] up to 240 m downwind in "very typical" weather conditions.

29. In the applicants response to the Examiners first written question 1.1.9 they state:

    "The controls in the Design Principles also include: (i) that the chemistry of the BESS will be lithium ion, and (ii) that an assessment will be undertaken, based on the detailed design for the BESS to demonstrate that the environmental and social impacts from such a fire will be no worse than as assessed in ES Appendix 16D: Unplanned Atmospheric Emissions from Battery Storage Systems [APP-124]."

30. The assessments in ES Appendix 16D [APP-124] have not sufficiently considered potential environmental and social impacts.

Potential environmental considerations from LFP and NMC cell types

31. The below table is taken from a recent publication by Mrozik et al and shows potential environmental pollution from a range of battery cell types, including NMC and LFP.

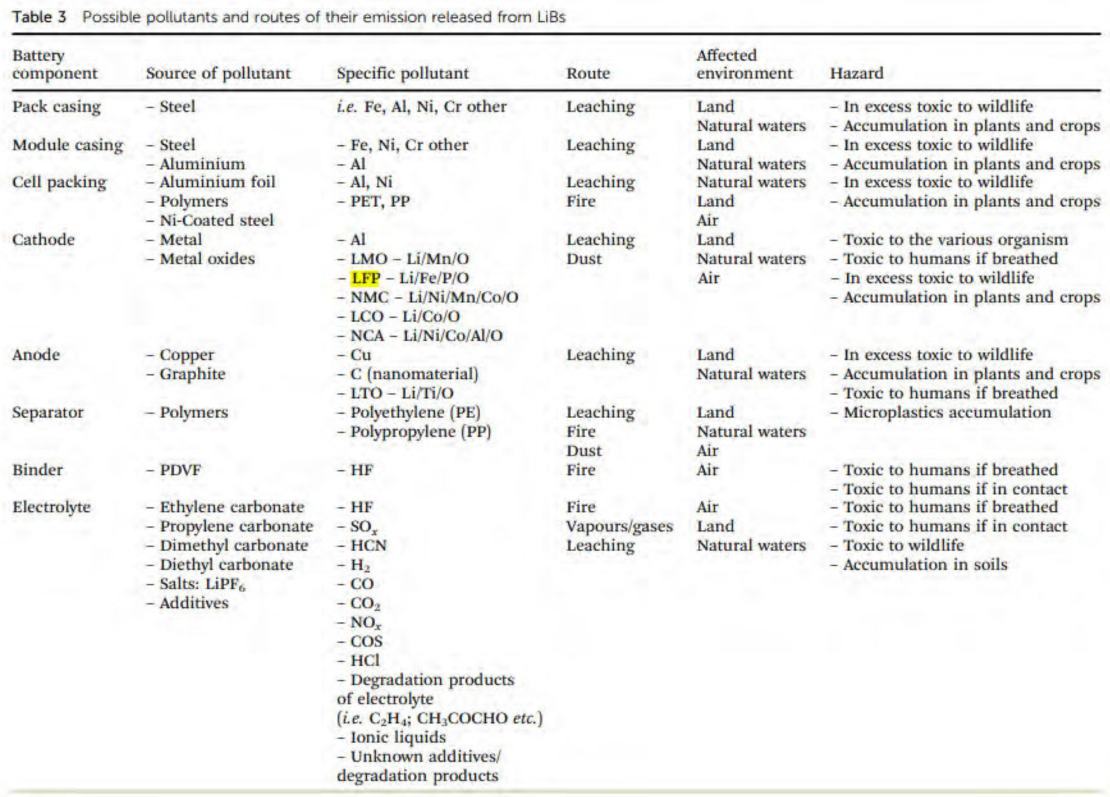

Table 3 Possible pollutants and routes of their emission released from LiBs

Battery component	Source of pollutant	Specific pollutant	Route	Affected environment	Hazard
Pack casing	– Steel	*i.e.* Fe, Al, Ni, Cr other	Leaching	Land Natural waters	– In excess toxic to wildlife – Accumulation in plants and crops
Module casing	– Steel – Aluminium	– Fe, Ni, Cr other – Al	Leaching	Land Natural waters	– In excess toxic to wildlife – Accumulation in plants and crops
Cell packing	– Aluminium foil – Polymers – Ni-Coated steel	– Al, Ni – PET, PP	Leaching Fire	Natural waters Land Air	– In excess toxic to wildlife – Accumulation in plants and crops
Cathode	– Metal – Metal oxides	– Al – LMO – Li/Mn/O – LFP – Li/Fe/P/O – NMC – Li/Ni/Mn/Co/O – LCO – Li/Co/O – NCA – Li/Ni/Co/Al/O	Leaching Dust	Land Natural waters Air	– Toxic to the various organism – Toxic to humans if breathed – In excess toxic to wildlife – Accumulation in plants and crops
Anode	– Copper – Graphite	– Cu – C (nanomaterial) – LTO – Li/Ti/O	Leaching	Land Natural waters	– In excess toxic to wildlife – Accumulation in plants and crops – Toxic to humans if breathed
Separator	– Polymers	– Polyethylene (PE) – Polypropylene (PP)	Leaching Fire Dust	Land Natural waters Air	– Microplastics accumulation
Binder	– PDVF	– HF	Fire	Air	– Toxic to humans if breathed – Toxic to humans if in contact
Electrolyte	– Ethylene carbonate – Propylene carbonate – Dimethyl carbonate – Diethyl carbonate – Salts: $LiPF_6$ – Additives	– HF – SO_x – HCN – H_2 – CO – CO_2 – NO_x – COS – HCl – Degradation products of electrolyte (*i.e.* C_2H_4; CH_3COCHO *etc.*) – Ionic liquids – Unknown additives/ degradation products	Fire Vapours/gases Leaching	Air Land Natural waters	– Toxic to humans if breathed – Toxic to humans if in contact – Toxic to wildlife – Accumulation in soils

32. According to Dr Fordham[7] Hydrogen Fluoride gas is soluble in firewater and moisture in the atmosphere. The result is formation of a highly corrosive hydrofluoric acid, which could contaminate a wider area. Dissolved gases and particulates must be accounted for in terms of potential contamination.

33. Dr Fordham also considers that lithium ion BESS cells contain many components which in fire may give rise to substances that are Acute or Chronic Toxic to the Aquatic Environment, as outlined in his Written Representation (Dr Edmund Fordham – Written Representation – REP2-129).

34. In the Atkins report[12] commissioned by the HSE in Northern Ireland, there is discussion of HF plumes being directed to ground level depending on conditions, which should also be taken into account:

> *"Any generation of HF which is released from the ISO container will be advected downwind, though the plume will tend to rise due to the buoyancy of the hot fire plume. The container may also entrain some or all of the fire plume into its downwind wake, which may spread the plume out and bring it down to ground level, depending primarily on the wind speed."*

35. Further, given the substantial water requirements for tackling a thermal runaway incident (900,000 L was used to contain the Moorabool incident[13]) this puts pressure on the containment requirements, and increases the potential for leakage.

Thermal Runaway Statistics, Safety and Social Considerations

36. In response the Examiners first written question Q1.1.9 the applicant states that:

> *"The amount of power the BESS can store, and for how long, has no direct relationship to its environmental and social impacts. The only technical topic this affects is safety; although because any fire is likely to be associated with a single battery enclosure, safety is affected by the power energy rating of an individual battery enclosure rather than the BESS compound as a whole."*

37. Professor Christensen notes in a report[1] that DNV GL, who are arguably world experts in the risk analysis of large lithium-ion battery systems, acknowledges the risks of thermal runaway events, stating that:

> *“Over the life of a (industrial) BESS at least one failure will occur. It is unrealistic to eliminate all chance of failure”*

38. Per Dr Fordham, Emergency Response Plans for communities close to a major BESS accident could involve sealing doors and windows, up to evacuation (examples include thermal runaway incidents in Liverpool[8, 16] and Moorabool[13-15] where residents nearby were alerted to toxic emissions). The social impact of living with such a level of hazard would be extreme for the affected communities.

39. Cabin-to-cabin propagation of BESS accidents has occurred in the case of the 2021 Big Battery fire in Australia[13] and in the 2021 Beijing LFP incident where propagation to a second cabin that was spatially separated occurred.[17]

40. It cannot be assumed that an incident will be associated with a single enclosure only.

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(Appendix 6)

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Appendix 1

Briefing Note Professor Paul Christensen 13Nov22

Paul Christensen
LITHIUM ION SAFETY

Briefing note: lithium-ion battery energy storage systems

Disclaimer: the views stated in this document are those of Dr. Paul Christensen and are not representative of any other person, body or organisation.

Background

Lithium-ion batteries (LiBs) store a very large amount of energy in a very small space or mass (i.e. have a high energy density) and, as such, are the first to employ organic solvents rather than water. LiBs are invaluable as they have a range of uses – from mobile devices and cameras on the small scale, to storing electricity (including electricity from renewable energy generators) on the industrial scale. However, if the stored energy is released in an uncontrolled fashion, highly toxic gases are released that are also flammable and explosive.

The smallest unit of a LiB is the cell, many cells make a string or module and many strings or modules make a battery. There are three cell form factors (i.e. shapes and sizes): the smallest is the cylindrical cell and the largest the pouch cell, prismatic cells are intermediate in size between the other two. If a cell is abused by heating, overcharge or overdischarge, crush or penetration then chemical reactions supersede the normal electrochemical processes, and these chemical reactions generate heat and a mixture of gases that include hydrogen (ca. 30 – 50%), carbon monoxide, carbon dioxide, hydrogen fluoride, hydrogen chloride, hydrogen cyanide, ethane, methane and other hydrocarbons and nitrogen oxides. Spontaneous cell failure also occurs for reasons that are not yet understood, but defects or contamination introduced during manufacture are often suspected.

Thermal Runaway and Vapour Clouds

The heat generated by these chemical processes accelerates them exponentially, producing more heat and gas: when these exothermic (heat-producing) chemical processes become self-sustaining, the cell is in thermal runaway which has proved extremely challenging to stop. Adjacent cells are heated and also enter thermal runaway. Hence it propagates throughout the battery. When the gases vent from the cell they take with them small droplets of the organic solvent which gives the gases the appearance of steam – in other words, a vapour cloud. As may be deduced from its composition, the vapour cloud is toxic. In addition, if the cloud ignites immediately, long flare-like flames are typically produced, but if ignition is delayed, then a vapour cloud explosion can (and has been) produced. Vapour cloud explosions are violent deflagrations with overpressures that can exceed several atmospheres and can be lethal (an overpressure 1/10th of an atmosphere is lethal).

Statistics

The company DNV is acknowledged as a leader in lithium-ion battery energy storage (LiBESS) safety: at the DNV webinar “Best practice for energy storage system safety around the globe” on 29 October 2020, one of the company’s experts stated that:

“Over the life of a (grid-scale) BESS at least one failure will occur. It is unrealistic to eliminate all chance of failure”.

To date, there have been over 40 fires and explosions reported in grid-scale LiBESS across the world since 2012, primarily in installations that were 2 years old or less. Of these, 38 have been in the last 3 years (c.a. 30 occurred in South Korea). Overall, these incidents may have represented up to c.a. 6% of global installed capacity, with the high number of fires in South Korea simply reflecting the country's very rapid uptake of LiBESS. As other countries increase the number and capacity of their LiBESS there are likely to be more fires and explosions, if safety regulations are not rapidly improved.

Confirmed vapour cloud explosions have taken place in the 1MWh LiBESS in Drogenbos, Belgium in November 2017 as well as the 2 MW McMicken LiBESS in Surprise, Arizona in April 2019 and the 20 MW Carnegie Road LiBESS on Merseyside UK in September 2020.

- Four firefighters were injured in the explosion of the McMicken Arizona installation, two very severely and a total of 9 first responders were hospitalized due to contamination with hydrogen cyanide.
- Following the incident in Drogenbos, Belgium, 50 residents reported eye and respiratory irritation from a wide area downwind of the site.
- Two firefighters were killed and a third injured in the explosion of a 1.5 MW LiBESS on the roof of the Jimei Home Dahongmen shopping Mall in Beijing in April this year. The latter incident is notable for two reasons:

    (1) the LiBs employed in the LiBESS are widely perceived to be the safest and
    (2) the scale of the firefighting operation required 235 fire fighters and 47 fire engines.

The relatively small-scale Drogenbos 1 MWh BESS explosion required 1.4 million litres of water to finally extinguish the fire subsequent to the explosion.

The magnitude of the fire and rescue response and the very large volumes of water required are common factors in LiBESS fires and explosions.

Accepting DNV's assumption that failures will occur, the estimate of spontaneous cell failure is between 1 in 10 million to 1 in 40 million cell failures. This can be caused by e.g. the introduction of contaminants or defects at the manufacturing stage.

In the context of Grid-scale LiBESS, these installations typically comprise a number of 'shipping' containers (ranging from one container to hundreds). These containers may house hundreds of thousands of individual battery cells, of various forms (pouch cells, cylindrical cells etc). All form factors are employed in Grid-scale LiBESS and, depending on the form of the cell used, estimates of failure can range from 1 in 72 to 1 in 282 containers. These estimates do not include failures caused by poor design, human error, poor housekeeping etc.

A fire or explosion involving a Grid-scale LiBESS requires a large fire and rescue service response, including HAZMAT involvement. FRS personnel must be fully trained in dealing with large lithium-ion battery fires (such training is currently patchy across the UK).

Current Legislation

There are currently a number of electrical safety standards in place, but these fall short of adequately preventing and mitigating the risks of thermal runaway events, and the consequences of these (fires, explosions, gas emissions etc). LiBs play an invaluable role for our energy storage needs, but adequate and appropriate safety regulations must be put in place to ensure the ongoing safe functioning of these, especially when deployed at Grid scale.

Dr. Paul Christensen, Lithiumionsafety Ltd. 13 November 2021

Appendix 2

Paper - Environmental impacts, pollution sources and pathways of spent Li-ion batteries

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REVIEW

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Environmental impacts, pollution sources and pathways of spent lithium-ion batteries

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There is a growing demand for lithium-ion batteries (LIBs) for electric transportation and to support the application of renewable energies by auxiliary energy storage systems. This surge in demand requires a concomitant increase in production and, down the line, leads to large numbers of spent LIBs. The ever-increasing battery waste needs to be managed accordingly. Currently, there are no universal or unified standards for waste disposal of LIBs around the globe. Each country uses one or a combination of practices such as landfilling, incineration and full or partial recycling depending on the number of batteries leaving the market, current legislation and infrastructures. Informal disposal or reprocessing is not a rare activity. This review records, identifies and categorises the environmental impacts, sources and pollution pathways of spent LIBs. The drawbacks of the disposal practices are highlighted and the threats associated with them are discussed. The evidence presented here is taken from real-life incidents and it shows that improper or careless processing and disposal of spent batteries leads to contamination of the soil, water and air. The toxicity of the battery material is a direct threat to organisms on various trophic levels as well as direct threats to human health. Identified pollution pathways are *via* leaching, disintegration and degradation of the batteries, however violent incidents such as fires and explosions are also significant. Finally, the paper discusses some of the main knowledge gaps for future assessments. The current study offers a comprehensive overview of the threats and hazards that need to be managed in order to ensure the design and implementation of safe disposal and processing options for spent LIBs.

Broader context

Lithium-ion batteries (LIBs) are permeating ever deeper into our lives – from portable devices and electric cars to grid-scale battery energy storage systems, which raises concerns over the safety and risk associated with their disposal. Spent LIBs are currently landfilled, incinerated, partially/fully recycled, or a combination of these, depending on the existing infrastructure, legislation *etc.* of the country concerned. Spent LIBs are considered hazardous wastes (especially those from EVs) due to the potential environmental and human health risks. This study provides an up-to-date overview of the environmental impacts and hazards of spent batteries. It categorises the environmental impacts, sources and pollution pathways of spent LIBs. Identified hazards include fire and explosion, toxic gas release (*e.g.* HF and HCN), leaching of toxic metal nanooxides and the formation of dangerous degradation products from the electrolyte. Ultimately, pollutants can contaminate the soil, water and air and pose a threat to human life and health. In this work, we discuss some of the main knowledge gaps and probe questions on the environmental impacts of spent LIBs that might help to manage these better in the future to design and implement safe disposal and processing options for spent LIBs.

1. Introduction

Lithium-ion batteries (LIBs) are found in all aspects of our lives – from small portable electronic devices through electric vehicles (EVs) to battery energy storage systems (BESS). LIBs are perceived as crucial to support the wide adoption of renewable energy sources as these do require BESS to manage the intermittency in their power supply for a reliable operation of the electricity grid. The application of LIBs in electric traction has initiated a revolution in the automotive industry that is motivated to decarbonise the transport sector and reduce local air pollution. In 2009, there were nearly 25.6 GW h (about 134 000 tons) of LIB energy storage capacity placed on the global market, in 2019 it was about 218 GW h (over 1.2 million tons), and it has been

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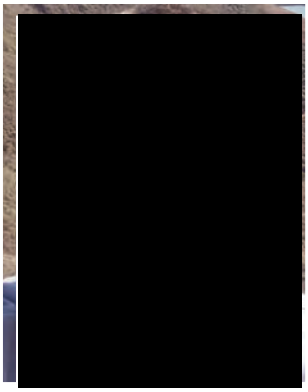
[c] *Faraday Institution (SafeBatt project), Quad One, Harwell Science and Innovation Campus, Didcot, UK.* [redacted]

estimated that in 2030 more than 2500 GW h (over 12.7 million tons) will be placed on the market, which subsequently results in a vast amount of waste from the spent LIBs.[1]

Various international and domestic initiatives like the European Green Deal in the EU,[2] the UK Government pledge to ban new ICE cars by 2030 (hybrids by 2035)[3] or the need to establish zero-emission mobility as an urgent priority,[4] require a very large increase in the production of new LIBs. Moreover, transitioning to a low carbon economy[5] requires building new, more powerful BESS all around the world. These installations will be used as storage of intermittent solar, wind, or wave electricity, grid support, frequency stabilisation and behind-the-meter-storage, replacing conventional technologies. On one hand, the increased number of LIBs has created concerns over the availability of some critical metals, and their wild short-term price volatility which could affect the sustainable supply of such energy storage devices.[6] There are also some ethical and environmental concerns with the extraction of some metals for LIBs.[7] On the other hand, this surge in demand for batteries will require a concomitant increase in production and, down the line, large numbers of LIBs reaching end-of-life (EoL). Hence, that will cause an ever-increasing battery waste that needs to be managed accordingly.[8] However, many types of batteries currently do end up in landfills or are incinerated, primarily due to the lack of adequate standards; enforcement of regulatory controls, inefficient, or absence of, national battery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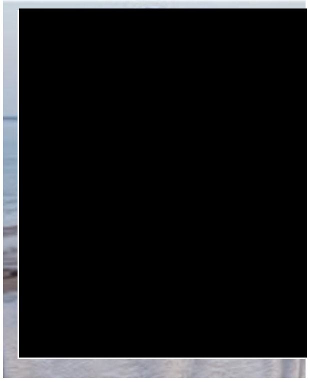
Wojciech Mrozik

Wojciech Mrozik is a Faraday Institution Research Fellow at Newcastle University, UK. He is part of the "SafeBatt – Science of Battery Safety" and previously "Reuse and Recycling of lithium-ion Batteries" projects funded by Faraday Institution. He is an expert in environmental and analytical chemistry with a particular interest in environmental fate assessment and removal of anthropogenic pollutants. Last few years Wojciech's research focused on the safe application, operation and utilization of lithium-ion batteries. That concerns understanding of battery thermal runaway, fire prevention and mitigation.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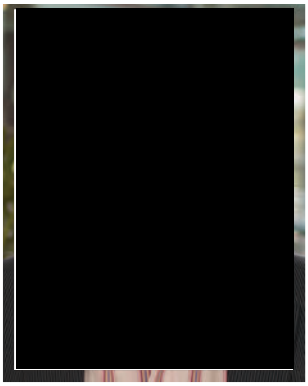
Mohammad Ali Rajaeifar

Mohammad Ali Rajaeifar is currently a research associate at Newcastle University. He studies technologies and management strategies and provides sustainability analysis of different production systems. He started his MSc in the area of sustainable agriculture and biofuel production in 2013. Then he extended his research to sustainability assessment of biorefineries, low carbon transport systems and waste management systems during his PhD and post-doctoral studies. More recently, he has developed his research area by focusing on the sustainability of EVs and lithium–ion batteries. Mohammad is also an expert in data collection and analysis, compiling data inventories, and assessing the environmental impacts of complicated industrial systems.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Oliver Heidrich

Since 1992 Oliver has worked with national and international companies, local authorities and Universities in waste, recycling, environmental, life cycle assessment, stakeholder and corporate management. He was a director of Econoplas, a plastic manufacturing business and SEQM a business consultancy business. He provides detailed understanding of the inter-relationships between resource use and their spatial distribution within and outside cities, in relation to climate change, the built environment, and associated resource requirements. Besides his many expert reports and research papers, Oliver is concerned to see the results of his research disseminated through the wider press and digital media.


[redacted]

Paul Christensen

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Fig. 1 Disposal routes of LIBs.

collection and recycling schemes.[9] As a result, human health and environmental quality could be placed at risk as a wide range of pollutants could be released like heavy metals or hydrofluoric acid (HF) when batteries are disposed of inappropriately.

The main aim of this study is to provide an up-to-date overview of the environmental impact and hazards of spent batteries. This paper reports and discusses the fate, disposal routes and potential pollution sources and pathways from spent LIBs. Despite the clear importance of this area, the data on the environmental impact of EoL LIBs is extremely limited, thus, this study identifies the possible environmental impacts associated with battery EoL. There is an urgent need from manufacturers, waste handling companies, recycling firms and public stakeholders to understand this matter as wrong disposal practices, lack of data or improper identification of hazards will drastically increase the number of incidents, fires and potentially fatal accidents. The possible emission routes and pollution pathways *e.g.* air, water and land, are also evaluated through the course of this study. We have also recognised possible hazards to human health and ecosystem quality due to different battery treatment and disposal practices. Finally, the knowledge gaps are identified that need to be covered if the right disposal practices and management systems are to be implemented.

2. Disposal of spent batteries

The management of spent LIBs incorporates reuse, recycling, landfilling, processing or (unfortunately) illegal disposal (Fig. 1). The local disposal routes depend on national legislation and regulations, recycling capacities, collection systems, consumer behaviours and the battery retail markets.[10] Clearly, different approaches are required for small batteries compared to large ones.

Small LIBs are returned by the customer either through battery drop-off points (LIBs that can be easily detached from the device) or given to waste electrical and electronic equipment sites (WEEEs) if the user cannot remove them from the electrical device. From these collection points, they are transported to sorting facilities and later to be recycled or landfilled. Through ignorance of the collection system or idleness, small spent LIBs may be put into general waste or into recycle bins by customers, which led to damaging fires during transportation or in material recovery facilities (MRFs). Veolia, one of the global waste handling companies, has noted a 38% increase of incidents since 2017,[11] due to the presence of the LIBs in the waste stream. At MRFs, LIBs will be crushed or penetrated during the standard processing, which can also lead to fires or even explosions. The Environmental Services Association estimates that[12] there were *ca.* 250 fires in the UK waste treatment facilities caused by small LIBs between April 2019 and March 2020, compared to *ca.* 130 in the year to March 2020, a rise of 25% of all fires in these facilities.[13,14] The German steel recyclers confederation (BDSV) has claimed that 90% of fires at their associated sites in the last years were caused by LIBs.[15] Some specific examples of such fires are the incident at the Great Blakenham scrapyard, UK (15th Sep 2017) where 100 tonnes of metal and a crane were caught up in fire;[16] multiple incidents at Tokyo's Musashino Clean Center garbage disposal facility, Japan, in 2017 and 2018;[17] and some other regular incidents in the UK, USA, Scotland, and Germany.[18]

Large LIBs are typically transported by professional services once removed from EVs,[19] however, their health status is usually unknown. If internally damaged, they are in slow thermal runaway and hence remain unnoticed for a long time, after which they may either burst into flames or they release gases and droplets of solvent, the "white vapour", composed of toxic and explosive gases.[7,20–24] These events may take place during transportation, storage, recycling or landfilling.

2.1 Recycling

2.1.1 Low recovery rates. Material recovery from the EoL batteries is the preferred option over the other disposal routes[10,25,26] since LIBs are now considered a strategically valuable waste stream containing relatively valuable metals such as cobalt, nickel or lithium.[27,28] These are of significant value, especially in light of the shrinking global supply of critical materials.[29–32] Material recovery is also the way to be less dependent on raw mining elsewhere or to protect the country's own small reserves. For instance, the lithium demand for LIBs produced in China by 2050 could meet up 60% by recycling.[33] Currently, China is the largest consumer and producer of LIBs and recycling of spent LIBs has only started recently.[34] Although some 14 pieces of legislation try to manage the emission pathways of all types of batteries waste, effective regulation of controlling spent LIB is still in its infancy.[34] In the USA the management and regulation of LIBs is also fragmented, due to its Federal States, with some federal policies guiding battery disposal, specifically the 1996 Mercury-Containing and Rechargeable Battery Management Act to manage certifications and standards of batteries.[35] However, overall, it is patchwork of state by state regulations with different levels of maturity and control.[36] In the EU, new legislation is coming into force in 2022 to manage and control the raw material sourcing, disposal and recycling of LIBs.[1]

Clearly, material recovery should avert the environmental burden from ore mining and beneficiation of metals used in LIBs by replacing the recycled ones in the production chain,[37] and could also avoid the environmental burdens from the other harmful disposal routes. In 2018, it is estimated that 97 000 tonnes of LIBs were recycled globally,[19] including LIBs from portable electronics as well as LIBs from EVs and BESS applications. Small LIBs currently dominate recycling (*i.e.* more than 80% of the recycled batteries) as the number of batteries reaching actual EoL from EVs is relatively low.[38] This is due to the relatively nascent application of LIBs in EVs, and the fact that when EV LIBs have reached EoL they still have potential use in other applications, such as supporting the Grid or renewable energy generation, as they typically retain up to 80% of their original capacity.[39] Thus, LIBs from EVs may be finally discarded up to 10 years after their first life.[40]

A closer look at the recovery of LIBs reveals that compared to the amount of LIBs placed on the global market, the actual recovery rates are quite low. For example, the average collection rate in the EU, one of the well-regulated markets, is nearly 40% while only 12% belongs to LIBs.[41] The average recovery rates are also lower for some other less-regulated markets such as Australia and the US.[29,42] However, there are still few markets that perform better than the EU. More specifically, South Korea and China together showed better recovery rates. Actually, these countries are the destination of most of the exported batteries (either in a separate battery form or as part of electronic devices) from many parts of the world especially Europe and North America. This is also reflected in the total quantity of LIBs recycled: from 97 000 tonnes treated globally in 2018, 67 000 were processed in China and 18 000 in South Korea.[19] However, it is estimated that less than 40% of the total battery materials actually can be recycled under the current materials flow scheme.[43] For instance, in 2016, only around 30% of nickel, 33% of cobalt, 23% of lithium and 5% of graphite were recovered in China.[44] Such poor management resulted in economic loss due to the free discharge of valuable materials, as well as damage to the environment and human health.[45,46] Various national and international initiatives have been implemented to tackle this low recovery problem such as the 2006 EU battery directive[47] and the proposed new EU regulation which concerns batteries and waste batteries.[48] The key challenge, however, is the lack of recycling infrastructure around the world, there are only a few full-scale recycling facilities (Table 1).[49,50] Illustration of this problem is the UK situation. Prior to exiting the EU on the 31st December 2020, the regular practice was to ship batteries to mainland Europe for recycling, *e.g.* to Umicore in Belgium. However, with the restricted access to the EU market and strict regulations treating large LIBs as hazardous materials, the UK, without proper recycling infrastructure, may either have to landfill its batteries[51] or temporarily store them in dedicated facilities until suitable facilities are built or until an appropriate trade deal with the EU is agreed.

Both landfilling and stockpiling will have a potentially negative effect on the surrounding environment as they can release pollutants, contaminants and cause accidental fires, which are discussed below.

2.1.2 Recycling methods.

Material recovery from the EoL LIBs is currently carried out by one of three major processes: pyrometallurgy, hydrometallurgy, and direct recycling.[25,40] Pyrometallurgy employs smelting in a high-temperature process, which usually involves burning and subsequent separation to produce a mixed metal alloy of Co, Cu, Fe and Ni.[52] That is an established technology commonly applied to small and large LIBs, especially to cobalt-rich batteries. Usually this method does not require pre-sorting of battery types, however, the resulting alloy requires further processing. Hydrometallurgy recovers the desired metals from cathode material *via* leaching in an acidic or basic aqueous solution. Additional steps such as subsequent concentration and purification are later required. This process allows the recovery of almost all LIBs components with high purity.[53] However, the separation of the metals from each other requires additional purification steps: in addition, unlike pyrometallurgy, sorting is required. Finally, direct recycling involves the direct re-use of the cathode and/or anode material from the electrodes of spent LIBs after reconditioning. Although promising in principle, as it allows the simple recovery and re-use (without further processing) of most of the battery constituents,[25,54,55] it is still not fully matured as a technology. There are also alternative technologies under investigation such as plasma smelting technology,[37] bioleaching,[56] redox targeting-based material recycling,[57] *etc.*

Each of the listed technologies has its own limitations in recovering LIB's materials. Therefore, the final process should involve a combination of various techniques with a well-defined material flow chart to assure the highest efficiency of recycling.[58] The enormous research and development effort should tackle this issue, however, the gradual but constant change in battery chemistry will require the facilities to shift their operational mode in just a few years. Is the process safe to operate with new chemistry? Are there any hazardous by- and end-products that need to be treated accordingly? These and

Table 1 Current recycling facilities around the world adopted from ref. 49 and 50

Company name	Location	Process[a]	Capacity (tonne of battery per year)
Accurec Recycling	Germany	P, M	4000
Akkuser	Finland	M	1000
Aubermacher Redux	Germany	M	1000
Bangpu Ni\\& Co High Tech	China	H	3600
Batrec	Switzerland, Wimmis	P	200
Dowa Eco-System Co. Ltd	Japan	P, H	1000
Duesenfeld	Germany	M	3000
Envirostream	Australia	P	3000
Euro Dieuze	France	M, H	6000
GEM	China	H	100 000
Glencore	USA, Canada, Norway	P	7000 (Norway)
High Power International	China	P, H	10 000
Huayou Cobalt	China	H	60 000
Hunan Brunp Recycling Tech	China	H	30 000
Inmetco	USA	P	6000
Jiangxi Ganfeng Lithium	China	H	5000
JX Nippon Mining & Metals Corp	Japan, Tsuraga	P, H	600
KOBAR	South Korea	H	1000
LiCycle	Canada	H	2500
Nickelhütte Aue	Germany	P, H	1000
Nippon Recycle Center Corp	Japan	P	2000
Recupyl	France/Singapore	H	110/1200
SNAM	France	P, M, H	1500
SungEel Hitech	South Korea	H	8000
Sungeel Hi-tech	Hungary	M, H in South Korea	3000
Taisen Recycling	China & South Korea	H	6000
Tele Recycle	China	H	2000
TES (Recupyl)	France	M, H in Singapore	1000
Umicore	Belgium	P, H	7000
Ute Vilomara	Spain	H	> 53.32

[a] P – pyrometallurgy, H – hydrometallurgy, M – physical separation.

other questions must be answered to ensure the safety of the workers and mitigate the environmental impact of the process.

2.1.3 Pollution specific to recycling and the potential environmental impacts. Materials recovery is not a pollution-free activity. For example, pyrometallurgy is a highly energy-demanding process, resulting in GHG emissions and the generation of toxic gases or hazardous slag that may need to be landfilled.[31] Moreover, the intermittent product, so-called ''black mass'' (a sludgy mixture of lithium, manganese and cobalt), may also contain other hazardous substances such as alkylfluorophosphates that are a serious health concern.[59] Pyrometallurgical recycling process could impose environmental risks in global warming, photochemical ozone creation, carcinogenic and non-carcinogenic effect, ozone layer depletion and eutrophication impact categories.[18] A recent study on plasma smelting recycling showed that the employed energy source (for the smelter), recycling efficiency, the quality of the recycled materials, aluminium recovery and adopting a battery waste improvement process could significantly affect the overall environmental impacts of pyrometallurgy.[37]

In contrast, hydrometallurgy produces far less GHG emissions but requires supplementary wastewater treatment to ensure that receiving waters do not suffer additional pollution, *e.g.* from acids. Hydrometallurgical recycling processes were reported to impose environmental risks on freshwater and terrestrial acidification.[18] Mohr *et al.* (2020) compared the environmental impacts of recycling of different battery chemistries (*i.e.* NMC, NCA, LFP and solid-state) using a conventional pyrometallurgical, a conventional hydrometallurgical process and an advanced hydrometallurgical process (that recovers graphite and electrolyte).[60] The results indicated that the advanced hydrometallurgical processes could perform the best (in terms of global warming impact) due to additional recovery of graphite and electrolyte, while the pyrometallurgical process performs the worst due to high energy consumption and lack of Li recovery. The authors also suggested that a cell chemistry specific approach for recycling should be taken into consideration since some recycling processes could lead to unfavourable impact on the environment when treating some specific chemistries, for example, hydrometallurgical recycling of LFP and sodium-ion batteries (SIB) could add more burden in abiotic resource depletion potential; or pyrometallurgical recycling of LFP cells could increase the global warming impact.

As direct recycling is still in its very early stages of development, there are no real-world data on potential pollution. According to Dunn *et al.* (2015), using a direct recycling process for NMC, LCO, LFP and LMO batteries could significantly reduce the emissions of GHGs and SO_x (from the production of batteries) and thus mitigate global warming and acidification potential of the whole battery life cycle.[61] It should be noted that when talking about the environmental impacts of a specific recycling process, the net impact on the environment is usually considered which is calculated by subtracting the released emissions from the avoided emissions (recycling benefits). Thus, a recycling process itself may have a negative impact on the environment in a specific environmental impact category while the credits from the recycled materials (environmental impacts avoided due to returning the recovered material to the market) might compensate those negative impacts and make the net environmental impact favourable. Overall, it should be noted that the environmental impacts of different recycling processes could vary based on the processed cell chemistry, the employed emission reduction technology, recycling efficiency and the quality of the materials recovered.

2.1.4 Comparison to non-lithium ion battery recycling methods. Finally, there is a lesson to be learnt from the already established recycling processes for other battery types. For example, the processing of lead-acid batteries is of major concern especially in developing, countries[62] as, in such locations, recycling is often performed without controlling lead emissions.[63] In addition, there is also often a lack of appropriate regulation and the consequent existence of informal and polluting recycling industries. Thus, in the absence of adequate standards and/or lack of enforcement of regulatory controls, the lead recycled from batteries results in significant environmental contamination and human exposure even in established, industrial-scale recycling facilities.[64] It has been estimated that over 495 000 deaths and more than 9 million disability-adjusted life years (DALYs) occur as a result of the long-term impact of lead exposure on health. Reports also show that low- and middle-income countries have the highest death rates associated with lead exposure.[65] Comparative analysis reveals that current environmental and social influence such as consumption of raw material/metal, energy demand, scrap emissions, recycling or disposal cost; of the lead-acid battery system is greater than that of the LIB system.[66] However, it should be highlighted that such studies are performed on retrospective data (*i.e.* for China in 2016) and do not fully reflect the future with much higher numbers of production and recycling/disposal of LIBs. Therefore, it is essential to assess in detail all the gaps in knowledge and technology, as well as socio-economic issues, and apply these to the future LIB recycling industry. This is important not only for developed countries but even more for emerging economies that usually have lax or weak environmental legislation.[67]

2.2 Landfill

Landfilling is the main method of disposing of solid waste[68] – with the rates of deposition of municipal waste ranging from 53% in the USA,[69] 79% in China[70] to 94% in Malaysia.[71] Of these, around 4% includes electronic wastes (e-waste), often containing batteries.[72] Given the low global recovery rates, it is clear that most e-wastes containing small LIBs are discarded into the landfill sites rather than recovered.[73–76] This is the case not only for many emerging economies but also in developed ones due to (as stated above) lax or weak regulations as well as the lack of recycling infrastructure. Therefore, in the short-term at least, it is certain that LIBs (especially those from small portable devices) will be buried. Currently, due to the relatively small number of EVs, large LIBs are usually recovered.[44] However, with the rapid growth in volume and still inadequate infrastructure, even high-powered batteries may be either landfilled or temporarily stored. Yet, in the long-term, it is more likely they will follow the recovery route rather than landfilling, as it would be a waste of a significant resource of valuable materials.[67]

The landfill itself can be both a sink or source of pollution that can have negative impacts on surrounding communities.[68] The main sources of emissions from landfills are surface dust, landfill gases (*e.g.* biogas), leachate and fires.[77,78] The extent of pollution from a site depends upon location, waste composition and age, and geo-climatic conditions.[51,79–81] However, in the future it's possible that landfills may be a place of valuable resources for urban mining – the sink of the rare and needed metals that can be extracted without actual mining.

2.2.1 Landfill fires. Landfill fires are clearly undesirable but unfortunately quite frequent.[82–86] There are two types of fire, surface and subsurface (cavity): and in most cases, they are due to the spontaneous auto-ignition of methane.[87] Surface fire spreads outside the landfill area but is relatively easy to extinguish. Cavity fires are a form of combustion (pyrolysis) where the thermal reaction takes place under anoxic conditions deep below the landfill surface.[77,88] These are difficult to detect and may create large voids in the landfill, which can cause the landfill surface to cave in. Buried LIBs, which may be holding a charge and contain flammable electrolytes, may trigger, amplify and prolong landfill fires.

Landfill fires caused by (usually small) LIBs are a major emerging problem. The Environmental Services Association (ESA), the trade body representing the UK's resource and waste management industry, reported that 25% of total landfill fires (>500) in the UK in the period 2017–18, were attributed to LIBs: a significant 20% increase in comparison to the previous year.[89] Examples of such fires include that at the Dunbar landfill site on 22nd January 2019, where around 300 tonnes of waste burst into flames in waste sorting building.[90] Fires in pre-landfilling facilities may be illustrated by Shoreway MRF, USA. At least 25 fires at this facility were caused by LIBs between April 2013 and September 2017. The most severe fire, on the 9th September 2017, required over 100 firefighters to extinguish it, and the fire shut the facility for 3 months and cost over $8.5M in restoration.[91]

Accurate prediction of the ignition potential of LIBs is challenging, as spent batteries will have various compositions, States of Health (SoH) and charge (SoC); besides, it is likely that cells, modules and packs will be dumped and landfilled. In landfills, batteries may be damaged during compacting and hence ignite either immediately or after burial: in the latter case, serious fires could result due to surrounding flammable materials and existing methane in the landfill environment. Even if damaged batteries do not ignite, the pyrolysis that accompanies thermal runaway will generate significant heat and toxic and potentially explosive gases.[92] It should be noted that fires caused by batteries may occur months or even years after they were buried.

The hazards of damaged LIBs are in addition to conventional landfill fires, which produce a mixture of toxic gases and smoke[77,93] consisting of polycyclic aromatic hydrocarbons (PAHs),[94–96] dioxins/furans,[97–101] volatile organic compounds (VOCs),[102,103] heavy metals[104,105] polychlorinated biphenyls or organochlorine pesticides[104] and finally, particulate matter (PM) with an aerodynamic diameter smaller than 2.5 μm.[106,107] Subsurface fires favour the generation of harmful gases such as CO, SO_2 or H_2S[77] – some of these gases are also generated within burning batteries.[7,20–24] Landfill fires do not only affect the air around the site as the smoke can carry particulate matter and chemicals to further distances: for example, it has been shown that there may be a short term rise in the concentrations of heavy metals and Chemical Oxygen Demand (COD) or PAHs[86] in water bodies next to burning sites. Therefore, avoiding battery landfilling or at least neutralization/immobilization of hazardous content must be seriously considered. That could be for instance (i) complete discharging-no excess of the energy, immobilization of copper on aluminium foil; (ii) removal of the flammable electrolyte from the battery – reduced fire risk, formation of hazardous gasses and vapour cloud explosion; (iii) using additional liners (bentonite clay *etc.*) capable of binding heavy metals – no transport through landfill layers.

2.3 Illegal disposal and processing

Wherever there is a potential of making profit there are attempts to bypass official routes of making business. As the recycling of LIBs will be profitable at least to some degree, there is a big chance that some illegal processing will occur, as it happened for waste electronic equipment. Such activity will result in pollution surrounding the processing site, poor working conditions of workers and thus worsening their health and quality of life. Illegal disposal will occur if the recycling or official landfilling will be to "too expensive" for some "business". The dumpsites will be located in very random places, completely not fit for purpose and that will result in severe pollution, unexpected fires and huge additional costs to local residents/councils – utilization and remediation of the area. Unexpected incidents (*e.g.* fires) may even occur months after the disposal making the process of finding responsible/guilty person very tricky.

It is certain that LIBs will be illegally recycled and disposed of.[67,108] Moreover, the burden of illegal processing will be mostly put on emerging economies due to the high costs of labour, lack of recycling facilities and strict environmental laws in developed countries.[6] A good example of this exploitation is the export of e-waste facilitated by rich and developed nations to poor and developing ones.[109,110] This is also reflected in the statistics: for instance, two-thirds of global e-waste collected in 2014 were exported, but more importantly, half of it was through illegal routes.[111] This resulted in over 3 million tonnes of e-waste exported outside of regulated schemes. Data for 2019 show that 82.6% of global e-waste flows were neither formally collected, properly managed nor documented.[72] The EU generates *ca.* 44.3 Mt of e-waste annually, however only 0.6 Mt is known to reach landfills whilst the rest is dumped, traded, informally exported or recycled in a non-environmentally appropriate way.[112] Hence there is no guarantee that exported EoL LIBs will be recycled or processed in regulated, safe and environmentally friendly ways.[44]

2.3.1 E-Waste problem. Interestingly, even now with a relatively low number of EoL EVs, it is possible to buy used LIB cells, modules on the popular, online, auction portals. This means that they are sold outside official collection/recycling schemes, even though they have reached their first EoL. With the growing demand from individuals, *e.g.* for behind-the-meter energy storage, some of the batteries may be illegally sold, especially in countries with weak or no regulations, and the obvious question arises: what happens to such self-made systems when they reach real EoL? Will they be passed to accredited recycling centres or dumped? In addition, what would be the impact of the illegal processing of LIBs on human health and the natural environment? These issues can be illustrated by current informal WEEE operations - often the recycling is carried out without any environmental and health protection, and this results in the contamination of soil, air and water and a serious impact on human health.[108,113–121] The findings include the fact that heavy metals (*i.e.* lead or cadmium) and polycyclic aromatic hydrocarbons in the soils or watercourses surrounding such centres are significantly above national safety limits. Cobalt, copper and nickel are also heavy metals included in LIBs that might cause hazards if LIBs are inappropriately treated. Lead-acid battery informal processing can highlight potential issues for LIBs in the future. For instance, estimates have shown that there could be between 10 000 and 30 000 informal lead-acid battery recyclers in 90 low- and middle-income countries that pose a major threat to up to 16 million people.[122] Such sites elevate levels of lead in soils and plants[123] and have caused higher concentrations of the metal in children's blood in Serbia,[124] Australia,[125] China[126] and India.[127,128] Informal sites rarely control their harmful emissions, are subject to weak or no regulation, and are often located within residential areas.[124,129,130]

2.4 Incidents involving LIBs

Incidents involving LIBs are mostly focused on fires and the release of toxic gases. In addition to the risk of these hazards to first responders and spectators at, for example, a road traffic accident, there is also the broader spectrum of the environmental impact of such fires. Fig. 2[131,132] shows typical emission pathways from a burning LIB to the surroundings. In addition to heat, fire or a toxic and potentially explosive vapour cloud there is also a possibility of air transportation of substances and with time, their deposition in other, distant places. The close surroundings are also affected by the fire debris, transportation of pollutants by fire extinguishing agents and release of remaining contamination from burnt carcasses – depending on the type and place of the disposal.

The sometimes explosive failure of LIBs is always due to some form of abuse which can be from heat, penetration, blunt trauma or overcharging, and examples of the results of these can be found in the literature citing examples on the land, sea and in the air.[133,134] Spontaneous ignition of LIBs has also been reported, particularly concerning electric vehicles;[135] the events leading to this remain essentially unknown, but contamination

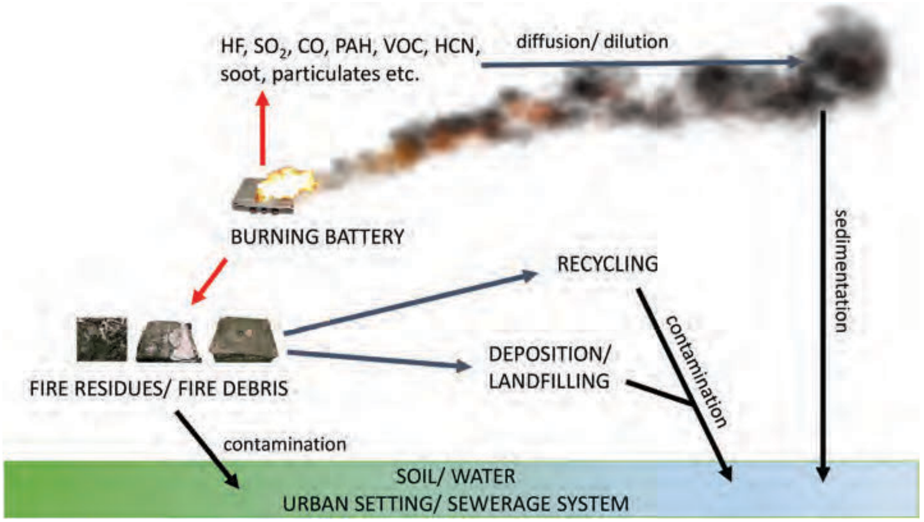

Fig. 2 Emission pathways from fires (adapted from ISO, 2011; Stec *et al.*, 2019).

during production or poor design is often quoted. An increasing and slightly worrying phenomenon is the incidence of fires and explosions in large LIB energy storage systems (LIBESS). The first such incident occurred in Arizona in 2012 in a new 1.5 MW LIBESS owned by Arizona Public Services.[136] Several design flaws were identified following the incident including a lack of proper ventilation and inadequate monitoring all of which were supposed to have been addressed[137] when a second LIBESS owned by APS exploded in April 2019 injuring four first responders, two of whom badly. The incident is now believed to have been a vapour cloud explosion.[138,139] We listed some other examples of LIBESS incidents in Table 2 to illustrate the rising problem.

In essence, LIBs in thermal runaway produce gases that are a mixture including hydrogen, carbon monoxide, carbon dioxide, HF, short-chain alkanes and alkenes, HCN, NO_x and droplets of solvent,[21,23,138,140–142] the last giving the mixture the appearance of a white cloud.[143] In broad terms, the composition of the white vapour varies little as a function of cell chemistry, form factor or manufacturer.[138] The gas mixture will be vented either when safety valves/blast caps activate or when a pouch cell bursts: at high SOC and in the presence of sufficient oxygen, the white vapour ignites to produce flare-like flames. At low SOC or in the absence of sufficient air (*e.g.* the air is displaced by the vapour or by fire suppressant) the white vapour does not ignite,[144] in which case, in a confined space, there could be a possibility of a flash fire, fireballs developing, or in extreme cases, even a vapour cloud explosion.

LIBs are also more and more used in marine transportation. They can work as a propulsion system, powering ferries or even submarines,[145] energy recapture systems or hybrid systems. The advantage is usually lower weight and better efficiency in comparison to *i.e.* lead-acid systems.[146] As in the case of the EVs and BESS, there is a possibility of faults, incidents, fires and thus pollution of water ecosystems. An example of such an incident is a fire and subsequent gas explosion on board a diesel-electric ferry in Norway on the 10th of October 2019[147] – the fire was spotted during the crossing, but the ferry returned to the harbour under its power where everyone was safely evacuated. Overnight, however, a serious gas explosion rocked the battery room causing significant damage. It was reported that twelve firefighters were hospitalized due to exposure to hazardous gases associated with the burning batteries. Table 2 also shows some other known up-to-date incidents.

Fire extinguishing agents (water, foam *etc.*) used to mitigate the incidents will be a carrier to all pollutants released from LIBs. That can broader the area of the impact. For instance, HF released during a fire may form a solution with the fire extinguishing agent and thus, at concentrations as low as 0.01%, could cause injury to the more sensitive areas of human skin following exposures as short as 5 min.[148] If we add that between 20 and 200 mg of HF could be released per W h of an EV battery pack,[22] such solution or even higher concentrations may be of no surprise. This reaction should be also taken into account when designing and using any extinguishing systems in places dealing with larger amounts of LIBs. The first responders must also be aware of the additional hazards, thus proper personal protective equipment (PPE) and operating procedures should be in place.

When the fire is gone there are left carcasses of burnt batteries. Except probably some steel parts (pack cover, module case *etc.*) they would not represent any value for recycling thus probably discarded/landfilled. These carcasses may be treated as fire debris according to Fig. 2. Currently, there are no data directly revealing what kind of pollutants may be released from such waste. Given the typical post-fire analysis[132,149] and the composition of LIBs, we can suspect these may be remains of nanooxides, metals, PAHs and VOCs.

3. Sources and pollution pathways

Spent LIBs are considered hazardous wastes (especially those from EVs) due to the potential environmental and human

Table 2 List of some major involving LIBESS and Maritime incidents

Major LIBESS incidents

Place	Date	Comments
APS Arizona, USA	February 2012	Testing a new 1.5 MW BESS linked to a solar energy system when it was destroyed by fire. Subsequent investigation concluded that lack of ventilation and inadequate monitoring were the major causes of the incident and recommended improved ventilation, 24/7 monitoring and the ability to send remote alarms.[a]
Wisconsin, USA	August 2016	The damage is estimated up to $4M. The fire started in the DC power and control system rather than the lithium ion batteries.[b]
Drogenbos, Belgium	November 2017	Fire badly damaged the container of a 1 MW BESS after the fire detection and control system failed to control the blaze.[c]
Various places across South Korea	2018–2019	Up to 30 fires involving LG Chem lithium ion BESS. The causes of these fires have not been made public as yet, but defective lithium ion cells were not believed to be a major contributing factor. The concatenation of multiple factors have been postulated.[d]
Surprise Arizona	April 2019	Vapour cloud explosion. Four first responders were injured, 2 very badly. 9 first responders contaminated with hydrogen cyanide.[e]
Nathan campus of Griffiths University, Brisbane, Australia	March 2020	LFP BESS exploded causing major damage to buildings. The cause of the fire and explosion has been stated as having been an internal short circuit.[f]
Carnegie Road, Merseyside, UK	September 2020	One of three containers exploded in the early hours of 15 September, followed by a fire. The ventilation units were blown off the roof of the container by the blast, with debris (including one of the doors) scattered across a wide area. The cause of the explosion remains under investigation.[g]
Perles-et-Castelet, Ariège France	December 2020	A BESS containing 60 ''batteries'' ignited. The container was situated on top of a second container and presented some difficulties to the fire service, which had to pull the burning container down. The cause of the fire is under investigation.[h]
SBG-2 OVHcloud data centre in Strasbourg, France	March 2021	One data centre was completely destroyed and 4 of the 12 rooms of a second centre were also destroyed. Unconfirmed reports that fire started in BESS.[i,j]
Hongseong, South Chungcheong Province, China	April 2021	Fire in the BESS supporting a solar energy facility, supplied by LG Energy Solution (LGES). The fire destroyed the facility causing *ca.* 440 M Won damage[k].
Shopping mall in Beijing, China	April 2021	Explosion and fire in a 25 MW h LFP BESS situated on the roof of a shopping mall. The BESS supported a solar array. 2 firefighters were killed, 1 injured. The BESS consisted of two sections, North and South: whilst dealing with a fire in the Southern section and explosion occurred in the Northern section, killing the firefighters.[l]
Invenergy storage facility, LaSalle County, USA	July 2021	Fire in one of the 18 containers at a LFP BESS near the La Salle Generation Station nuclear power plant.[m]
''Victorian Big Battery'', Moorabool, Geelong, Australia	July/August 2021	The Moorabool installation is the largest LiBESS in Australia. The fire started in one container and spread to a second, paired container which was adjacent to the first. The firefighters adopted a defensive strategy due to the challenges of the installation, and allowed the containers to burn out in a controlled manner over 3 days.[n]

Maritime incidents

Place	Date	Comments
Hybrid tug Campbell Foss, USA	November 2012	Fire in BESS of the vessel after it had finished assisting a second vessel in the port of Long Beach. The fire started in the battery compartment and spread to the engine room *via* a ventilation duct. The vessel's engineer was hospitalized. The incident has been attributed to long term overcharging of the battery.[o]
Boat Carila Sis, Sneek harbour, Netherlands	May 2019	The explosion occurred on board a pleasure craft whilst moored in the harbour. A fireball was observed above the boat by local residents.[p]
Russian nuclear submarine Losharik, Barents Sea	July 2019	An electrical short circuit occurred while the nuclear submarine was docking with the Podmoskovye, its mothership. This caused lithium ion cells to go into thermal runaway resulting in explosions and fire, killing 14 high-ranking officers on board.[q]
Hybrid electric ferry Ytterøyningen, Norway	October 2019	Coolant leaked from the 1989 kW h BESS on the vessel causing a small fire. This was extinguished by the seawater sprinkler system. However, the seawater then caused short circuits in the battery which exploded on the following day. 12 firefighters were hospitalized due to exposure to hazardous gases.[r]
Hybrid passenger vessel Brim, Norway	March 2021	Fire in the 790 kW h battery compartment of the 24-meter hybrid catamaran passenger vessel Brim in Oslofjord.[s]

[a] [redacted]y. [b] [redacted]. [c] Deign J. In: Media G, editor. Engie investigates source of Belgian battery blaze. Boston, MA, USA: Greentech Media Headquarters; 2017. [redacted] (accessed 25th May 2020). [d] Yoon-seung K. Faulty batteries blamed for ESS fires: panel. South Korea: Yonhap News Agency; 2020. [e] DNV GL, *McMicken Battery Energy Storage System Event Technical Analysis and Recommendations*, Arizona Public Service, [redacted] 2020. [f] Dennien M. Firefighter' knocked on his back' in fire blast at Griffith University. Brisbane, Australia: Brisbane Times; 2020. [g] [redacted] [j] [redacted] [k] Fire at Solar Plant in Hongseong Involves EV Batteries from LG Energy Solution – Businesskorea. [l] [redacted]/. [m] [redacted]

health risks associated with heavy metals.[74,150–154] The disposal and processing of LIBs, as well as their properties (*e.g.* chemistries), will have a significant impact on various environmental compartments (Fig. 3). LIBs contain a variety of chemicals including reactive salts, volatile organic electrolytes and additives: the latter are often commercial secrets and hence their toxicity and combustion products are largely unknown.[155,156] Moreover, battery fires, in combination with biogas from landfills, may release toxins into the air or leach the harmful contents into the soil, groundwater and surface water.[118,157,158] Once released, they pose risks to the surrounding environment alone or in combination with other pollutants.[159–165]

Fig. 3 shows likely pollution routes (originated from EoL LIBs disposal/processing) to the environment and possible cross-contamination within different compartments. Pollutants once released from LIBs may enter one compartment first and later be transported to another one. For instance, heavy metals may be collected by dumpsite leachate and transported into the soil or groundwater outside the initial site. On the other hand, if a battery leaches onto open ground, heavy metals may run-off with the rain to a nearby river or lake. However, due to knowledge and data gaps, not all routes could be fully reviewed in this work.

3.1 Emissions to air

3.1.1 Dust. Fine particles may be released from LIBs to the air during disassembly and recycling processes; from a landfill or dumpsite by degradation or fire/explosion; and are considered as a part of the total dust emissions.[166] Generally, dust is a mixture of solid particles and liquid droplets of a wide range of sizes (nanometres to few micrometres) and chemical composition, all together suspended in the atmosphere.[167,168] Particulate matter with aerodynamic diameters of less than 10 or 2.5 μm (PM_{10} and $PM_{2.5}$) can jeopardize human health, adversely affect climate and reduce visibility at local and regional scales.[169–171] Particulates may contain matter-bound metals such as arsenic, cadmium, chromium, cobalt, copper or lead due to the decomposition of recyclable batteries, scrap metals and electronic waste.[172–174] Dust can enter the respiratory system causing adverse health effects such as cardiovascular and respiratory diseases, carcinogenicity, or disruption of the endocrine system.[175–187]

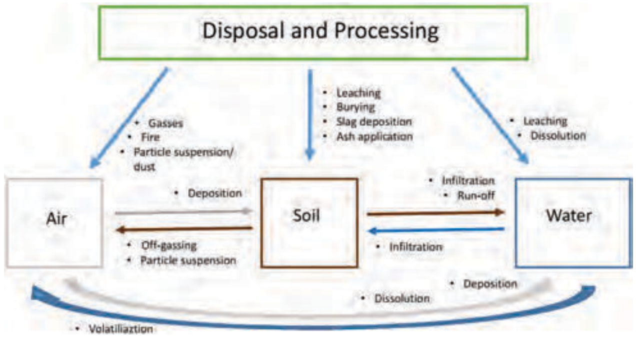

Fig. 3 Possible emission routes of pollutants from LIBs into the environment.

During disassembly and material recovery of LIBs, shredding is the main mechanical processing option[25] that could generate dust emissions. These emissions could potentially cause a respiratory hazard to workers in recycling centres as well as those living or working in the vicinity. Moreover, particles and chemicals (*e.g.* PAHs) released from batteries may aggregate together in the atmosphere, be transported on larger distances and settled down causing for example soil pollution. As LIBs particles may be of different materials and sizes, it is mandatory to assess and investigate their possible toxicity and respiratory hazard.

The potential negative effect of three battery materials: lithium iron phosphate (LFP), lithium titanium oxide (LTO) and lithium cobalt oxide (LCO) was studied utilizing mouse bioassays.[188] The mixed metal oxides present in the cathodes of LIBs could release particles small enough to penetrate the lungs and induce inflammation. The extent of the impact varies depending on the chemistry of the LIB. From the materials tested by Sironval *et al.* (2018), LTO was the least harmful, whereas LCO induced the strongest inflammation. As a result, the fibrotic responses were observed in cells with higher inflammation rates.[188]

Another generator of dust and particles are explosions and fires. During thermal runaway the particles are first ejected from the safety vent together with other gases, resulting in heavy smoke with black colour.[189,190] After cooling down, they settled as surface dust. The composition of these powders from lithium nickel cobalt manganese (NMC) cells was mainly C, O, Al, Mn, and F. This result suggests that it is mostly the negative carbon particles of the battery, as well as the oxidized positive substances of the electrode, that are ejected during gas venting.[190] Another study[191] found that thermally abused prismatic automotive NMC cells released PM that contained heavy metals. The authors found that nickel and copper were detected in all collected fractions (1.45 to 500 μm) whereas zinc and chromium settled with bigger fractions (50 to 500 μm). Ni had the largest mass percentage followed by Cu, Zn and Cr. In terms of the total emitted quantity, PM accounted for 1.7% of the cell mass. Once settled, such particulates may interact with surrounding waters and soil and ultimately be of threat to crops.

3.1.2 Hydrofluoric acid. Out of various hazardous gases released from LIBs to air, HF is of the highest concern and must be treated with high caution. It can enter the human body *via* the skin or respiratory systems and causes severe corrosive effects and systemic toxicity.[192] Inhalation of just a few ppm of HF can result in serious toxic effects. HF readily penetrates the skin and moves quickly to the deeper tissue layers where it releases the freely dissociable fluoride ion. This ion is extremely toxic, due to its strong reactivity.[193] Moreover, HF gas is hygroscopic and readily soluble in water.[158,194,195] Concentrated solutions of HF are highly corrosive to the skin and underlying tissues and accidental dermal exposure has been reported to cause death in humans.[148,196]

HF is generated in LIBs during the first charge and by subsequent cycling, a phenomenon known as gassing.[197–200]

The acid can also be produced due to accidental spillage and hence the exposure of the $LiPF_6$ in the electrolyte to humid air[158] according to:

$$LiPF_6 + H_2O \rightarrow LiF + 2HF + POF_3 \quad (1)$$

although this is disputed.[201]

As well as the direct reaction of $LiPF_6$ with water, at ambient temperature in the organic carbonate solvents employed, $LiPF_6$ exists in equilibrium with its decomposition products according to:

$$LiPF_6 \leftrightarrow LiF + PF_5 \quad (2)$$

PF_5 is prone to degradation upon exposure to traces of water, moisture or alcohols[202] to form HF which is also highly toxic:[158]

$$PF_5 + H_2O \leftrightarrow POF_3 + 2HF \quad (3)$$

To mitigate the effect of reaction (3), commercial LIB electrolytes often contain additives, up to 5% by mass or volume, some of which suppress PF_5 formation. Others are added to protect against overcharge, provide fire-retarding protection or improve Solid Electrolyte Interphase (SEI) formation or quality.[203] It is not clear what effect these may have on reaction (2) or other decomposition reactions, or their toxicity or the identity of the products from their combustion.

The second likely source of HF from LIBs is a thermal runaway and fire. The amount of HF produced during an incident depends on the size of the cell and its chemistry[21,23,142,204–206] and may incorporate endothermal decomposition of the binder – polyvinylidene fluoride (PVDF).[159]

Sturk *et al.* (2015) detected significant quantities of HF from burning NMC and LFP type pouch cells.[141] Surprisingly, LFP cells produced the highest levels of hydrofluoric acid fumes. So far this type of chemistry was regarded as one of the safest as having the highest cathode decomposition temperature;[135] however, the cells employed in the LIBESS that exploded at Griffiths University in March 2020 were LFP cells.[207]

Larsson *et al.* (2017) have estimated that between 20 and 200 mg of HF could be released per W h of an EV battery pack.[22] Thus, the amount of HF could be greater than 80–800 times the US National Institute for Occupational Safety and Health Immediate Danger to Life or Health (IDLH) level.[208]

3.1.3 Vapours and gases. It is now apparent that thermal runaway generates a white vapour during venting the cells, essentially independent of chemistry, form factor and manufacturer.[139] This white vapour contains H_2, SO_2, NO_2, HF, HCl, CO, CO_2, droplets of organic solvent (giving the white colour) and a large range of small chain alkanes and alkenes.[7,20–24] The exact composition of the white vapour appears to depend on the State of Charge (SoC) and battery chemistry.[20,142,209,210] The white vapour is produced when cell is venting as a result of various chemical processes, triggered at successively higher temperatures.[135] There is insufficient oxygen produced when the cathode structure collapses to sustain fire, but when the white vapour vents from the cells it may or may not ignite: at SoC $> 50\%$ and if sufficient oxygen is present, the vapour can ignite to produce jet-like flames.[144] However, if there is insufficient oxygen, *e.g.* inside a LIBESS with air displaced by the vapour and/or a suppressant,[138] the vapour represents a wholly novel hazard concerning LIBs; if the white vapour contacts an ignition source, there could be a possibility of a flash fire, fireballs developing, or in extreme cases even a vapour cloud explosion.[211]

3.2 Emissions to soil and water

Once physically disposed of, LIBs will leach their contents into the surrounding soils, infiltrate to deeper layers, pollute groundwater and can run-off into surface waters. As water is very often a carrier of pollutants in the soil, it is challenging to ascertain the individual impact of LIBs on these two spheres alone, and hence we discuss the impact on them jointly.

3.2.1 Landfill/dump leachate. One of the most important hazards associated with landfilling and illegal processing is the generation of leachate: it is formed as a result of various biological and chemical degradation processes, and rain percolating through waste. Non-LIB related leachates are a complex mixture of substantial amounts of dissolved organics, inorganic salts, ammonia, heavy metals and xenobiotic organic compounds that are remains of personal care products, pharmaceuticals, industrial, household chemicals, their transformation and degradation products, especially from landfills.[212–214] Leachate could impose a serious environmental impact as it can act as a transportation medium for hazardous species. It may pollute soils or groundwater and transport contaminates over considerable distances, often many kilometres from the site[215–219] potentially contaminating groundwater.[212]

LIB leachates will potentially carry various pollutants such as heavy metals, additives, electrolyte degradation products but also dissolved gases. The latter, such as HF, HCl or SO_2 (in form of sulphuric acid) not only have a straightforward toxic effect but also alter the properties of receiving waters and solutions in soil. The acidification caused by these corrosive species may have the same effect as ''acid rain'', lowering the pH and thus strongly impacting plants and animals.[220] They would also enhance the release of soil-bound heavy metals. Under more acidic conditions the actual toxicity of heavy metals is higher than it would be predicted from the metal concentration alone.[221]

3.2.2 Heavy metals. The content of metals in batteries depends upon their design and size (*i.e.* cylindrical, prismatic or pouch cells), as well as their chemistry (*i.e.* NMC, LCO *etc.*). Typically they are in the range of 0.05–0.37 kg Co per kW h, 0.25–0.86 kg Ni per kW h and 0.46–0.9 kg Li per kW h.[222–225] These figures translate to tens of kilograms of such materials in EV packs that potentially may be released to the environment if improperly disposed of, representing a series of threats to human health and the environment.

The toxicity of heavy metals from LIBs includes attaching, blocking and disturbing the conformational structure of carbohydrates, lipids, proteins or enzymes.[226–228] Heavy metals polluting crops, fruits or dust are known to induce genetic damage in children[229,230] and cause lower academic performance.[231]

Nickel released into the environment binds strongly to small solid particles, especially containing iron or manganese. Ni has a low tendency to accumulate in fish and small animals. With respect to human health, nickel is the most common allergic metal. It may also cause respiratory disorders and even cancer at higher concentrations.[232] Lithium has relatively low toxicity and small dosages are beneficial for various trophic levels of organisms.[233] Nevertheless, it is quite an active element and, in higher concentrations, may cause digestive and neurologic systems disorders.[234,235] Small dosages of cobalt are beneficial to humans (synthesis of vitamin B12) but larger dosages cause respiratory problems and skin rashes.[236] In general, adverse reactions to Co exposure depend primarily on its chemical form.[237]

The leachate from LIBs penetrating through landfill or illegal dumpsites will collect and carry various metals, including lithium, cobalt, nickel, manganese, iron, chromium and copper.[155] A few studies have reviewed various leaching scenarios to assess the correlation of typical mass compositions in different types of LIBs to their contamination potential.[238–241] Metals found in leachates (both real and artificial) that exceeded toxicity limits were lead, mercury, cobalt, copper, nickel, chromium and thallium – depending on the type of test used. One of the studies[242] analysed the leachate from a landfill containing NMC batteries: the authors found that less than 4% of the total cobalt, nickel, aluminium, copper, and iron from the battery were in solution, whilst 11.45% of the manganese and 42.50% of the lithium were present.

It is unlikely that metals will be released only in metallic or ionic form from buried LIBs: they will likely be mobilized as nanoparticles (NPs) as well. Such nanomaterials (mostly of cathode origin) and their ecotoxicological potential towards various organisms were assessed by several studies. Thus Hang *et al.* (2017) studied the impact of NMC on the soil bacteria *Shewanella oneidensis* MR-1 and found that exposure to 5 mg L^{-1} NMC significantly impaired bacterial population growth and respiration.[243] The authors showed that these effects were due to the release of metal ions from the NMC, with the largest effects arising from Ni^{2+} and Co^{2+} species. Gunsolus *et al.* (2017) also investigated the toxicity of NMC towards the same bacteria, varying the relative composition of the metals in the mixed metal oxide.[244] The authors found that lowering the Ni and Co content and increasing the Mn content, lowered the biological impact significantly. In fact, reducing the cobalt content and increasing Ni has been a key aspect of NMC battery development over the last few years, driven by safety considerations[245,246] and global supply chain issues.[247,248] Another study assessed the biological impact of NMC on a Gram-positive model bacterium, *Bacillus subtilis*.[249] Growth and cellular respiration of the bacteria were inhibited significantly by free Ni^{2+} and Co^{2+} ions released from the incongruent dissolution of the NMC. DNA damage tests at the single-cell level confirmed that the toxicity caused by the redesigned NMC (enriched in Mn) was lower in comparison to solutions containing either free Ni and Co or original NMC material. A recent paper[250] reported a study on the influence of multiphase lithiated cobalt phosphate (mLCP) nanomaterial on *Shewanella oneidensis* MR-1 and *Bacillus subtilis*. The authors found that mLCP was toxic to both species due to the release of cobalt ions.

The toxicity of NMC and LCO materials towards eukaryotic organisms was studied using *Daphnia magna*.[251] The work showed that there is negligible acute toxicity to daphnid at the highest concentrations of 25 mg L^{-1}, whereas there is a significant impact on daphnid reproduction and survival during chronic exposure (21 days) at concentrations of 0.25 mg L^{-1} for LCO and 1.0 mg L^{-1} for NMC. They confirmed that toxicity depends on chemical composition – the replacement of Co by Ni and Mn resulted in better daphnid survival, reproduction, and body size. Finally, the authors highlighted there was a strong nanomaterial-specific impact – probably due to adhesion.[252] Although, the effect could not be fully confirmed by experiments with just free Li, Ni, Mn, and Co ions dissolved in suspension metal.

LCO and NMC have been shown to have adverse effects on the benthic invertebrate *Chironomus riparius*[253] by inhibiting growth and development. The increased toxicity of these materials was associated with quick sedimentation of nanoparticles and thus faster interaction with benthic organisms. As in previous studies, a reduction in the biological impact of NMC *versus* LCO was observed.

On the higher trophic level, the fish class, there is an evident impact of LCO on rainbow trout gill epithelial cells.[254] It was found that exposure to Li^{+} and Co^{2+} alone, did not reduce cell viability, however strong toxic effects were observed for LCO nanoparticles and these were found to increase the concentration of reactive oxygen species (ROS). Overproduction of ROS may cause biochemical damage, overstress to cells and ultimately, their damage.[255] These negative effects were measured at sub-toxic concentrations of LCO which are close to predicted environmental levels. Finally, it was found that the nanomaterials were internalized in cellular organelles, which was not the case for bacteria.[243] A subsequent paper[256] reported studies on the response of the same type of cells to LCO-induced oxidative stress. The authors postulated a "two-hit" model for LCO toxicity. Initially, the intact LCO material induces high levels of ROS leading to gradual engagement of stress response genes ("first hit"). In the next step, the gradual release of metal ions from NPs starts to suppress the expression of these genes, disrupting the cell response to elevated ROS levels ("second hit"). This mode of action ultimately confuses the cell response to stress and may lead to severe damage.

The take-home message from all ecotoxicity studies is that the replacement of toxic metals (Co and Ni) with less toxic ones (Mn) may increase the environmental compatibility and sustainability of the next generation of LIB materials.

Heavy metals from LIBs may also enter the natural environment due to materials recovery processes, as well as legal and illegal disposal routes. Due to the lack of valid data concerning the recycling of LIBs, for analytical purposes, we can consider other well-established processing of automotive batteries. Critical analysis of the lead-acid batteries recovery reveals that large quantities of potentially toxic slag have to be dealt with. In most countries, such wastes are often disposed of in waste dumps that may lack properly designed engineered landfills, especially in emerging economies. Analysis of slag revealed that apart from high pH (12.22) it contained also high concentrations (g kg^{-1}) of Pb (>101), Cu (>2.5), Cr (>1.2), Zn (0.5), Cd (>0.5) and Ni (0.1), indicating a poor metal recovery in the recycling processes.[257] The authors suggested that there was a greater risk of release of these heavy metals over the long-term following disposal into the environment. Fujimori *et al.* (2016) found elevated levels of Pb in some China soils located next to recycling plants.[258] In the case of LIB recycling, we also have to deal with the slag resulting from the pyrometallurgical route, mainly containing Mn, Li, and Al.[259]

3.2.3 Battery degradation products. The study undertaken by Grützke *et al.* (2015) may give indications of the fate of processed battery material when kept in storage (*i.e.* prior to recycling) or landfilled.[59] The authors shredded NMC LIBs from EVs and enclosed them in sealed tinplate and plastic cans. Their main goal was to assess which compounds are released from spent, processed material, and if there is any further degradation of original compounds, and the possible emergence of hazardous transformation products. The so-called "black mass" was monitored for over 20 months with regular analyses of gases, liquids and remaining salts. Their results showed that the tinplate cans underwent fast corrosion – first spots were visible after a few days, and after five months some of the cans were already perforated by rusting. Plastic cans did not show any visual signs of degradation. In addition to HF, the authors found traces of phosphoric acids, $LiPF_6$, other additives (***i.e.*** cyclohexylbenzene) and solvents – DMC, EC, EMC and their degradation products. More importantly, they identified several alkylfluorophosphates, including dimethyl fluorophosphate (DMFP) and diethylfluorophosphate (DEFP). Alkylfluorophosphates are of concern as they have similar structures to the chemical warfare agents such as sarin.[260] DMFP and DEFP were also detected by Kraft *et al.* (2015 and 2016) who investigated the thermal degradation of LIB electrolytes.[160,261] Although present in manageable low concentrations, they still may have toxic potential both to humans and the environment.

These studies highlight the important issue of storing spent and processed battery materials. If real-life scenarios are envisaged, such as temporary storage in the canister or landfilling, certainly, the corrosion of containers or battery metal case (module or pack) will be speeded up by external environmental factors such as leachate or humid air. It also indicates that spent degraded battery already contains harmful content – these products may enter the air or be transported with the solution to other compartments.

3.2.4 Additives. Finally, LIBs may also leach the remains of electrolyte and its additives.[262,263] The most common additives are polymers, Lewis acids, sulphur-containing and phosphorous containing additives, polyfluoroalkyl substituted ethylene carbonates or ionic liquids (ILs). The latter, ILs, are particularly interesting as they can play many roles in the battery system: as a pure electrolyte; in mixture with conventional solvents; as a gel polymer electrolyte or as a binder.[264,265] ILs are non-volatile and a non-flammable class of organic salts consisting of an organic cation and an organic or inorganic anion and there is a broad spectrum of cations (*i.e.* imidazolium, pyridinium, choline *etc.*) and anions (organic and inorganic).[266] Therefore, there is a very broad spectrum of the environmental impact of these compounds depending on their structure. However, due to their properties, the routes of exposure and potential hazards are limited to interactions with solutions. The distribution of ionic liquids in the environment is governed by their structure *e.g.* ILs with longer alkyl chains absorb more easily on the soil surface. Therefore, some ionic liquids may be quite mobile in water or soil columns whereas others may bind strongly to various environmental compartments and may become persistent pollutants. Additionally, the properties of soil such as high cation exchange capacity and/or abundance of organic matter will greatly increase the uptake of ILs.[267–275] Although their use is usually restricted to small quantities, ILs could still have considerable negative effects on wildlife and human health. For instance, most of the ionic liquids in battery systems are considered toxic and poorly biodegradable compounds.[276,277] As in the case of the mobility and transport in environmental media, the toxicity of ILs depends on the lipophilicity and alkyl chain length, the direct interaction with the biological system (membrane, cell or organism) and trophic levels (bacteria, plants, invertebrates or human cells). Usually, the longer the derivative the more toxic it is but there is also a strong impact of the counter-ion, especially fluorinated ones.[278–287]

4. Recommendations for future studies

Table 3 illustrates the possible routes of emission and pollutants released from LIBs. Although partially supported by the existing literature (see Sections 2 and 3), this is more of an indicative list. There are lots of unknowns, incomplete data, not yet researched specific topics or even contradictory results that need to be clarified to mitigate any negative impact of spent batteries.

Therefore, we identified some of the main knowledge gaps and probe the following questions on the environmental impacts of spent LIBs that might help to manage these better in the future:

(1) What are the current and prospective volumes of spent LIBs?

(2) How much spent batteries reach the relevant disposal stream?

(3) Where spent batteries will be processed/disposed of/abandoned?

(4) In what form: as a whole, partitioned, shredded *etc.* LIBs will be processed/disposed of/abandoned?

(5) What is the impact of changing chemistries on the waste streams in terms of needed technology but also in terms of the life span?

(6) What, how, where and in which volumes are hazards released from the spent batteries?

(7) What is the prevalence and distribution of battery pollutants once being released into the natural environment?

Table 3 Possible pollutants and routes of their emission released from LiBs

Battery component	Source of pollutant	Specific pollutant	Route	Affected environment	Hazard
Pack casing	– Steel	*i.e.* Fe, Al, Ni, Cr other	Leaching	Land Natural waters	– In excess toxic to wildlife – Accumulation in plants and crops
Module casing	– Steel – Aluminium	– Fe, Ni, Cr other – Al	Leaching	Land Natural waters	– In excess toxic to wildlife – Accumulation in plants and crops
Cell packing	– Aluminium foil – Polymers – Ni-Coated steel	– Al, Ni – PET, PP	Leaching Fire	Natural waters Land Air	– In excess toxic to wildlife – Accumulation in plants and crops
Cathode	– Metal – Metal oxides	– Al – LMO – Li/Mn/O – LFP – Li/Fe/P/O – NMC – Li/Ni/Mn/Co/O – LCO – Li/Co/O – NCA – Li/Ni/Co/Al/O	Leaching Dust	Land Natural waters Air	– Toxic to the various organism – Toxic to humans if breathed – In excess toxic to wildlife – Accumulation in plants and crops
Anode	– Copper – Graphite	– Cu – C (nanomaterial) – LTO – Li/Ti/O	Leaching	Land Natural waters	– In excess toxic to wildlife – Accumulation in plants and crops – Toxic to humans if breathed
Separator	– Polymers	– Polyethylene (PE) – Polypropylene (PP)	Leaching Fire Dust	Land Natural waters Air	– Microplastics accumulation
Binder	– PDVF	– HF	Fire	Air	– Toxic to humans if breathed – Toxic to humans if in contact
Electrolyte	– Ethylene carbonate – Propylene carbonate – Dimethyl carbonate – Diethyl carbonate – Salts: $LiPF_6$ – Additives	– HF – SO_x – HCN – H_2 – CO – CO_2 – NO_x – COS – HCl – Degradation products of electrolyte (*i.e.* C_2H_4; CH_3COCHO *etc.*) – Ionic liquids – Unknown additives/ degradation products	Fire Vapours/gases Leaching	Air Land Natural waters	– Toxic to humans if breathed – Toxic to humans if in contact – Toxic to wildlife – Accumulation in soils

(8) What is the circulation and interactions of battery pollutants among the land–water–air-emission pathways and the wildlife nexus?

(9) What is the (eco)toxicity and (bio)accumulation of LIBs materials to various organisms and humans?

(10) How should or would environmental studies support the design and disposal of spent LIBs?

Although, some of these questions could be partially answered already based on approximations *i.e.* prospective volumes are estimated on sales number; but there is an urgent need for reliable and verified data. Obtaining reliable and accurate data will have serious implications for the safety of the recycling and disposal facilities and helps to shape, implement and regulate appropriate practices and legislations. The real data should be supported by various Life Cycle Assessments methodology, cost-benefit studies and the use of more modelling in the prediction of *i.e.* life cycle of the specific battery in a given application.

As the growing demand for new LIBs will result in increased numbers of spent batteries, we recommend that this quantity must be appropriately managed and controlled across the various disposal routes. The best-case scenario assumes high collection rates of spent batteries with an almost full recovery of materials that can be reused (boosting the circular economy). It is evident that domestic *i.e.* decentralised recycling will be more profitable than centralised recycling, however, it will take time for the industry to scale up collection, processes and infrastructures.[6] It is also argued that latecomers will be threatened by the existing industry that may benefit more quickly from the larger economies of scale. Decentralised systems do require a substantial amount of spent LIBs (especially large EV) to reach economy of scale as it was estimated that recycling costs will decrease if between 1000 and 15 000 tonnes per year are recycled at one plant.[6] Collection of spent and ''second-life'' large batteries, might be linked with some business model *e.g.* sale of the car but the lease of battery – then the responsibility is on dealer/seller or can be governed by local councils with *i.e.* specialized collection centre – responsibility on the user. To improve the collection and later decision on the re-use, recycling or landfilling knowing the usage history of ''first life'' of EV/BESS batteries would be of great use – the battery's condition can be determined much faster and more economically. That will speed up the streamlining of LIBs to an accurate route of processing. However, we must bear in mind that modules in the pack can age differently[288] – so possible that the selection will be on the modules not pack level. Nevertheless, improving the reuse of the materials could reduce the environmental, economic and social burden of the existing battery supply chain including disposal practices is inevitable. However, the challenges in the collection, dismantling and recycling of LIBs must be overcome. It is of crucial importance to develop innovative technologies to lower the cost of material recovery and reduce the environmental impacts of this industry.[6] Furthermore, illegal disposal and informal processing that leads to serious pollution must be prevented. This could be achieved through better collection schemes, expansions, and improvements in the current recycling infrastructure and posing legal obstacles for exporting second-hand EVs or LIBs. The last anybody wants is that LIBs to become, for instance, a source of soil pollution by heavy metals. Moreover, there should be a constant drive to produce LiBs containing less hazardous and more ''green'' materials[289] that not only improve the capacity and efficiency of the battery but also prevent destructive behaviour and have minimal negative impact on the environment if improperly disposed of.[290] New LIBs should be designed for recycling meaning the materials can be easy separate from each other and able to be re-used in new batteries (direct recycling). That links to new technologies of material recovery that are less energy intensive, cheaper and produce less or no secondary pollution.

The improvements must be guided by appropriate legislation, regulations and management structures. These must encourage customers and manufacturers to properly handle spent batteries, highlighting the benefits of recycling (in light of the obligations for economic operators as regards the sourcing of raw materials) and promote the circular economy model and finally, must also clearly ensure where each liability lays.[48]

Finally, we must address the problem of penetration of large ''2nd life'' LIBs into society. There is a general perception, particularly in Europe, that the re-use (using an EV battery without change in an EV), remanufacture (using an EV battery after replacing defective modules in an EV) and repurposing (using modules from an EV at end-of-life to assemble a battery for a purpose other than traction, *e.g.* stationary storage) of LIBs can make a positive contribution to the decarbonization of the planet.[48] The safety of new cells, modules and battery packs can be assessed using the ''type tests'' that form the basis of all codes, standards and regulations governing, for example, domestic and industrial battery energy storage systems. Type testing relies on testing a sample of cells from a batch, usually to destruction, and accepting the result as representative of the batch. The use of type testing on new cells is valid due to the extremely tight quality control of their manufacture, however, such type testing is now accepted as inappropriate to assess the safety of second life LIBs due to the wide variation in SoH across an EV pack during its life and possible exposure to extremes of temperature, overcharging and/or charging at high currents,[291–293] all of which can increase the potential for thermal runaway.[294,295] The draft standards IEC63330[296] (Requirements for reuse of secondary batteries) and IEC63338[297] (General guidance for reuse of secondary cells and batteries) fully acknowledge the fact that type tests cannot be employed to assess the safety of second life LiBs. The key challenge is determining the SoH, or more correctly, the State-of-Safety of second life LIBs.[298] A part of the latter must be full knowledge of the first life of the LIB in the EV, including full details of any abuse (*e.g.* overcharging) maximum charge and discharge currents & operational temperatures. The draft standards IEC63330 and IEC63338 were intended to address this problem and hence facilitate the safe application of second life LiBs, but have failed to do so, as they do not require any testing and rely completely on the original manufacturers of the EVs passing on full BMS data (and hence potentially valuable intellectual property) to remanufacturers & repurposers, which is perceived as highly unlikely. The draft EU Batteries Regulation also sidesteps the safety issue of second-life batteries by requiring only that BMS data is made fully available.

It is generally accepted that the re-use, remanufacturing and repurposing of complete packs where the original EV manufacturer is retained in the supply chain is of low risk.[299] However, second life cells, modules and even full battery packs are freely available from online retailers, such that inexperienced organisations and even the general public can repurpose LIBs. Thus, a major concern is the use of these suppliers by homeowners to build do-it-yourself domestic BESS: domestic battery energy storage systems are currently completely unregulated in the UK with respect to the application of lithium-ion batteries. Concerns over the hazards posed by such systems in the home environment have been addressed in other countries: thus the US NFPA 855 standard[300] and the draft DR2 AS/NZS 5139 : 2019 Australian and New Zealand standard[301] do not permit domestic lithium-ion BESS inside the home, and NFPA 855 does not permit do-it-yourself lithium-ion BESS at all.

The online trade-in 2nd life LIBs is completely unregulated, and delivery of these devices is often offered by means illegal under UN 38.3[302] as they are classified as dangerous goods and hence require transportation in accordance with the European agreement ''Accord européen relatif au transport international des marchandises dangereuses par route'' (ADR) requirements.[303]

5. Conclusion

There is no doubt that the urgent need to decarbonise transportation puts LIBs at the forefront of the action. However, the growing stream of spent LIBs would impose an enormous threat to the natural environment and human health, as batteries contain hazardous materials. In this review, the current, possible and likely waste management practices of LIBs were identified – from collection and recycling to landfilling, through the EoL incidents up to illegal disposal. Currently, landfilling is the most common practice but there is a growing share of recycling. The current review also assessed the most likely hazards and incidents during each EoL practice. The fire and explosion incidents are currently the most common events that have been evidenced by real-life incidents. Leaching is another pollution pathway that will co-dominate in the future. Identified hazards released from LIBs contain vapours and gases (*i.e.* HF, CO or HCN), metal nanooxides (*i.e.* LMO, NMC), degradation products of the electrolyte (alkylfluorophosphates) and possible traces of additives. These pollutants may be released to soil, water (groundwater) and air, depending on recycling, disposal method or abuse incident. Released pollutants may pose a serious threat to wildlife and humans with often immediate effects like in the case of contact with HF during EV fire. Degradation of the battery content (especially electrolyte) in some cases may lead to the emergence of chemicals structurally similar to chemical warfare agents. The initial studies on the (eco)toxicity of the cathode nanomaterials showed that LIBs may pose a threat to living organisms and human health. But the replacement of toxic metals (Co and Ni) with less toxic ones (Mn) may increase the environmental compatibility and sustainability of the next generation of lithium battery materials. Finally, we identified several urgent knowledge gaps that need to be covered to mitigate the negative impact on the environment of LIBs, and recommended some actions to tackle these issues.

Author contributions

Wojciech Mrozik: writing – original draft, writing – review & editing, conceptualization, visualization, investigation; methodology; Mohammad Ali Rajaeifar: writing – original draft, writing – review & editing; Oliver Heidrich: writing – original draft, writing – review & editing, conceptualization, funding; Paul Christensen: writing – original draft, writing – review & editing, funding.

Abbreviations

Aging	The loss of capacity due to, *e.g.* loss of lithium ions or spallation of the anodes. This can be due to use (charging and discharging) and/or sitting at open circuit (calendar aging)
Anode	The negative electrode. In lithium-ion batteries this is most typically small particles of graphite
Battery (pack)	The complete energy storage unit consisting of a number of modules
BESS	Battery energy storage system
Cathode	The positive electrode. These typically comprise lithium plus metal oxides: *e.g.* lithium nickel manganese cobalt oxide ($LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$)
Cell	The smallest unit of a battery
Electrolyte	In electrochemistry, this term is ambiguous as it can refer to the inorganic salt (*e.g.* $LiPF_6$) or to the salt + organic solvent
End of Life (EoL)	The point at which a battery ceases to be suitable for its current application. For automotive batteries this is typically 75–80% State-of-Health
GHG	Greenhouse gases, gases that cause the greenhouse effect *e.g.* CO_2 and CH_4
Landfill	A site for the disposal of waste materials
LCO cathode	Lithium cobalt oxide, $LiCoO_2$
LIB	Lithium-ion battery
LIBESS	Lithium-ion battery energy storage system
LFP cathode	Lithium iron (ferrous) phosphate, $LiFePO_4$
LMO cathode	Lithium manganese oxide $LiMnO_2$
LTO anode	Lithium titanium oxide $Li_4Ti_5O_{12}$
MRF	Material recovery facilities; solid-waste management plant that processes recyclable materials to sell to manufacturers as raw materials for new products
NCA cathode	(lithium) Nickel cobalt aluminium oxide, *e.g.* $LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$
NMC cathode	(lithium) Nickel manganese cobalt oxide, *e.g.* $LiNi_{0.33}Mn_{0.33}Co_{0.33}O_2$ (NMC 111), $LiNi_{0.6}Mn_{0.2}Co_{0.2}O_2$ (NMC 622)
PAHs	Polycyclic aromatic hydrocarbons; made up of fused aromatic rings molecules
Recycling	The process of converting waste materials into new materials and objects
Separator	A plastic film permeable to lithium and hexafluorophosphate ions that prevents the anode and cathode from touching and causing a short-circuit
Solid Electrolyte Interphase (SEI)	The protective layer that forms on the anode during the first charge from reduction of the $LiPF_6$ and solvent which prevents further, explosive degradation of the electrolyte and thermal runaway
Solvent	Mixture of organic carbonates, containing ethylene carbonate, as this is essential for the formation of the SEI. Ethylene carbonate is a solid at room temperature and other carbonates are essential to reduce viscosity
State of Charge (SoC)	The amount of charge stored compared to that equivalent to full charge, expressed as %
State of Health (SoH)	The amount of charge stored currently when fully charged compared to that stored (when fully charged) at the beginning of the cell or battery life, expressed as %
VOCs	Volatile organic compounds; compounds that have a high vapour pressure and low water solubility

Conflicts of interest

There are no conflicts to declare.

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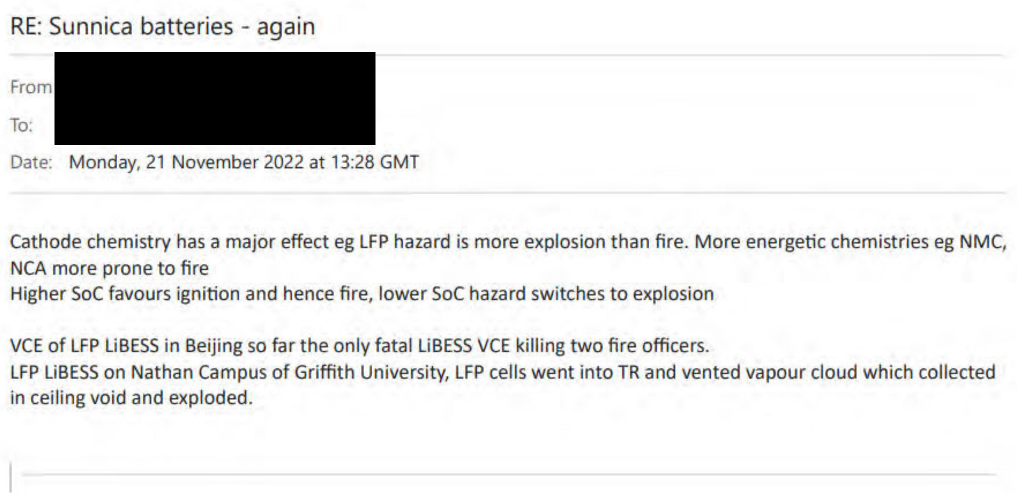
Appendix 3

Email dialogue Professor Paul Christensen and Dr C Judkins



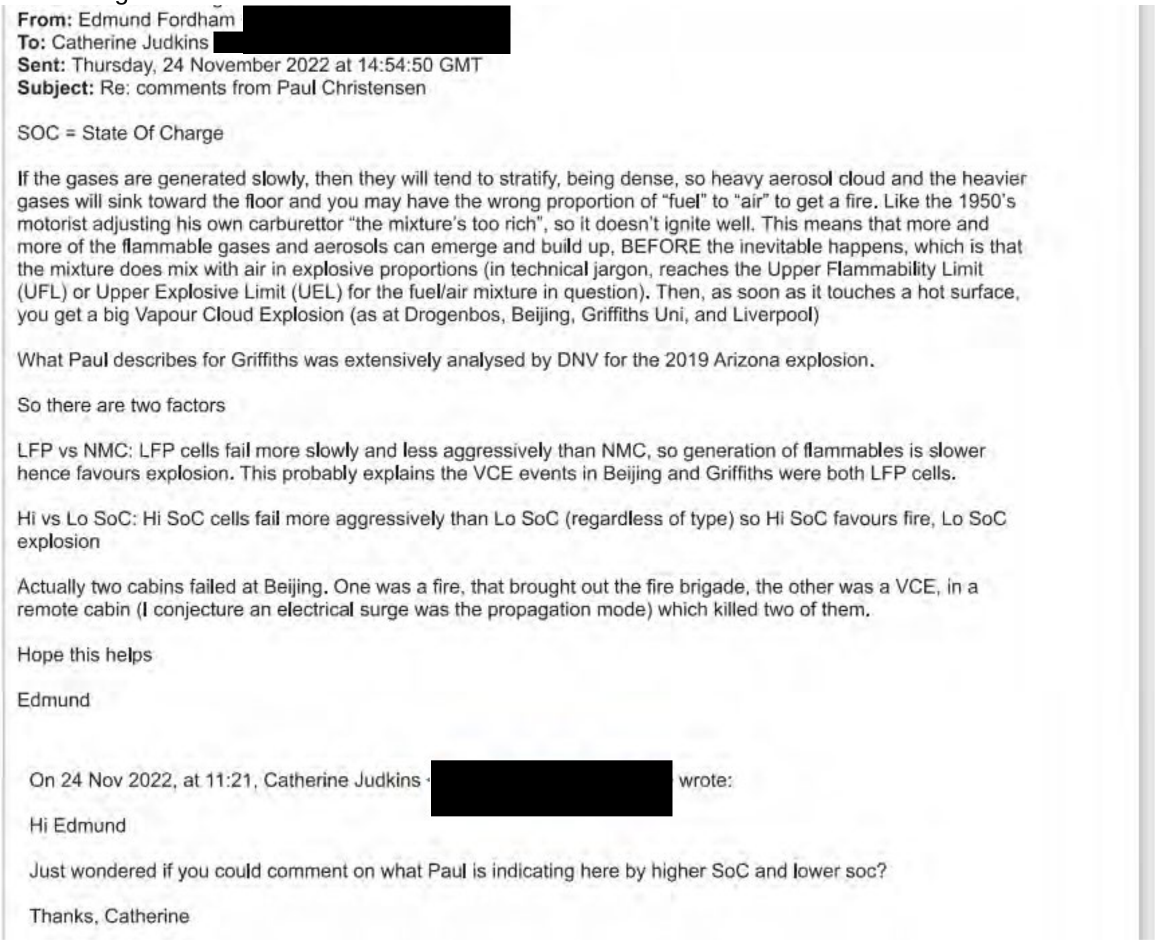
RE: Sunnica batteries - again

From [redacted]
To:
Date: Monday, 21 November 2022 at 13:28 GMT

Cathode chemistry has a major effect eg LFP hazard is more explosion than fire. More energetic chemistries eg NMC, NCA more prone to fire
Higher SoC favours ignition and hence fire, lower SoC hazard switches to explosion

VCE of LFP LiBESS in Beijing so far the only fatal LiBESS VCE killing two fire officers.
LFP LiBESS on Nathan Campus of Griffith University, LFP cells went into TR and vented vapour cloud which collected in ceiling void and exploded.

Email dialogue between Dr Edmund Fordham and Dr C Judkins



From: Edmund Fordham [redacted]
To: Catherine Judkins [redacted]
Sent: Thursday, 24 November 2022 at 14:54:50 GMT
Subject: Re: comments from Paul Christensen

SOC = State Of Charge

If the gases are generated slowly, then they will tend to stratify, being dense, so heavy aerosol cloud and the heavier gases will sink toward the floor and you may have the wrong proportion of "fuel" to "air" to get a fire. Like the 1950's motorist adjusting his own carburettor "the mixture's too rich", so it doesn't ignite well. This means that more and more of the flammable gases and aerosols can emerge and build up, BEFORE the inevitable happens, which is that the mixture does mix with air in explosive proportions (in technical jargon, reaches the Upper Flammability Limit (UFL) or Upper Explosive Limit (UEL) for the fuel/air mixture in question). Then, as soon as it touches a hot surface, you get a big Vapour Cloud Explosion (as at Drogenbos, Beijing, Griffiths Uni, and Liverpool)

What Paul describes for Griffiths was extensively analysed by DNV for the 2019 Arizona explosion.

So there are two factors

LFP vs NMC: LFP cells fail more slowly and less aggressively than NMC, so generation of flammables is slower hence favours explosion. This probably explains the VCE events in Beijing and Griffiths were both LFP cells.

Hi vs Lo SoC: Hi SoC cells fail more aggressively than Lo SoC (regardless of type) so Hi SoC favours fire, Lo SoC explosion

Actually two cabins failed at Beijing. One was a fire, that brought out the fire brigade, the other was a VCE, in a remote cabin (I conjecture an electrical surge was the propagation mode) which killed two of them.

Hope this helps

Edmund

On 24 Nov 2022, at 11:21, Catherine Judkins [redacted] wrote:

Hi Edmund

Just wondered if you could comment on what Paul is indicating here by higher SoC and lower soc?

Thanks, Catherine

From: Edmund Fordham [redacted]
To: Catherine Judkins
Sent: Thursday, 24 November 2022 at 16:01:28 GMT
Subject: Re: Actions from committee+ meeting. Please read as we have some pressing deadlines for document review

Catherine

What is true is that LFP cells fail less aggressively - slower temperature rise, lower maximum temperatures (say 400 deg C approx) and have *higher* thermal runaway thresholds (say 200 deg C instead of 150 deg C). But that's still 200 degrees difference from a failed cell to the neighboruing one and quite enough to kick off thermal runaway.

NMC cells more likely to develop flame immediately, but good luck putting them out.

Appendix 4

Fire Protection Research Foundation study (FPRF) 2016
Hazard Assessment of Lithium Ion Battery Energy Storage Systems

Hazard Assessment of Lithium Ion Battery Energy Storage Systems

FINAL REPORT

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FOREWORD

In recent years, there has been a marked increase in the deployment of lithium ion batteries in energy storage systems (ESS). Many ESS are being deployed in urban areas both in high rise structures and single- and multi-family residences. Local Authorities Having Jurisdiction (AHJs) along with the ESS integrators and installers are challenged by the lack of clear direction on fire protection and suppression in these installations. Without a recognized hazard assessment made available to standards developers, AHJs, emergency responders, and industry, guidance on safe installation of these systems will lack a technical basis.

The purpose of this project is to develop a hazard assessment of the usage of lithium ion batteries in ESS to allow for the development of safe installation requirements and appropriate emergency response tactics.

The Fire Protection Research Foundation expresses gratitude to the report author Andew Blum and Tom Long, who are with Exponent, Inc. located in Bowie, Maryland. The Research Foundation appreciates the guidance provided by the Project Technical Panelists, the funding provided by the project sponsors, and all others that contributed to this research effort. Thanks are also expressed to the National Fire Protection Association (NFPA) for providing the project funding through the NFPA Annual Code Fund.

The content, opinions and conclusions contained in this report are solely those of the authors and do not necessarily represent the views of the Fire Protection Research Foundation, NFPA, Technical Panel or Sponsors. The Foundation makes no guaranty or warranty as to the accuracy or completeness of any information published herein.

About the Fire Protection Research Foundation

The Fire Protection Research Foundation plans, manages, and communicates research on a broad range of fire safety issues in collaboration with scientists and laboratories around the world. The Foundation is an affiliate of NFPA.

About the National Fire Protection Association (NFPA)

Founded in 1896, NFPA is a global, nonprofit organization devoted to eliminating death, injury, property and economic loss due to fire, electrical and related hazards. The association delivers information and knowledge through more than 300 consensus codes and standards, research, training, education, outreach and advocacy; and by partnering with others who share an interest in furthering the NFPA mission.

All NFPA codes and standards can be viewed online for free.

NFPA's membership totals more than 65,000 individuals around the world.

Keywords: energy storage systems, lithium ion batteries, fire hazard assessment, stranded energy

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PROJECT SPONSOR

National Fire Protection Association

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Thermal Sciences

Fire Hazard Assessment of Lithium Ion Battery Energy Storage Systems

Fire Hazard Assessment of Lithium Ion Battery Energy Storage Systems

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February 26, 2016

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Acronyms and Abbreviations

Ah	ampere hours
AHJ	authority having jurisdiction
APS	Arizona Public Service Company
BATSO	Battery Safety Organization
BMS	battery management system
CH_4	methane
Cl_2	chlorine
CO	carbon monoxide
CO_2	carbon dioxide
DC	direct current
DOE	Department of Energy
DOT	Department of Transportation
EDV	electric drive vehicle
EES	electrical energy storage
ELC	equivalent lithium content
ESS	energy storage system
FMEA	Failure Modes and Effects Analysis
FPRF	Fire Protection Research Foundation
ft	feet
g	grams
HCl	hydrogen chloride
HCN	hydrogen cyanide
HECO	Hawaiian Electric Company
HF	hydrogen fluoride
HFD	Honolulu Fire Department
HFG	heat flux gauge
HRR	heat release rate
IBC	International Building Code

ICC	International Code Council
ICE	internal combustion engine
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IFC	International Fire Code
in	inch
IRC	International Residential Code
JSA	Japanese Standards Association
kg	kilograms
kWh	kilowatt hours
LER	light electric rail
Li-ion	lithium ion
lpm	liters per minute
mph	miles per hour
MW	megawatt
NEC	NFPA 70, *National Electrical Code*
NEMA	National Electrical Manufacturers Association
NFIRS	National Fire Incident Reporting System
NFPA	National Fire Protection Association
NiCad	nickel cadmium
NO_x	nitrogen oxides
OSHA	Occupational Safety and Health Administration
PF_5	phosphorus pentafluoride
POF_3	phosphoryl fluoride
ppm	parts per million
psi	pounds per square inch
PVES	photovoltaic energy systems
SAE	Society of Automotive Engineers
SCBA	self-contained breathing apparatus
SDS	safety data sheet
SOC	state of charge

TC	thermocouple
UN	United Nations
UL	Underwriters Laboratories
UPS	uninterrupted power supplies
VOC	volatile organic compound
Wh	watt hours

Limitations

At the request of the Fire Protection Research Foundation (FPRF), Exponent performed a fire hazard assessment of lithium ion (Li-ion) batteries used in energy storage systems (ESSs). This report summarizes a literature review and gap analysis related to Li-ion battery ESSs, as well as full-scale fire testing of 100 kilowatt hour (kWh) Li-ion battery ESSs. The scope of services performed during this literature review and testing program may not adequately address the needs of other users of this report, and any re-use of this report or the findings, conclusions, or recommendations presented herein are at the sole risk of the user.

The full-scale Li-ion battery ESS test strategy, ignition protocols, and any recommendations made are strictly limited to the test conditions included and detailed in this report. The combined effects (including, but not limited to) of different battery types, ESS types, ESS size/battery capacity, internal or external ESS/battery damage, battery energy density and design, state of charge, and cell chemistry are yet to be fully understood and may not be inferred from these test results alone.

The findings formulated in this review are based on observations and information available at the time of writing. The findings presented herein are made to a reasonable degree of scientific and engineering certainty. If new data becomes available or there are perceived omissions or misstatements in this report, we ask that they be brought to our attention as soon as possible so that we have the opportunity to fully address them.

Executive Summary

In an effort to provide guidance to standards developers, authorities having jurisdiction (AHJs), emergency responders, and the energy storage system (ESS) industry, Exponent, in conjunction with FPRF, the Project Technical Panel, and industry sponsors, performed a fire hazard assessment of Li-ion battery ESSs. Currently, these entities do not have a clear direction regarding the fire hazards of ESS installations and have few, if any, technical studies, reports, or scientific literature to rely upon when making decisions regarding the safe installation of these systems. This report summarizes a literature review and gap analysis related to Li-ion battery ESSs, as well as full-scale fire testing of a100 kWh Li-ion battery ESS.

The scope of work included, but was not limited to, the following four primary tasks:

1. A literature review and gap analysis related to Li-ion battery ESSs;
2. Development of a detailed full-scale fire testing plan to perform an assessment of Li-ion battery ESS fire hazards;
3. Witnessing the implementation of the fire test plan through full-scale fire testing; and
4. A report of final results and a fire hazard assessment.

The overall project research objective was to develop a technical basis through a fire hazard assessment of Li-ion battery ESSs. This project is the first phase of an overall initiative with the goal to develop safe installation practices, fire protection guidance, and appropriate emergency response tactics for Li-ion battery ESSs based on the literature review and full-scale test results, as applicable. This project did not include an analysis or testing of fire detection systems, fire suppression systems, or emergency response tactics related to Li-ion battery ESS fire scenarios. A full listing of project observations/key findings as they relate to ESS fire hazards is provided in Section 7 of this report.

1 Background

1.1 Project History

Energy storage is emerging as an integral component of a resilient and efficient electrical grid through a diverse array of potential applications. It is anticipated that the evolution of the electrical grid will result in a greater need for services best provided by energy storage systems (ESSs). It is expected that the increase in demand for these systems will further drive energy storage research to produce systems with greater efficiency at a lower cost, which will lead to an influx of energy storage deployment across the country. To enable the success of these deployments, the hazards of these systems, namely the fire hazard of the ESS, must be understood.[1]

In recent years, there has been a marked increase in the deployment of lithium ion (Li-ion) batteries in ESSs. Many ESSs are being deployed in both high-rise structures and single- and multi-family residences. Local authorities having jurisdiction (AHJs) along with ESS integrators and installers do not have a clear direction regarding the fire hazards of these installations. A recognized fire hazard assessment available to standards developers, AHJs, emergency responders, and industry will provide guidance with a technical basis on the evaluation and safe installation of these systems.

1.2 Research Objectives and Project Scope

The overall project research objective was to develop a technical basis through a fire hazard assessment of Li-ion ESSs. This project is part of an overall initiative with the goal to develop safe installation practices, fire protection guidance, and appropriate emergency response tactics for ESSs. This project did not include an analysis or testing of fire detection systems, fire suppression systems, or emergency response tactics related to Li-ion battery ESS fire scenarios.

---

[1] Energy Storage Safety Strategic Plan, U.S. Department of Energy, December 2014.

The scope of work included, but was not limited to, the following four primary tasks:

1. A literature review and gap analysis related to Li-ion battery ESSs;
2. Development of a detailed full-scale fire testing plan to perform an assessment of Li-ion battery ESS fire hazards;
3. Witnessing the implementation of the fire test plan through full-scale fire testing; and
4. A report of final results and a fire hazard assessment.

A more detailed description of the tasks Exponent performed to fulfill the project objectives is provided below.

1.2.1 Literature Review and Gap Analysis

Exponent collected, reviewed, and summarized available literature related to Li-ion battery ESSs, including the Department of Energy (DOE) Safety Roadmap, relevant codes and standards, incident reports, related test plans, and previous fire testing/research. The literature review also identified existing gaps in the information currently available and the practices utilized in the deployment of Li-ion ESSs, if any.

1.2.2 Fire Test Plan

Exponent, in conjunction with the Project Technical Panel, developed a detailed test plan to provide an assessment of fire hazards posed by Li-ion ESSs. Li-ion ESSs with an approximate capacity of 100 kilowatt hours (kWh) designed for use in commercial applications were tested.

1.2.3 Witness of Fire Testing

Exponent witnessed the full-scale fire testing at the manufacturer's testing site and summarized the test observations and data provided to Exponent.

1.2.4 Final Report

Exponent collected and summarized the results of the above tasks in a formal research engineering report, including:

1. An overview of the project work to date;
2. A summary of the full-scale fire tests;
3. A fire hazard assessment; and
4. Identification of future potential research.

2 Literature Review and Gap Analysis

Exponent collected, reviewed, and summarized available literature related to ESSs and Li-ion batteries. The literature review provides an overview of energy storage (Section 2.1), commercial and residential ESSs (Section 2.2), a brief summary of Li-ion technology (Section 2.3), codes and standards related to ESSs (Section 2.4), fire incidents involving ESSs (Section 2.5), large format Li-ion battery fires (Section 2.6), and a gap analysis (Section 2.7).

2.1 Energy Storage Overview

An ESS provides a means to store energy for later use to supply the utility grid or local grids.[2] An ESS may utilize any of the following technologies:

1. **Electrochemical.** Consists of a secondary battery, electrochemical capacitor, flow battery, or hybrid battery-capacitor system that stores energy and any associated controls or devices that can provide electric energy upon demand.
2. **Chemical.** Consists of hydrogen supply equipment or other fuel supply equipment combined with a fuel cell power system or generator to convert the fuel to electrical energy.
3. **Mechanical.** Consists of a mechanical means to store energy, such as through compressed air, pumped water, or fly wheel technologies and associated controls and systems, which can be used to run an electric generator to provide electric energy upon demand.
4. **Thermal.** Consists of a system that uses heated fluids, such as air, as a means to store energy along with associated controls and systems, which can be used to run an electric generator to provide electrical energy upon demand.

This report focuses on Li-ion battery ESSs for commercial and residential installations, which are an electrochemical technology.

---

[2] UL 9540, *Outline of Investigation for Energy Storage Systems and Equipment*, Issue Number 1, June 30, 2014.

An ESS allows for the balance of supply and demand of electrical energy, utilizing stored energy during “peak demand” times and storing energy during times of “low demand.” An example of a common ESS is pumped-storage hydroelectricity (pumped hydro). Pumped hydro stores large quantities of water in elevated reservoirs by utilizing excess electricity at times of low demand to pump water into the reservoirs. The facilities then release the water, which passes through turbine generators and converts the stored potential energy to electricity when electrical demand peaks.[3]

Recently, a more common solution is the storage of energy in a battery. Batteries have historically been of limited use in large scale electric power systems due to their relatively small capacity and high cost. However, newer battery technologies have been developed that can provide significant utility scale capabilities.[4] In addition to utility scale applications, smaller commercial and residential ESSs utilizing batteries are also becoming more prevalent.

2.2 Commercial and Residential ESS Overview

The most common commercial and residential ESSs are electrochemical systems utilizing batteries. Currently, there are many different battery chemistries (e.g., lead acid, sodium sulfur, lithium iron phosphate, Li-ion) utilized in ESSs deployed in North America; however, Li-ion is the most popular[5] and will likely continue to grow in popularity with the planned release of new ESS products in the coming years.

Residential ESSs are typically sized between 1 and 10 kWh[6,7,8] and standalone commercial systems can be much larger (20 to 100 kWh), modular, and interconnected to produce even greater capacity. The systems can vary in voltage depending on the design of the batteries, the ESS power management systems, and the manufacturer. Current products installed in the market have voltages as low as 48 volts and as high as 1000 volts DC. ESSs typically work by

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[3] Wald, Matthew, L. Wind Drives Growing Use of Batteries, *The New York Times*, July 27, 2010.

[4] Wald, Matthew, L. Wind Drives Growing Use of Batteries, *The New York Times*, July 27, 2010.

[5] Energy Storage Safety Strategic Plan, U.S. Department of Energy, December 2014.

[6] [redacted]

[7] [redacted]

[8] [redacted]

storing power collected from the grid, a solar installation, wind installation, or other source during a low demand time (typically during the day) and then using the stored energy during peak hours (typically in the mornings and evenings), as illustrated in Figure 1.[9,10]

The ESS typically consists of the batteries, a mounting frame or shelf for the batteries, a cooling system (i.e., fan, radiator, and hoses), power electronics, and an enclosure (the outer cover or cabinet) that these components are stored within. A residential ESS can be installed inside a residence or building, typically within the garage or attic, or installed on the exterior of the structure. A commercial ESS can be installed outside along a property line, next to a building, or inside a shipping container.

Pumped hydro remains one of the oldest and most mature energy storage technologies, having been utilized safely since the 1800s. Its hazards are well known and defined. Battery ESSs, however, are much earlier in their development and deployment cycle and, given recent trends, have not reached the full extent of their deployed capacity.[11] The hazards associated with these systems are not well known and are less defined than other traditional ESS technologies, such as pumped hydro. When discussing ESSs in the remainder of the report, Exponent is referring to Li-ion battery ESSs for use in commercial applications.

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[9] [redacted]

[10] [redacted]

[11] Energy Storage Safety Strategic Plan, U.S. Department of Energy, December 2014.

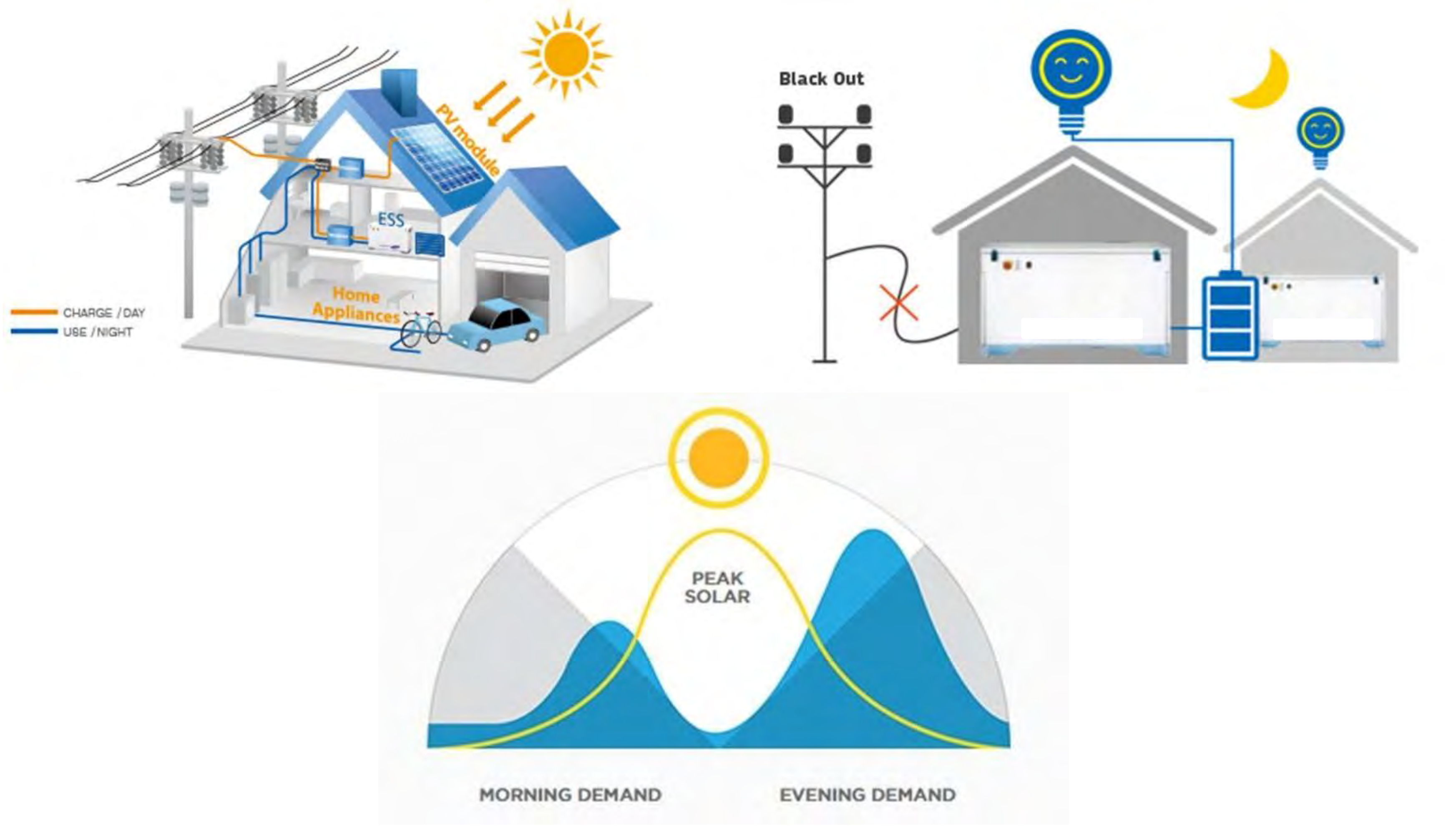

Figure 1 Illustration of energy storage during off peak hours (top left); use of energy storage during peak hours or power interruptions (top right); and the typical energy consumption curve (bottom)[12]

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[12] [redacted]

2.3 Li-ion Battery Overview

Li-ion battery cells are in wide consumer use today. As this technology has evolved and the energy densities have increased, the use of this technology has been applied across many consumer products, including the energy storage industry. Li-ion battery cells arranged in large format Li-ion battery packs are being used to power ESSs. As ESSs enter the United States consumer marketplace, there is an expectation of a steep increase in the number and size of battery packs in storage and use. Recent studies by the National Fire Protection Association (NFPA) Fire Protection Research Foundation (FPRF)[13,14,15,16] highlight the potential hazards of Li-ion battery cells and large format packs during the life cycle of storage, distribution, and use in products. An overview of the Li-ion technology and its failure modes is also included. A brief summary of Li-ion technology is provided here.

Li-ion has become the dominant rechargeable battery chemistry for consumer electronic devices and is poised to become commonplace for industrial, transportation, and energy storage applications. This chemistry is different from previously popular rechargeable battery chemistries (e.g., nickel metal hydride, nickel cadmium, and lead acid) in a number of ways. From a technological standpoint, because of high energy density, Li-ion technology is an effective battery type to use in ESSs. From a safety and fire protection standpoint, a high energy density coupled with a flammable organic, rather than aqueous, electrolyte has created a number of new challenges with regard to the design of batteries containing Li-ion cells, and with regard to fire suppression.

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[13] Mikolajczak, C., Kahn, M., White, K., and Long, RT. "Lithium-Ion Batteries Hazard and Use Assessment." Fire Protection Research Foundation Report, July 2011.

[14] Long RT and Mikolajczak CJ. "Lithium-ion batteries hazards: What you need to know." Fire Protection Engineering Q4 2012.

[15] Long RT, Blum AF, Bress TJ, and Cotts BRT. "Emergency response to incidents involving electric vehicle battery hazards." Fire Protection Research Foundation Report, July 2013.

[16] Long RT, Sutula JA, and Kahn MJ. "Lithium-ion batteries hazard and use assessment Phase IIb." Fire Protection Research Foundation Report, 2013.

2.3.1 Anatomy of a Li-ion Cell

The term "Li-ion" refers to an entire family of battery chemistries. It is beyond the scope of this report to describe all of the chemistries used in commercial Li-ion batteries. In addition, Li-ion battery chemistry is an active area of research and new materials are constantly being developed. Additional detailed information with regard to Li-ion batteries is available in a number of references[17,18] and a large volume of research publications and conference proceedings on the subject.

In the most basic sense, the term "Li-ion battery" refers to a battery where the negative electrode (anode) and positive electrode (cathode) materials serve as a host for the lithium ion (Li+). Lithium ions move from the anode to the cathode during discharge and are intercalated (inserted into voids) in the crystallographic structure of the cathode. The ions reverse direction during charging, as shown in Figure 2. Since lithium ions are intercalated into host materials during charge or discharge, there is no free lithium metal within a Li-ion cell,[19,20] thus, if a cell ignites due to external flame impingement or an internal fault, metal fire suppression techniques are not appropriate for controlling the fire.

In a Li-ion cell, alternating layers of anodes and cathodes are separated by a porous film (separator). An electrolyte composed of an organic solvent and dissolved lithium salt provides the media for Li-ion transport. A cell can be constructed by stacking alternating layers of electrodes (typical for high-rate capability prismatic cells), or by winding long strips of electrodes into a "jelly roll" configuration typical for cylindrical cells, as shown in Figure 3. Electrode stacks or rolls can be inserted into hard cases that are sealed with gaskets (most commercial cylindrical cells), laser-welded hard cases, or enclosed in foil pouches with heat-

---

[17] *Linden's Handbook of Batteries*, 4th Edition, Thomas B. Reddy (ed), McGraw Hill, NY, 2011.

[18] *Advances in Lithium-Ion Batteries*, WA van Schalkwijk and B Scrosati (eds), Kluwer Academic/Plenum Publishers, NY, 2002.

[19] Under certain abuse conditions, lithium metal in very small quantities can plate onto anode surfaces. However, this should not have any appreciable effect on the fire behavior of the cell.

[20] There has been some discussion about the possibility of "thermite-style" reactions occurring within cells. See the NFPA FPRF report titled, "Lithium-Ion Batteries Hazard and Use Assessment," for an in-depth analysis.

sealed seams (commonly referred to as Li-ion polymer cells[21]), as shown in Figure 4. A variety of safety mechanisms might also be included in the mechanical design of a cell, such as charge interrupt devices and positive temperature coefficient switches.[22,23]

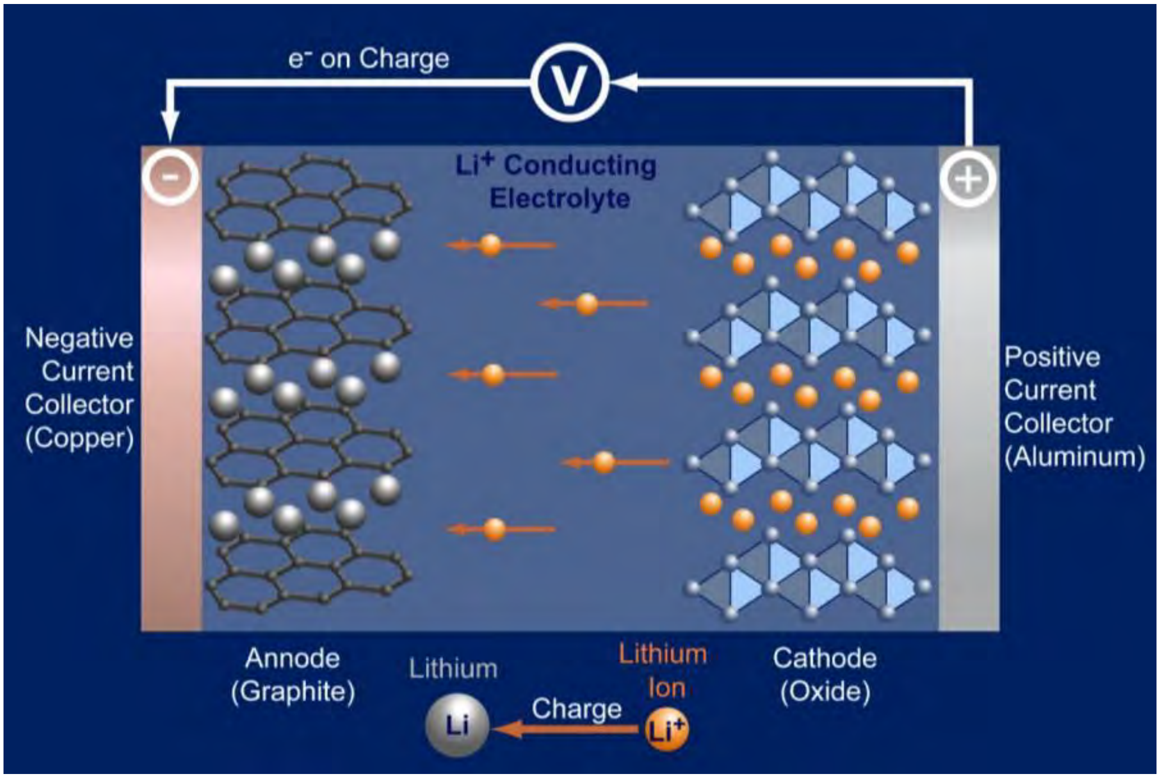

Figure 2 Li-ion cell operation: During charging, lithium ions intercalate into the anode, the reverse occurs during discharge

2.3.2 Li-ion Cell Characteristics and Hazards

The electrolyte within a typical Li-ion cell includes a volatile hydrocarbon-based liquid and a dissolved lithium salt (which is a source of lithium ions), such as lithium hexofluorophosphate. Battery cells are hermetically sealed to prevent moisture in the air from degrading the cells. Li-ion cells are not vented to the atmosphere like lead acid batteries, therefore, under normal usage

---

[21] The term “lithium polymer” has been previously used to describe lithium metal rechargeable cells that utilized a polymer-based electrolyte. Lithium polymer is now used to describe a wide range of Li-ion cells enclosed in soft pouches with electrolyte that may or may not be polymer based.

[22] For a more detailed discussion of Li-ion cells see: Dahn J, Ehrlich GM, “Lithium-Ion Batteries,” *Linden’s Handbook of Batteries*, 4th Edition, TB Reddy (ed), McGraw Hill, NY, 2011.

[23] For a review of various safety mechanisms that can be applied to Li-ion cells see: Balakrishnan PG, Ramesh R, Prem Kumar T, “Safety mechanisms in lithium-ion batteries,” Journal of Power Source, 155 (2006), 401-414.

conditions, they do not exhaust vapors. In normal usage, cell electrolyte should not be encountered by anyone handling a Li-ion battery, making the risk of a spill of electrolyte from any commercial Li-ion battery pack very remote. Furthermore, in most commercial cells, the electrolyte is largely absorbed in electrodes, such that there is no free or "spillable" electrolyte within individual sealed cells. In those instances, severe mechanical damage (e.g., severe crushing) can cause a small fraction of total electrolyte quantity to leak out of a single cell; however, any released electrolyte is likely to evaporate rapidly.

Li-ion cells are sealed units, and thus under normal usage conditions, venting of electrolyte should not occur. If subjected to abnormal heating or other abuse conditions, electrolyte and electrolyte decomposition products can vaporize and be vented from cells. Accumulation of liquid electrolyte is unlikely in the case of abnormal heating. Vented electrolyte is flammable, and may ignite on contact with a competent ignition source, such as an open flame, spark, or a sufficiently heated surface. Vented electrolyte may also ignite on contact with cells undergoing a thermal runaway reaction. Cell vent gas composition will depend upon a number of factors, including cell composition, cell state of charge, and the cause of cell venting. Vent gases may include volatile organic compounds (VOCs, such as alkyl-carbonates, methane, ethylene, and ethane), hydrogen gas, carbon dioxide, carbon monoxide, soot, and particulates containing oxides of nickel, aluminum, lithium, copper, and cobalt. Additionally, phosphorus pentafluoride (PF_5), phosphoryl fluoride (POF_3), and hydrogen fluoride (HF) vapors may form. Vented gases may irritate the eyes, skin, and throat. Cell vent gases are typically hot and upon exit from a cell, can exceed 600 ºC (1,112 ºF). Contact with hot gases can cause thermal burns.[24]

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[24] Lithium-Ion Battery Emergency Response Guide, Tesla Energy Products, September 2015, Revision 02

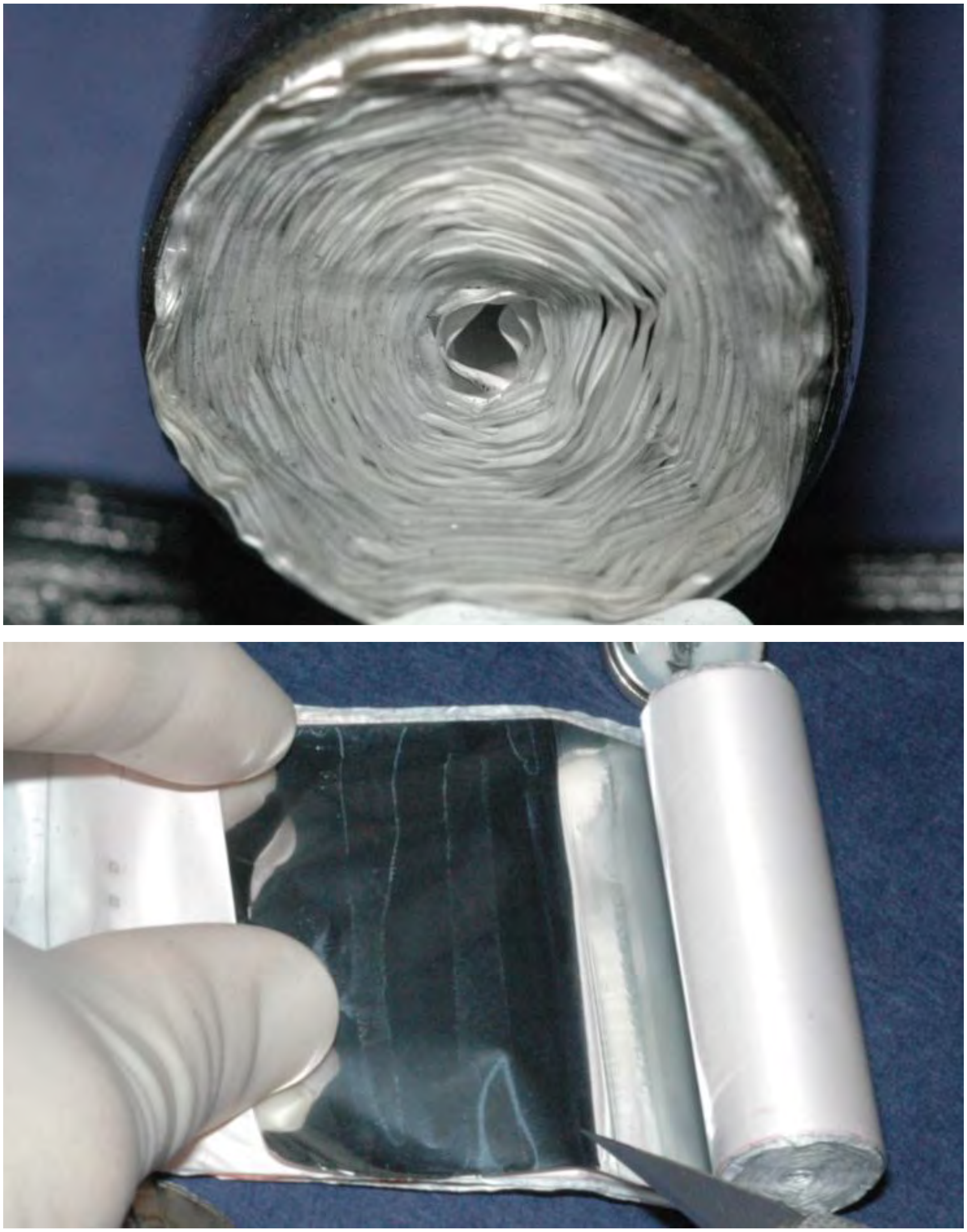

Figure 3 Base of a cylindrical Li-ion cell showing wound structure (top); Cell being unwound revealing multiple layers: separator is white, aluminum current collector (part of cathode) appears shiny (bottom)

Figure 4 Example of 18650 cylindrical cells; these are the most common consumer electronics Li-ion cell form factor (top); hard case prismatic cell (bottom left); and soft pouch polymer cell (bottom right)

2.3.3 Li-ion Battery Design

A Li-ion battery is made from multiple individual cells packaged together with their associated control system and protection electronics. By connecting cells in parallel, designers increase pack capacity. By connecting cells in series, designers increase pack voltage. Thus, most battery packs will be labeled with a nominal voltage that can be used to infer the number of series elements and, along with total battery pack energy (in watt hours [Wh]), can be used to determine the capacity (in ampere hours [Ah]) of each series element (size of individual cells or the number of cells connected in parallel). A Li-ion battery, despite conformance to a number of safety standards, may pose a significant high voltage and electrocution risk if it has been significantly damaged. Since Li-ion cells are not cycled to zero volts, a Li-ion battery pack, even in a normally discharged condition, is likely to contain substantial electrical charge. Cutting into a normally discharged battery pack can cause sparking or create electrocution hazards.

For large format battery packs, cells may be connected together (in series and/or in parallel) in modules. The modules may then be connected in series or in parallel to form full battery packs. Modules are used to facilitate readily changed configurations and easy replacement of faulty portions of large battery packs. Thus, large format battery pack architecture can be complex.

ESS batteries typically utilize many individual cells comprised into modules, which are assembled to form a large format battery pack. Large format battery packs typically contain an active safeguarding system to monitor electrical current, voltage, and temperature of the cells to optimize pack performance and mitigate potential failures, including fire. Numerous standards and protocols are available for these packs, including documents created by Underwriters Laboratories (UL), Institute of Electrical and Electronics Engineers (IEEE), National Electrical Manufacturers Association (NEMA), Society of Automotive Engineers (SAE), International Electrotechnical Commission (IEC), United Nations (UN), Japanese Standards Association (JSA), and Battery Safety Organization (BATSO). It is beyond the scope of this report to discuss all potential standards and protocols; however, a summary of the many standards and testing protocols for Li-ion cells has been published previously.[25]

2.4 ESS Codes and Standards

Exponent reviewed relevant codes and standards relating to the design, testing, and installation of Li-ion ESSs.

2.4.1 Safety Standards

In addition to the numerous standards and protocols available for Li-ion batteries, there are a number of safety standards for the overall construction of Li-ion stationary battery systems and ESSs. These safety standards generally include a minimum set of construction requirements

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[25] UL, "Safety Issues for Lithium-Ion Batteries," 2012.

with which the system should comply, as well as a number of performance tests to ensure the system will operate safely over its anticipated life. These construction requirements typically address some or all of the following: material choices/requirements; electrical spacing of components; wiring criteria; controls and other components; failure modes and effects analysis (FMEA); and functional safety requirements, markings, signage, and instructions.

Performance tests are conducted to ensure that the Li-ion battery ESS operates safely under normal use and foreseeable misuse conditions. Some examples of performance tests include: normal operation at a variety of expected temperatures; anticipated abnormal events, such as short circuit tests or other tests for foreseeable fault conditions; electrical spacing and insulation tests, such as a dielectric voltage test; and environmental conditions, such as exposure to water or other environmental stresses.

The published safety standards for Li-ion ESSs are often divided into technology specific and/or application specific documents. Some standards are intended for specific countries or geographical regions, while others are written as international standards. For battery ESSs, many of these standards were written for more traditional technologies, such as lead acid or nickel-cadmium (NiCad) battery systems and many of the documents are in the form of guides or recommended practices rather than standards; however, they still contain valuable information for evaluating and determining the safety of the ESS. It is beyond the scope of this report to discuss in detail all of the potential standards, guides, and recommended practices; however, a summary of many testing protocols for stationary battery systems and ESSs has been published previously.[26] The following is a list of many of the relevant documents and a brief summary of those documents that directly apply[27] to Li-ion battery ESSs and/or stationary battery systems:

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[26] UL, "Draft Storage/Stationary Batteries Standards List."

[27] Other documents that apply to battery ESSs or stationary battery systems that do not include Li-ion technologies within their scope were reviewed. Examples of such documents include: IEC 62485-2, *Safety Requirements for Secondary batteries and battery installations: Part 2 stationary*; IEC 60896-11, *Stationary lead-acid batteries Part 11: Vented types - General requirements and methods of tests*; IEC 60896-22, *Stationary lead-acid batteries Part 22: Valve regulated types – Requirements*; IEC 60896-21, *Stationary lead-acid batteries Part 21: Valve regulated types – Methods of test*; EN50272-2, *Safety Requirements for Secondary batteries and battery installations: Part 2 stationary*.

- UL 1973, *Batteries for Use in Light Electric Rail (LER) and Stationary Applications* (UL 1973), is a safety standard for stationary batteries for energy storage applications that is not specific to any one battery technology or chemistry, and can apply to Li-ion battery ESSs, as well as ESSs using other battery chemistries. The standard includes construction requirements, safety performance tests, and production tests.[28] The Li-ion batteries assessed in the testing described in this report are listed to UL 1973.

  UL 1973 contains a series of construction parameters, including requirements for non-metallic materials, metallic parts resisting corrosion, enclosures, wiring and terminals, electrical spacing and separation of circuits, insulation and protective grounding, protective circuits and controls, cooling/thermal management, electrolyte containment, battery cell construction, and system safety analyses.

  UL 1973 also outlines a series of safety performance tests for ESSs, including electrical tests such as an overcharge test, short circuit test, over-discharge protection test, temperature and operating limits check test, imbalanced charging test, dielectric voltage test, continuity test, failure of cooling/thermal stability system test, and working voltage measurements. In addition, UL 1973 requires testing of electrical components, including a locked-rotor test for low voltage direct current (DC) fans/motors in secondary circuits, input, leakage current, a strain relief test and a push-back relief test.

  Mechanical tests are also required by UL 1973, including a vibration test, shock test, and crush test, which only apply to LER applications. Other mechanical tests that apply to all systems include a static force test, impact test, drop impact test, wall mount fixture/handle test, mold stress test, pressure release test, and a start-to-discharge test.

  Additional environmental tests are also required by UL 1973, including a thermal cycling test, resistance to moisture test, and a salt fog test.

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[28] UL 1973, *Batteries for Use in Light Electric Rail (LER) and Stationary Applications*

Of particular relevance to this study, UL 1973 also requires two fire exposure tests: an external fire exposure test and an internal fire exposure test. The purpose of the external fire test is to ensure that an ESS will not explode as a result of being exposed to a hydrocarbon pool/brush fire. In the external test, a fully charged ESS is subjected to a heptane pool fire, or another similar hydrocarbon fuel pool fire, for 20 minutes. The fuel is held in a pan placed 24 inches under the ESS and is sized (in diameter) to be large enough to cover the dimensions of the ESS. After the 20 minute exposure, the ESS is subjected to a hose down in accordance with UL 263, *Conduct of Hose Stream Test of the Standard for Fire Tests of Building Construction and Materials*, to represent the firefighter response that the system may be exposed to during a fire. The ESS must demonstrate that no explosion hazards exist by the observation and measurement of any projectiles that occur during the external fire test.

The internal fire test is meant to demonstrate how the ESS will prevent a single cell failure within the battery system from cascading into a fire and/or explosion. In the internal fire test, the fully charged ESS is subjected to heating until thermal runaway of one internal battery cell that is centrally located within the ESS. Once the thermal runaway is initiated, the mechanism used to create thermal runaway is shut off or stopped and the ESS is subjected to a one hour observation period. Fire cannot propagate during this observation period or result in an explosion.

- IEC 61427-1, *Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 1: Photovoltaic off-grid applications*, provides general information relating to the requirements for the secondary batteries used in photovoltaic energy systems (PVES) and the typical test methods used for the verification of battery performance. This standard deals with cells and batteries used in photovoltaic off-grid applications and is applicable to all types of secondary batteries, including Li-ion.[29]

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[29] IEC 61427-1, *Secondary cells and batteries for renewable energy storage - General requirements and methods of test - Part 1: Photovoltaic off-grid applications,* 2013 Edition

- IEC 61427-2, *Secondary cells and batteries for renewable energy storage – General requirements and methods of test – Part 2: On-grid applications*, is a standard currently under development by IEC that relates to secondary batteries used in on-grid electrical energy storage (EES) applications. It provides test methods for the verification of their endurance, properties, and electrical performance in such applications. The test methods are essentially battery chemistry neutral, i.e., applicable to all secondary battery types, including Li-ion. On-grid applications are characterized by the fact that batteries are connected via power conversion devices to a regional, nation-, or continent-wide electricity grid and act as instantaneous energy sources and sinks to stabilize the grid's performance when major amounts of electrical energy from renewable energy sources are fed into it.[30]

- IEC 62619, *Secondary cells and batteries containing alkaline or other non-acid electrolytes - Safety requirements for large format secondary lithium cells and batteries for use in industrial applications*, is under development by IEC and will provide requirements on safety aspects associated with the erection, use, inspection, maintenance and disposal of cells and batteries for stationary applications and motive (other than on-road vehicles). It includes safety requirements for Li-ion cells for stationary and off-road motive applications and some battery requirements (evaluation of battery and battery management system [BMS] combination). The standard is not a system standard however, as it covers only battery and BMS interactions.

Two standards are currently under development by UL and the IEC that, when finished, will directly apply to commercial and residential Li-ion battery ESSs, including:

- UL Subject 9540, *Outline of Investigation for Energy Storage Systems and Equipment* (UL 9540), which will cover various types of ESSs and is not specific to just one battery chemistry or technology. Its scope includes requirements for ESSs that are intended to store energy from power or other sources and provide electrical or other types of energy

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[30] IEC 61427-2, *Secondary cells and batteries for renewable energy storage – General requirements and methods of test – Part 2: On-grid applications*, 2015 Edition

to loads or power conversion equipment. The ESSs may include equipment for charging, discharging, control, protection, communication, controlling the system environment, fuel or other fluid movement and containment. The system may be standalone to provide energy for local loads or can be in parallel with an electric power system, electric utility grid or applications that perform multiple operational modes. The standard contains a series of construction parameters with material flammability criteria and performance tests for ESSs. Although no full-scale fire test of the ESS as an assembly is required, UL 9540 does require that Li-ion ESSs meet the requirements of UL 1973, which contains two fire tests, as described previously.[31]

- IEC 62897, *Stationary Energy Storage Systems with Lithium Batteries – Safety Requirements*, is under development by IEC and will provide general safety requirements for stationary ESSs with lithium batteries. The standard will incorporate a number of requirements to address potential hazards with ESSs, including: electric shock or burn; mechanical hazards; spread of fire from the equipment; excessive temperature; effects of fluids and fluid pressure; liberated gases, explosion; and chemical hazards (e.g., electrolyte). The standard intends to cover small battery systems for residential or similar use that can be connected to a main source of supply.[32,33]

2.4.2 Codes and Regulations

In addition to safety standards, there are local, state, and national electrical, building, and fire codes to consider that could impact the installation of ESSs. In the United States, the codes affecting ESSs include the electrical installation codes, such as NFPA 70, *National Electrical Code* (NEC) and fire codes, such as NFPA 1, *Fire Code* (NFPA 1) or the International Code Council (ICC) code suite for building and fire codes. Electrical codes, such as the NEC, include requirements, among others, for wiring methods, grounding criteria, signage, and enclosures that impact ESS electrical safety.[34] Building and fire codes include requirements for battery

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[31] UL 9540, *Outline of Investigation for Energy Storage Systems and Equipment*, Issue Number 1, June 30, 2014.

[32] [redacted]

[33] UL, "Draft Storage/Stationary Batteries Standards List."

[34] NFPA 70, 2014 Edition, Article 480, *Storage Batteries*

rooms, spill containment, and fire protection systems for areas containing battery storage that impact the fire risk of the building, its occupants, and contents.

Concerns have arisen from the perceived lack of information contained in local, state, and national codes and regulations as they relate to Li-ion ESSs. Some of the concerns include: (1) limited information in the codes specifically relating to Li-ion batteries; (2) volume of electrolyte in the Li-ion battery being used to define its hazard level (which is not appropriate for Li-ion battery chemistry[35]); (3) fire suppression and detection systems required to protect ESSs; (4) whether or not these batteries are considered hazardous materials; and (5) separation of ESSs from other portions of the building.

2.4.2.1 Electrical Codes

NEC Article 480, *Storage Batteries*, applies to all stationary installations of storage batteries. Article 480 was originally written for and generally applied to stationary lead acid battery installations in the range of 48 volts. The section outlines a series of requirements for battery installations, however, most pertain to the electrical safety of the systems and have limited requirements specific to fire protection that would address the industry concerns listed above. For example, the NEC has sections on battery and cell terminations (Section 480.3), wiring and equipment supplied from batteries (Section 480.4), overcurrent protection (Section 480.5), disconnect methods (Section 480.6), insulation (Section 480.7), racks and trays that support the batteries (Section 480.8), battery locations (Section 480.9 Parts (A) , (B), and (G)), and safety vents[36] (Section 480.10). Section 480.9, *Battery Locations,* Parts (C) and (D) requires certain working spaces clearances for battery systems to allow for the units to be properly accessed. In addition, Part (E) requires that personnel door(s) intended for entrance to and egress from rooms designated as battery rooms open in the direction of egress and be equipped with listed panic

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[35] There are a number of reasons why the "volume of electrolyte" is not appropriate. One example is that the volume of electrolyte inside a battery cell is not extractable from a completed cell; therefore, the volume of electrolyte inside a Li-ion cell does not meaningfully translate to a hazard. The volume of electrolyte is appropriate for other chemistries, such as lead acid, where the failure of a battery could lead to spilling of the aqueous solution; however, the failure of a Li-ion battery or cell will more likely lead to the venting of a flammable gas, not the release of a liquid.

[36] Li-ion batteries do not typically require venting due to their technology and design, which does not vent hydrogen.

hardware. Gas piping is also prohibited from being installed within a dedicated battery room in Section 480.9 Part (F).

The next edition of the NEC to be published, the 2017 edition, is proposed to have a new article (Article 706) dedicated to ESSs. This addition should further assist installers, AHJs and manufacturers with navigating the electrical installation requirements for these systems.

2.4.2.2 Building and Fire Codes

Below is a summary of the sections contained within the 2015 edition of the International Building Code (IBC), International Residential Code (IRC), International Fire Code (IFC), and NFPA 1 relating to Li-ion ESSs and the concerns listed above. Many of the identified gaps in the codes mentioned below are currently being worked on and may be addressed when the next round of codes are published.

1. **Limited information on Li-ion battery ESSs.** Recent additions to the building and fire codes have answered many industry concerns, providing more details and thresholds for when requirements are necessary for Li-ion battery systems. Starting in 2006 for the IFC and 2009 for NFPA 1,[37,38] Li-ion batteries for use in stationary storage battery systems were discussed. Many municipalities lag behind in the adoption of new editions of building and fire codes. As such, those areas still using older versions of the codes could encounter issues; however, this issue (besides the correlating issues highlighted below in #2) is one that should resolve itself with the adoption of the newer codes.

   The 2015 edition of the IRC does not contain language relating to stationary battery systems, ESSs, or other similar systems, which could be confusing for readers looking for guidance for systems being installed in one or two-family dwellings or townhouses.

2. **Volume of electrolyte.** Traditionally, the IBC, IFC, and NFPA 1 applied specific safety requirements to battery systems containing more than 50 gallons of electrolyte. However, this requirement cannot be applied to Li-ion battery systems, as the electrolyte

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[37] 2006 IFC, Section 608.1

[38] NFPA 1, 2009 Edition, Section 52.1

is not stored in an aqueous solution. To account for this, starting in 2006 for the IFC and 2009 for NFPA 1, the fire codes defined the threshold at which requirements are necessary for Li-ion stationary storage battery systems according to their weight (1,000 pounds).[39,40] Adding to some of the confusion in the marketplace when discussing Li-ion battery packs and how best to define/categorize them, other agencies beyond the ICC and NFPA also utilize varying methods. For instance, the United Nations, *Recommendations on the Transport of Dangerous Goods - Manual of Tests and Criteria*, also defines and categorizes batteries by mass, where anything larger than 12 kilograms (kg) of gross mass is a "large battery" and anything less than 12 kg is a "small battery." In addition, a "large cell" is defined as anything with a gross mass greater than 500 grams (g). A cell less than 500 g is considered a "small cell."[41] The Department of Transportation (DOT) in 49 CFR 173.185 defines and categorizes batteries by "equivalent lithium content" (ELC), where the ELC is the product of the rated capacity, in Ah, of a Li-ion cell times 0.3, with the result expressed in grams. The ELC for a battery pack equals the sum of the grams of ELC contained in the component cells of the battery.[42] As such, DOT categorizes Li-ion batteries by their capacity, not the volume of electrolyte or mass of the cell or battery pack.

Even with the addition of the weight threshold for Li-ion battery systems in 2006 and 2009, the IBC, IFC, and NFPA 1 each still contain language in other sections of the codes that discuss requirements when the volume of electrolyte is above the 50-gallon threshold, not taking into account the weight of a Li-ion battery system. Three instances identified in the codes where this occurs include:

a. IBC Section 907.2.23, which states that any battery room with greater than 50 gallons of electrolyte must have a smoke detection system. IFC Section 608 applies directly to stationary storage battery systems and Li-ion batteries and resolves any confusion that exists in the code, as Section 608.9 requires a smoke

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[39] 2006 IFC, Section 608.1

[40] NFPA 1, 2009 Edition, Section 52.1

[41] United Nations, *Recommendations on the Transport of Dangerous Goods - Manual of Tests and Criteria*

[42] 49 CFR 171.8

detection system for stationary battery systems that are large enough to trigger the thresholds, such as a Li-ion battery system greater than 1000 pounds.[43] However, if a reader were to miss that section of the IFC, and only read the section in the IBC, it could create confusion over how to apply section 907.2.23 to Li-ion battery systems.

   b. IFC Section 105.7.2, which states that battery systems with more than 50 gallons of electrolyte require a permit before installation. However, no weight threshold is provided for Li-ion batteries.[44] As such, there could be confusion regarding whether or not a permit is required for Li-ion battery systems.

   c. NFPA 1 Table 1.12.8(a), which states that lead-acid battery systems with more than 50 gallons (unsprinklered buildings) or 100 gallons (spinklered buildings) of electrolyte require a permit before installation. However, Li-ion battery systems are not addressed in Table 1.12.8(a).[45] As such, there could be confusion regarding whether or not a permit is required for Li-ion battery systems.

3. **Suppression and detection.** Where required, such as for a high-rise building, fire sprinklers are not required in the area where battery systems are installed, provided the space is equipped with an automatic fire detection system and is separated from the rest of the building with one hour barriers or two hour horizontal assemblies.[46] In addition, a smoke detection system is required for all Li-ion battery systems greater than 1,000 pounds.[47,48]

4. **Hazardous materials.** The IBC and NFPA 1 state that battery systems do not fall into the Hazardous Group H category (for the IBC) or should be considered a hazardous material (for NFPA 1) provided certain ventilation requirements for the ESS are met.[49,50]

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[43] 2015 IFC, Section 608.1 and 608.9

[44] 2015 IFC, Section 105.7.2

[45] NFPA 1, 2015 Edition, Table 1.12.8(a)

[46] 2015 IBC, Section 403.3 and Exception to Section 903.2

[47] 2015 IFC, Section 608.9

[48] NFPA 1, 2015 Edition, Section 52.3.10

[49] 2015 IBC, Section 307.1.1(9)

However, Li-ion batteries typically do not require room ventilation,[51] as off gassing does not occur during normal operation. It is unclear if the IBC and NFPA 1 requirement for room ventilation is necessary for a Li-ion battery ESS to ensure it does not fall into the hazardous category.

5. **Separation.** The IBC states that Li-ion battery systems more than 1,000 pounds in weight shall be separated from the remainder of the building by either a one hour separation or two hour separation depending on the occupancy in which it is installed.[52]

Section 608 of the IFC and Chapter 52 of NFPA 1 provide further guidance on the proper installation of Li-ion ESSs. However, many of the requirements do not apply to Li-ion due to the chemistry of battery, including safety caps, spill control and neutralization measures, and room ventilation. Signage, seismic protection, and a fire/smoke detection system are required for Li-ion battery systems larger than 1,000 pounds.[53,54] A review of these two sections also identified another potential area of confusion for a user of the codes. The IFC does not require thermal runway protection for Li-ion battery systems, while NFPA contains contradictory guidance. Thermal runaway can occur in Li-ion battery systems and it is unclear why thermal runaway protection in Li-ion battery systems is not required in the IFC. NFPA 1 Table 52.1 states that Li-ion battery systems do not require thermal runaway protection; however, Section 52.3.2 states that Li-ion battery systems, “shall be provided with a listed device or other approved method to preclude, detect, and control thermal runaway.” Table 52.1 and the language of Section 52.3.2 are in direct conflict with one another, leading to possible confusion for anyone using the code. A review of the Report on Proposals and Report on Comments from the 2009 NFPA 1 code development cycle provided some guidance regarding what the technical committee intended. It appears that the technical committee intended for the thermal runaway protection to be required; however, a typo in Table 52.1 was not fixed at the time of initial adoption or anytime during future code development cycles. This issue should be addressed in

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[50] NFPA 1, 2015 Edition, Section 60.1.2

[51] 2015 IFC, Table 608.1 and NFPA 1, 2015 Edition, Table 52.1

[52] 2015 IBC, Table 509

[53] 2015 IFC, Table 608.1

[54] NFPA 1, 2015 Edition, Table 52.1

the next code development cycle to remove any confusion as to what NFPA 1 requires for thermal runaway protection of Li-ion battery systems.

2.5 ESS Fire Incidents

A review of fire incidents reported in the National Fire Incident Reporting System (NFIRS) from 1999 to 2013 was performed during the literature review. During this time period, only 44% of fires that fire departments respond to were captured in NFIRS. Thus, the numbers listed below do not account for every fire in the United States during that time. In addition, NFIRS currently does not have a means to report a stationary battery system or ESS fire; however, they do have a coding system for uninterrupted power supplies (UPS; code 226) and batteries (code 229). Table 1 provides a summary of the number of UPS and battery fires that were reported in NFIRS between 1999 and 2013.

Table 1 Summary of NFIRS Data

Incident Type	UPS Fire (Code 226)	Battery Fire (Code 229)
Structure Fire or Fire in Mobile Property used as a Fixed Structure	142	318
All Fires (not just Structures)	227	1,014

Exponent also searched for public incidents tied directly to the involvement of Li-ion ESSs in a fire. Through this search, only two major events involving battery ESSs were identified, one at a wind turbine power generating facility in Hawaii and one at a solar energy facility in Arizona. However, only the Arizona facility contained a Li-ion battery ESS, which was a pilot ESS that the facility was testing. Summaries of these two incidents ascertained from public sources are provided in the following sections.

No publically reported fire incidents were identified to have started in or significantly involved a commercial or residential ESS.

2.5.1 Kahuku Wind Energy Storage Farm Battery ESS Fires

Three fires occurred at the Kahuku Wind Energy Storage Farm over the course of a year and a half span from April 2011 to August 2012. The ESS contained 12,000 individual lead acid battery packs for a capacity of 15 megawatts (MW). The battery packs were stacked six feet high inside a 9,000 square foot metal warehouse building. It was determined that the fires were caused by undersized capacitors used by the battery system. The first two fires were allowed to self-extinguish, with limited damage to the system and the building; however, the third fire resulted in a total loss of the building and contents, including the 12,000 battery packs.[55,56,57]

The first incident occurred on April 22, 2011; the alarm was received by dispatch at approximately 5:45 p.m. and the Honolulu Fire Department (HFD) arrived on scene approximately 10 minutes later. An engineer from Xtreme Power, Inc. (Xtreme) was alerted by a remote alarm indicating that an exhaust fan on the Hawaiian Electric Company (HECO) side of the structure had overheated. The engineer also stated that smoke and popping sounds were emanating from the structure before HFD arrived. When HFD arrived, they noted smoke coming from the battery storage building. Approximately an hour after the first alarm, other arriving HFD personnel reported moderate grayish black smoke emanating from the structure, with no flames visible and no other structures in immediate danger. Facility personnel provided battery safety data sheets (SDS) for the lead acid batteries and building plans, however, HFD chose to wait for daylight to make an interior attack, primarily due to concerns regarding the stored energy in the batteries and possibly unsafe night operations. Major hazards identified by Xtreme and HFD included the batteries themselves (possibly explosive or energized), the sulfuric acid from the batteries, toxic environment, and energized electrical equipment. Xtreme advised HFD that water could not be used to extinguish the fire and that dry chemical, carbon dioxide (CO_2), or specialty foam (FM200) would be the best extinguishing agent. HECO personnel arrived on scene to secure the power to the building and advised of a sulfuric acid odor at the HECO switch box, emanating from the conduits within the building. A firewatch was present throughout the night. The following day, HFD made entry into the building, but no

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[55] [redacted]

[56] [redacted]

[57] [redacted]

active burning was found. The building was ventilated and cleared and operators of the facility were allowed to investigate and notified HFD that the cause of the incident was a failed electrical inverter. HFD investigators concluded that the origin of the fire was in the battery ESS building, within the Inverter #9 cabinet. The first material ignited was most likely conductor insulation or associated components within the cabinet. The fire was classified as accidental, failure and/or malfunction of operating electrical equipment. Fire spread was confined to the object of origin.[58]

The second incident occurred on May 23, 2011; the alarm was received by dispatch at approximately 10:20 p.m. and HFD arrived on scene approximately 10 minutes later. When HFD arrived, they noted light smoke coming from the top of a roll up door at the same ESS building. Facility personnel advised HFD that the incident appeared to be the same as the first loss; therefore, the same actions were taken, including shutting down the power and closing the building until morning. The next morning, HFD arrived to no smoke. The building was ventilated and one inverter was found to be burned out, with no residual signs of heat.[59]

The third incident occurred on August 1, 2012; the alarm was received by dispatch at 4:44 a.m. and HFD arrived on scene approximately 15 minutes later. First Wind advised HFD that their sensors indicated the malfunction of an electrical inverter directly adjacent to the stacks of batteries in the ESS building. Due to the large amount of batteries stored on site and experiences in the prior incidents, HFD chose to standby and monitor the building until HECO arrived with their dry chemical extinguishing truck. The fire was monitored using a thermal imaging camera and smoke and heat intensified, eventually venting through the roof, with some flames visible. Water was used to cool the uninvolved side of the building, but was discontinued due to the risk of contact with the burning batteries. Once HECO arrived, HFD assisted with deploying the dry chemical extinguishing line; however, suppression efforts were unsuccessful, as the dry chemical could not reach all of the burning material and entry could not be made due to the hazardous conditions created by the burning batteries and lack of an adequate supply of dry chemical. The fire eventually involved the entire building. Water was

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[58] Honolulu Fire Department Incident Report 2011-0018972.

[59] Honolulu Fire Department Incident Report 2011-0023875.

used to prevent spread to adjacent buildings, however, water could not be applied to the incident building due to environmental concerns regarding runoff water, as well as the high potential for stored electrical energy in the malfunctioning system and the large quantities of sulfuric acid involved; therefore, the fire was contained to the original building and allowed to burn until it eventually self-extinguished. HFD noted that significant/unusual fuel load from contents was a factor in suppressing the fire; with the material contributing most to flame spread being plastic used as electrical wire, cable insulation. HFD investigators concluded that the origin of the fire was in the battery ESS building. The first alarm activation was within the Inverter #9 cabinet, followed by general building smoke alarm activation. Video taken inside the ESS building showed fire in the proximity of the Inverter #9 cabinet. The first material ignited was most likely conductor insulation or associated components within the cabinet. The physical construction of the 12,000 batteries and associated conductors contributed mostly to fire spread. The fire was classified as accidental, failure and/or malfunction of operating electrical equipment.[60]

These fires demonstrate the need for better understanding of ESS fires so that the owner and fire departments responding to these incidents can better prepared in the event of a fire.

2.5.2 Arizona Public Service Company ESS Fire

In November of 2012, a fire occurred at a state-of-the-art solar energy storage system the Arizona Public Service Company (APS) was testing. The system, the relative size of a shipping container with a capacity of 1.5 MW, had been running since February of 2012. Similar to the First Wind fires, fire department personnel allowed the fire to burn freely for some time. The cause of the fire was not reported.[61,62] Exponent requested the local fire department reports on these fire incidents to obtain further details of the incidents, however, no response was received.

To date, relatively few ESS systems have been commissioned. In addition, most systems commissioned have been lead acid battery systems, not Li-ion. The search for fires involving

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[60] Honolulu Fire Department Incident Report 2012-0038895.

[61] [redacted]

[62] [redacted]

ESSs has identified only a few from publically available sources. In order to gain insight into how Li-ion ESSs will behave in fire scenarios, we can examine fires involving similar systems or battery fires in general.

2.6 Li-ion Battery Fires

Given the lack of ESS fire incidents documented in the literature, a review of Li-ion battery fires was conducted. Fires may occur in an ESS high voltage battery, or a fire may extend to the battery, attacking the ESS from the outside in. Previous research programs have been conducted focusing on large format Li-ion battery fires, electric drive vehicle (EDV) Li-ion battery fires, and Li-ion battery storage fires. This research involved full-scale fire tests of Li-ion batteries that were polymer, prismatic, and cylindrical designs.

For large format Li-ion battery systems with polymer or prismatic designs, the research has generally shown the following hazards associated with fires:

1. Fire tests of identical vehicles indicated that the heat release rate (HRR) of an EDV compared to a more common internal combustion engine (ICE) vehicle are similar[63] and a free burn (no suppression) test of an EDV battery did not produce significant HRRs.[64]
2. Test results indicate that water can be an effective extinguishing agent on large format Li-ion battery fires, however, large quantities may be required for extinguishment.[65,66,67]
3. During fires tests of EDVs with polymer pouch battery cells, no projectiles or explosions from the large format batteries were observed. [68,69,70]

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[63] Lecocq, A, Bertana M, Truchot, B. and Marlair G. “Comparison of the Fire Consequences of an Electric Vehicle and an Internal Combustion Engine Vehicle.” INERIS – National Institute of Industrial Environment and Risks, Verneuil-en-Halatte, France. Second International Conference on Fires in Vehicles, September 27-28, 2012, Chicago, IL.

[64] Long RT, Blum AF, Bress TJ, and Cotts BRT. “Emergency response to incidents involving electric vehicle battery hazards.” Fire Protection Research Foundation Report, July 2013.

[65] Delphi Corporation. Hybrid Electric Vehicles for First Responders. Troy, MI. 2012.

[66] Long RT, Blum AF, Bress TJ, and Cotts BRT. “Emergency response to incidents involving electric vehicle battery hazards.” Fire Protection Research Foundation Report, July 2013.

[67] Egelhaaf, M., Kress, D., Wolpert, D., Lange, T., Justen, R., and Wilstermann, H., "Fire Fighting of Li-Ion Traction Batteries," SAE Int. J. Alt. Power. 2(1):37-48, 2013, doi: 10.4271/2013-01-0213.

4. Gas samples collected during fire tests of complete (i.e., full) ICE vehicles and EDVs identified similar levels of toxic compounds in the smoke, including CO_2, nitrogen oxides (NO_x), hydrogen cyanide (HCN), hydrogen chloride (HCl), carbon monoxide (CO), and hydrogen fluoride (HF).[71] In addition, water samples collected after extinguishing Li-ion batteries showed concentrations of fluoride and chloride.[72,73]

5. Fire tests have also demonstrated that in the tested scenario, with a battery pack tested inside a vehicle fire trainer (i.e., not a powered consumer EDV), the shock/electrocution hazards of applying a water stream directly to an energized high voltage battery that has been compromised by heat and fire were negligible.[74] In addition, other fire tests where hose streams were applied directly to energized electrical equipment have demonstrated that current leakage through the suppression water is not a hazard, provided sufficient clearance distances for the given voltage of the electrical equipment are observed between the hose stream and conductors.[75,76,77,78]

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[68] Long RT, Blum AF, Bress TJ, and Cotts BRT. “Emergency response to incidents involving electric vehicle battery hazards.” Fire Protection Research Foundation Report, July 2013.

[69] Watanabe, N., Sugawa, O., Suwa, T., Ogawa, Y., Hiramatsua, M., Tomonoria, H., Miyamotoa, H., Okamotoa, K., and Honmaa, M. “Comparison of fire behaviors of an electric-battery-powered vehicle and gasoline-powered vehicle in a real-scale fire test.” National Research Institute of Police Science, Japan. Presented at Second International Conference on Fires in Vehicles, September 27-28, 2012, Chicago, IL.

[70] Lecocq, A, Bertana M, Truchot, B. and Marlair G. “Comparison of the Fire Consequences of an Electric Vehicle and an Internal Combustion Engine Vehicle.” INERIS – National Institute of Industrial Environment and Risks, Verneuil-en-Halatte, France. Second International Conference on Fires in Vehicles, September 27-28, 2012, Chicago, IL.

[71] Lecocq, A, Bertana M, Truchot, B. and Marlair G. “Comparison of the Fire Consequences of an Electric Vehicle and an Internal Combustion Engine Vehicle.” INERIS – National Institute of Industrial Environment and Risks, Verneuil-en-Halatte, France. Second International Conference on Fires in Vehicles, September 27-28, 2012, Chicago, IL.

[72] Long RT, Blum AF, Bress TJ, and Cotts BRT. “Emergency response to incidents involving electric vehicle battery hazards.” Fire Protection Research Foundation Report, July 2013.

[73] Egelhaaf, M., Kress, D., Wolpert, D., Lange, T., Justen, R., and Wilstermann, H., "Fire Fighting of Li-Ion Traction Batteries," SAE Int. J. Alt. Power. 2(1):37-48, 2013, doi: 10.4271/2013-01-0213.

[74] Long RT, Blum AF, Bress TJ, and Cotts BRT. “Emergency response to incidents involving electric vehicle battery hazards.” Fire Protection Research Foundation Report, July 2013.

[75] Factory Mutual Handbook of Industrial Loss Prevention, “Electrical Conductivity of Extinguishing Agents”

[76] Sprague, C.S. and C.F. Harding. “Electrical Conductivity of Fire Streams” Research series no. 53. Engineering Experiment Station, Purdue University Lafayette, Indiana, January 1936.

[77] Bolander, G.G., Jughes, J. T., Toomey, T. A., Carhart, H.W., and J.T. Leonard. “Use of Seawater for Fighting Electrical Fires” Navy Technology Center for Safety and Survivability, Chemistry Division. May 25, 1989.

Previous research focusing on large format Li-ion battery fires with a polymer or prismatic design demonstrated that that some of the common concerns regarding Li-ion battery fires (namely explosions, projectiles, and toxic gas formation) have not been replicated in full-scale fire tests. However, fire tests of unconfined Li-ion batteries with a cylindrical design have demonstrated that "cell explosions" can occur with projectiles observed traveling up to 133 feet.[79]

2.7 Gap Analysis

Based upon the literature review conducted to date, Exponent has identified the following gaps in the knowledge base for commercial and residential Li-ion ESSs:

1. No public fire test data demonstrating the fire behavior of ESSs.

2. Limited public fire test data related to large format battery packs with cylindrical design utilized either in vehicles or storage systems.

3. No fire test data or publically available real world fire incidents involving residential or commercial Li-ion ESSs illustrating the hazards (projectiles, heat release, toxic gas production) to first responders and/or the best practices for fire department operations.

4. Limited real world fire incidents involving large-scale (grid size) ESSs.

5. No Li-ion ESS guidance in the IRC.

6. Some sections of the IBC, IFC, and NFPA 1 are confusing, as only the volume of the electrolyte (a requirement for older battery chemistries such as lead acid) and not the weight of the Li-ion battery system, is used as a threshold for when certain building or fire code requirements are necessary. In addition, other agencies, such as the United Nations and DOT, have other methods for defining and categorizing batteries. Many of

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[78] Backstrom, R., Dini, DA, "Firefighter Safety and Photovoltaic Installations Research Project." Underwriters Laboratories Inc. November, 2011.

[79] Webster, H, "Preliminary Full-Scale Fire Tests with Bulk Shipments of Lithium Batteries." 2012 FAA Fire Safety Highlights, US Department of Transportation Federal Aviation Administration, 2012.

these code sections are presently being revised and could be addressed by the next published code set.

7. NFPA 1 provides contradictory guidance regarding thermal runway protection for Li-ion battery systems, while the IFC does not require thermal runaway protection for Li-ion battery systems at all. Many of these code sections are presently being addressed and could be resolved by the next published code set.
8. No post-fire incident response and recovery (i.e., overhaul) procedures.
9. No stationary battery system or ESS fire reporting code in NFIRS to assist in analyzing fire incidents and differentiate battery systems from household batteries.

3 Testing Program Summary

Exponent, in conjunction with the Project Technical Panel, their advisory groups, and industry sources, identified and procured two (2) Li-ion battery ESSs for full-scale testing. The battery pack utilized in the ESS is a 100 kWh unit manufactured by Tesla Energy (Tesla) meant for commercial applications (Powerpack). The Powerpack consists of a 52-inch long by 38-inch wide by 86-inch tall steel cabinet containing the battery, protection electronics, and thermal management systems. The total weight of the unit is 3,970 pounds and it mounts directly to a concrete pad. A more detailed description of the ESS tested is provided in Section 4.

The full-scale fire tests were separated into two categories: (1) external ignition of the Powerpack and (2) internal ignition of the Powerpack. During the external ignition test, the Powerpack was exposed to an external fire source (a propane burner) to simulate a fire scenario where a fire originates outside of the Powerpack. During the internal ignition test, individual battery cells within the Powerpack were forced into thermal runaway.

3.1 Test Instrumentation Summary

Both tests were performed outdoors in open air, on a concrete pad, exposed to natural weather conditions, as would be typical of an outdoor commercial installation. In the external ignition testing, a propane burner system was used to apply the thermal assault to the Powerpack and cause thermal runaway of the batteries within. During internal ignition testing, the batteries of the Powerpack were forced into thermal runaway at the individual cell level.

Data collected during the tests included:

- Internal and external Powerpack surface temperatures;
- Heat fluxes at varying stand-off distances from the Powerpack;
- Internal Powerpack cabinet and pod pressures;
- Select products of combustion;
- Weather conditions;

- Projectile observations;
- Still photography; and
- High definition video.

3.2 Full-scale Fire Protocols

Exponent and Tesla created two protocols for the full-scale fire tests: one for the external ignition test and one for the internal ignition test.

3.2.1 External Ignition Testing

The test protocol for the external ignition testing was as follows:

1. The Powerpack was positioned and the test equipment was set up as described in Section 3.1.
2. The following background data was collected as a steady-state baseline for 3 minutes:
    a. Thermocouples;
    b. Heat flux gauges; and
    c. Gas sampling.
3. High definition video recordings were started simultaneously with data collection.
4. After the 3-minute baseline was established, the propane burners were ignited to provide a 400 kW[80] exposure.
5. The 400 kW exposure was continued for approximately 60 minutes. Once at least twenty (20) cell thermal runaways were confirmed audibly, the burner was turned off.
6. Once the burner was shut off at the end of the approximate 60-minute 400 kW exposure, the progression of the Powerpack fire in the free burn state was monitored thereafter.
7. Visual observations of importance were recorded, including when smoke was first observed, when cells went into thermal runaway, smoke production/color, projectiles, when flames were first observed, height and severity of flames, etc.
8. Still photographs were recorded throughout the test, as appropriate.

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[80] HRR from the propane burners was determined based upon the flow rate of propane recorded by a mass flow meter during testing times the heat of combustion of propane.

9. Data collection continued until all signs of combustion ceased.

3.2.2 Internal Ignition Testing

The test protocol for the internal ignition tests was as follows:

1. The Powerpack was positioned and the test equipment was setup as described in Section 3.1.
2. The following background data was collected as a steady-state baseline for approximately 1.5 minutes:
    a. Thermocouples and
    b. Gas sampling.
3. High definition video recordings were started simultaneously with data collection.
4. After the 1.5-minute baseline was established, multiple Powerpack cells were forced into thermal runaway through the use of heater cartridges by Tesla.
5. Visual observations of importance were recorded, including when smoke was first observed, when cells went into thermal runaway, smoke production/color, projectiles, when flames were first observed, height and severity of flames, etc.
6. Still photographs were recorded throughout the test, as appropriate.
7. Data collection continued until all signs of thermal runaway ceased.

4 ESS Description

This section provides an overview of the Powerpack (a 100 kWh commercial ESS) utilized for this testing program. The Powerpack can be a single standalone unit, as shown in Figure 5, or installed side by side with multiple Powerpacks if additional storage capacity is desired, as shown in Figure 6.

Figure 5 Single standalone Powerpack (100 kWh commercial ESS)

Figure 6 Multiple Powerpacks installed side by side in an array

4.1.1 ESS Battery Pack

The cells utilized within the Powerpack are 3.6 volt, 2.4 amp hour cylindrical 18650 cells. Two modules, each consisting of approximately 450 cells, are connected and enclosed inside a steel cover to form one energy storage pod, as shown in Figure 7. As such, one energy storage pod contains a total of two modules, or approximately 900 battery cells. Sixteen (16) energy storage pods are contained within the Powerpack cabinet for a total of approximately 14,400 battery cells within the Powerpack.

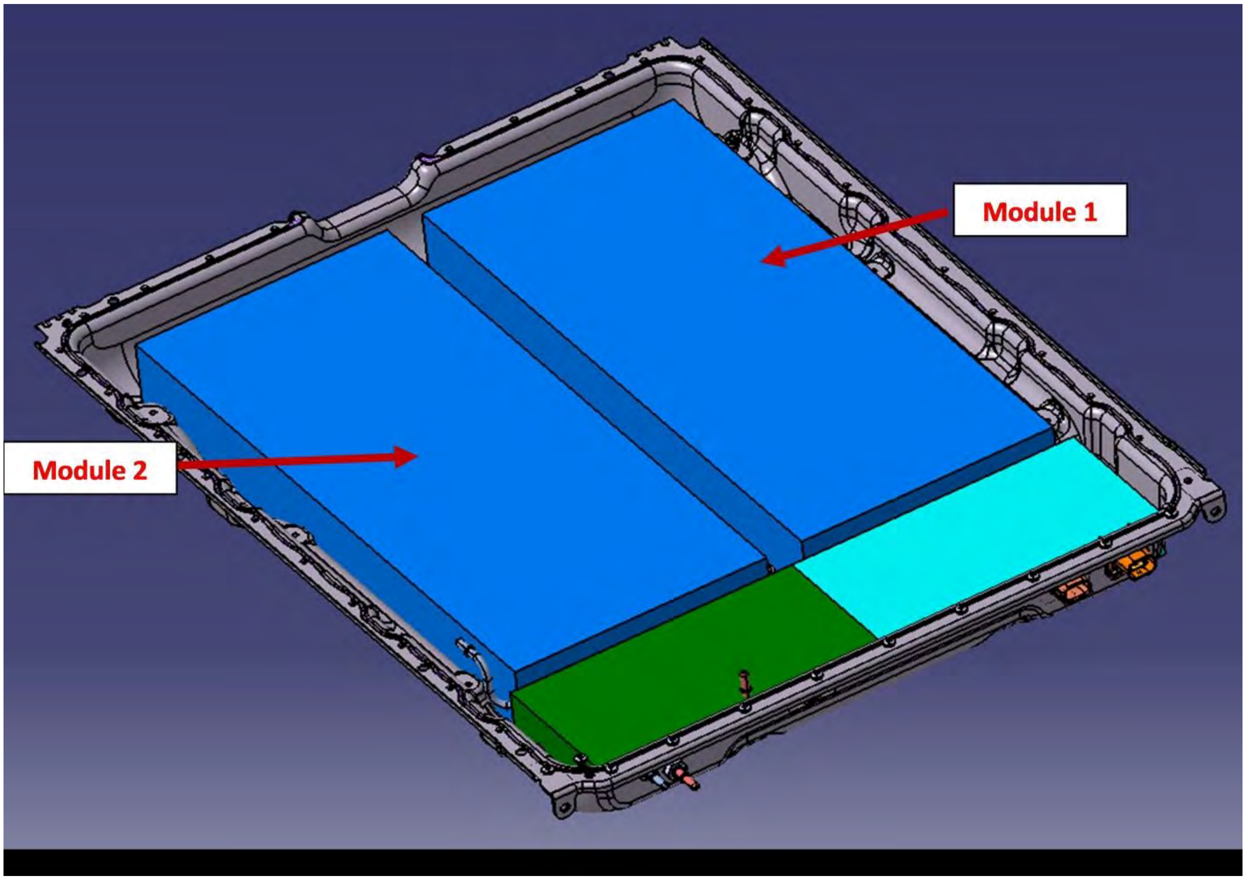

Figure 7 Illustration of a pod with two modules (blue); each module contains approximately 450 cylindrical Li-ion battery cells totaling 900 battery cells for each pod

4.2 ESS Design Layout

The Powerpack was designed for commercial installations. Within the Powerpack, Li-ion cells are contained within energy storage pods. The energy storage pods are housed inside a 52-inch long by 38-inch wide by 86-inch high steel cabinet. The total weight is 3,970 pounds. The front door of the Powerpack cabinet provides access to each of the 16 energy storage pods, as shown in Figure 8, and contains equipment designed to thermally cool the pods. The liquid cooling system pumps a 50% water / 50% ethylene glycol mixture to each of the 16 energy storage pods, as shown in Figure 9. The coolant pumps, reservoirs, and associated fans and radiators are mounted and contained within the front door of the Powerpack. A refrigerant system using 400 grams of R134a further cools the ethylene glycol and is also mounted on the front door of the Powerpack. The back of the energy storage pods connect to an exhaust manifold at the rear of the Powerpack that has a vent at the top, as shown in Figure 10.

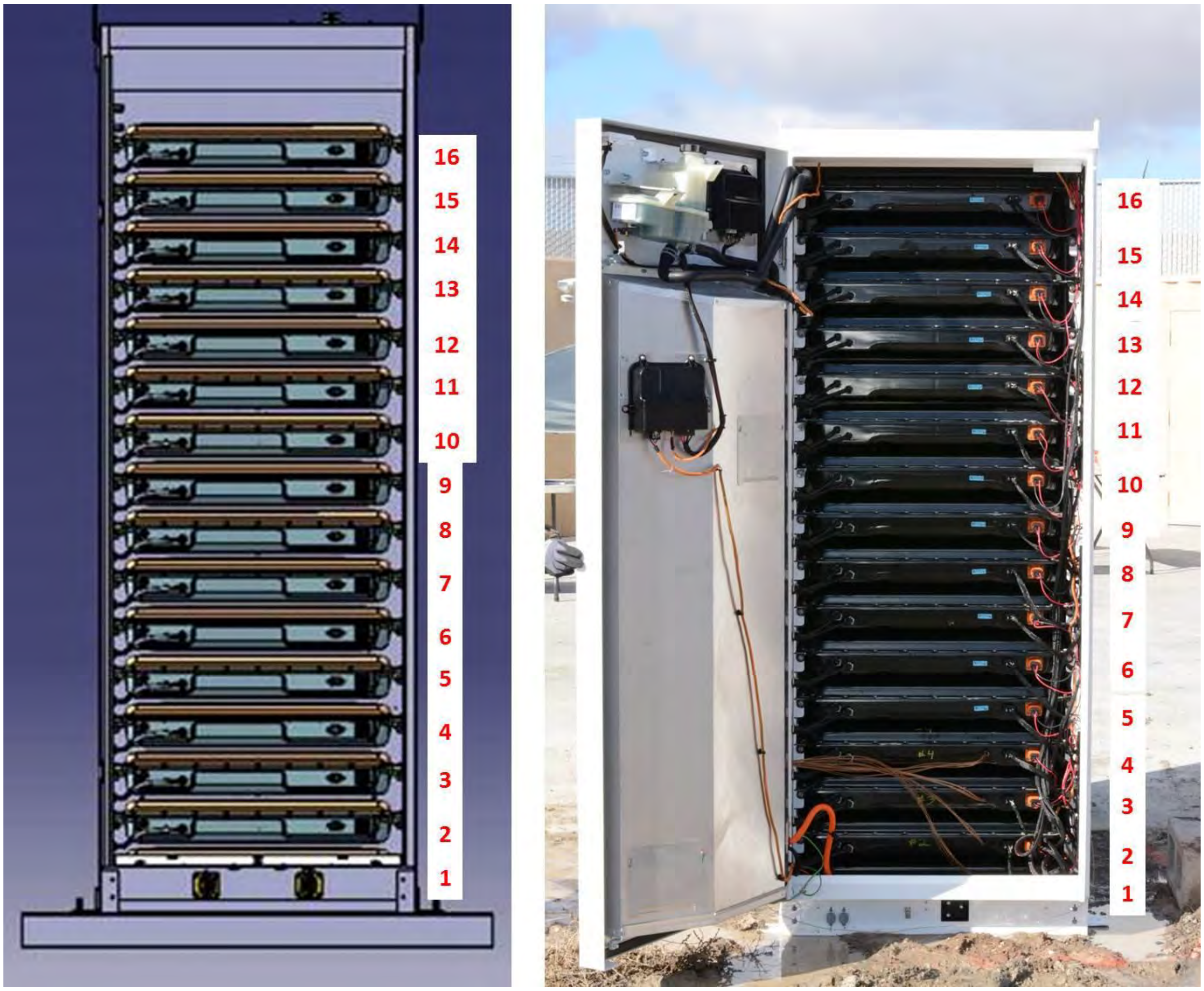

Figure 8 Powerpack illustration (left) and image (right); depicting the sixteen (16) energy storage pods installed within the cabinet and instrumented for testing

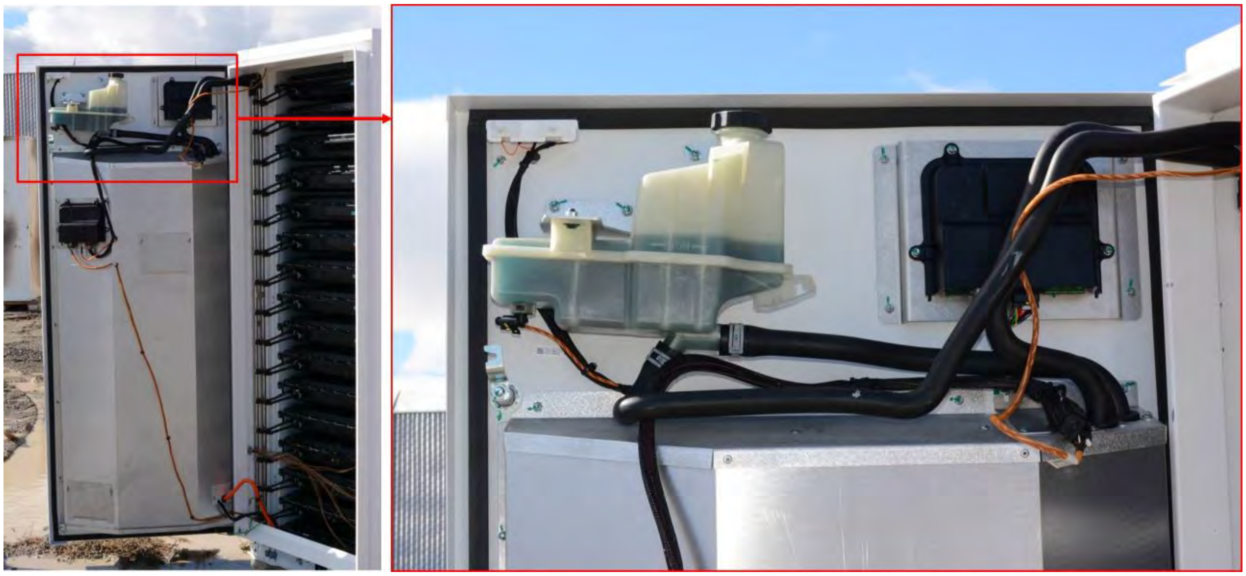

Figure 9 Powerpack thermal door (left) and close up of the refrigerant (right)

Figure 10 Illustration of the Powerpack exhaust vent (left) and an image of the vent at the top of the Powerpack (right)

4.3 ESS Safety Features

The Powerpack is listed to UL 1741, UL 1973, and IEC 62109. In addition, the Powerpack is designed to be compliant with UL 9540 and IEC 62619, currently under development by UL and IEC, respectively. UL1973, as described in Section 2.4.1, includes a number of construction requirements, performance tests, and production tests for stationary battery systems, including an external fire test and an internal fire test. The external fire test requires that the ESS not pose an explosion hazard if attacked by an external fire. The internal fire test demonstrates that a single battery cell failure within the center of the ESS battery pack will not result in a cascading thermal runaway of battery cells resulting in a propagating fire from the ESS and/or an explosion of the ESS.

Specific to the Powerpack design, each pod has a low voltage (approximately 50-volt) output that is later converted through power management electronics into the higher 400-volt Powerpack output. The energy storage pods are galvanically isolated and the 400-volt Powerpack output is only present when the Powerpack is in an active state and the power electronics are operational. Without active low voltage system electronics, because of the galvanic isolation, there is no electrical pathway from the live battery voltage to the exterior of a pod. As such, because of the design of the Powerpack, during charging or discharging, the cells are not at a high voltage. Each energy storage pod is encased inside a steel enclosure that prohibits any cell failure from projecting outside of pod. In addition, the pods are then enclosed within the steel Powerpack cabinet, which further reduces the possibility of projectiles from the unit. As described earlier, the energy storage pods are cooled by a thermal management system in the front door of the Powerpack cabinet that keeps the battery cells within safe operating temperatures. In the unlikely event of cell thermal runaway, the Powerpack has an engineered exhaust pathway, which directs runaway gas to a gas manifold that is directed out the top of the Powerpack. The Powerpack is designed to be installed side by side with multiple Powerpacks if additional storage capacity is desired. Clearance from the Powerpack is outlined in the manufacturer's installation manual, which requires that combustibles be kept six feet from the front, six inches from the sides and back, and five feet from the top of the Powerpack.

5 Testing Setup

The full-scale fire tests were separated into two categories: (1) external ignition of the Powerpack and (2) internal ignition of the Powerpack, as described below. For both tests, the Powerpack battery packs were charged to a full 100% state of charge (SOC) prior to testing.

5.1 External Ignition Testing

The external ignition test exposed the Powerpack to a propane burner to simulate a fire scenario where the fire originates outside of the Powerpack.

5.1.1 ESS Positioning

The Powerpack was positioned on a noncombustible surface similar to its intended end use for an outdoor installation on a concrete pad, as shown in Figure 5. The test instrumentation, including thermocouples (TCs), heat flux gauges (HFGs), pressure transducers, gas sampling, data acquisition, weather meter, and cameras were positioned around the Powerpack as illustrated in Figure 11. In addition, a propane burner, further described in Section 5.1.2, was placed to the right side of the Powerpack, allowing for direct flame impingement on the exterior of the Powerpack cabinet.

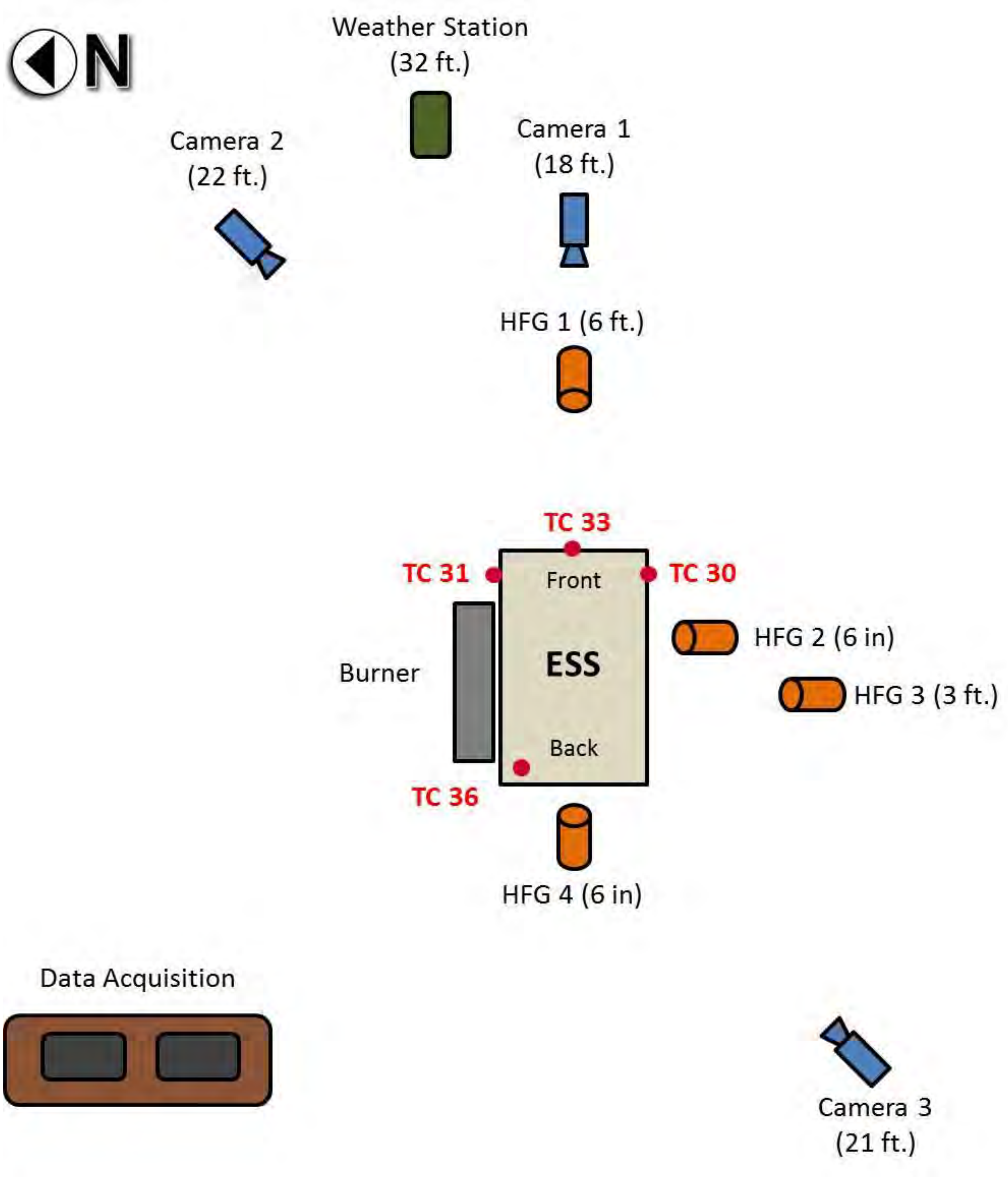

Figure 11 External fire test setup and instrumentation

5.1.2 Burner Description (Ignition Source)

The burner assembly consisted of three (3) drilled-pipe propane burners connected in parallel, as shown in Figure 12.

Each burner was 1.25 inches in diameter and 49 inches long and consisted of two rows of 2 mm orifices drilled at an angle 45 degrees apart. The orifices extended for 36 inches, spaced approximately 5 mm apart. The three burners were installed inside a five sided, 36 by 36 inch by 8 inch steel shell, with a steel mesh covering the opening to increase the amount of radiative heat load from the burner assembly to the exterior wall of the Powerpack enclosure. The burner assembly was positioned against the right side of the Powerpack cabinet to allow for direct flame impingement on the exterior of the unit, as shown in Figure 13. .

The flow of propane was monitored by a calibrated Omega FMA1845A mass flow meter, capable of measuring up to 1,000 liters per minute (lpm). The flow rate of propane was adjusted to provide an output of approximately 400 kW during the test.[81]

Figure 12 Burners utilized for testing

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[81] HRR from the propane burners was determined based upon the flow rate of propane recorded by a mass flow meter during testing times the heat of combustion of propane.

Figure 13 Burner assembly and positioning

5.1.3 Temperature and Heat Flux Measurements

Temperatures were monitored with 1/8th-inch diameter bare bead Type K Chromel-Alumel thermocouples with an accuracy of ± 2.2°C or 0.75%, whichever is greater. Twenty-nine (29) thermocouples were placed on the exterior surfaces of the Powerpack, at selected battery pods inside the Powerpack, and within the Powerpack cabinet and exhaust manifold. Six (6) thermocouples were installed inside pods 1, 2, 3, and 4, for a total of 24 thermocouples monitoring the thermal runaway progression inside the battery pods, as shown in Figure 14. One (1) thermocouple was positioned inside the Powerpack cabinet exhaust manifold and another at the exhaust vent, as shown in Figure 15. Three (3) additional thermocouples were installed on the exterior surface of the Powerpack cabinet on the front, right side (burner side), and the left side of the Powerpack, as shown in Figure 11.

Heat fluxes were monitored with Schmidt-Boelter heat flux gauges capable of measuring up to 50 kW/m^2 ±3%. The heat flux gauge has a target 0.60 inches in diameter that is enclosed within a water cooled body two inches in diameter. Four (4) heat flux gauges were placed three feet above the ground at standoff distances of six feet in front of the Powerpack, six inches and three feet from the left side (opposite of the burner) of the Powerpack, and six inches from the back of the Powerpack, as shown in Figure 11. These distances are related to the clearance distances outlined in the Powerpack installation manual.

The location of each thermocouple and heat flux gauge is provided in Table 2 and Table 3.

Table 2 Summary of Thermocouple Locations for External Ignition Testing

TC	Measurement Location	TC	Measurement Location	TC	Measurement Location
0	Interior Pod #1	10	Interior Pod #2	20	Interior Pod #4
1	Interior Pod #1	11	Interior Pod #2	21	Interior Pod #4
2	Interior Pod #1	12	Interior Pod #3	22	Interior Pod #4
3	Interior Pod #1	13	Interior Pod #3	23	Interior Pod #4
4	Interior Pod #1	14	Interior Pod #3	30	Exterior Left
5	Interior Pod #1	15	Interior Pod #3	31	Exterior Right
6	Interior Pod #2	16	Interior Pod #3	32	Exhaust Manifold
7	Interior Pod #2	17	Interior Pod #3	33	Exterior Front
8	Interior Pod #2	18	Interior Pod #4	36	Exhaust Vent
9	Interior Pod #2	19	Interior Pod #4		

Table 3 Summary of Heat Flux Gauge Locations for External Ignition Testing

Heat Flux Gauge	Measurement Location	Heat Flux Gauge	Measurement Location
1	Front (6 ft)	3	Left (3 ft)
2	Left (6 in)	4	Back (6 in)

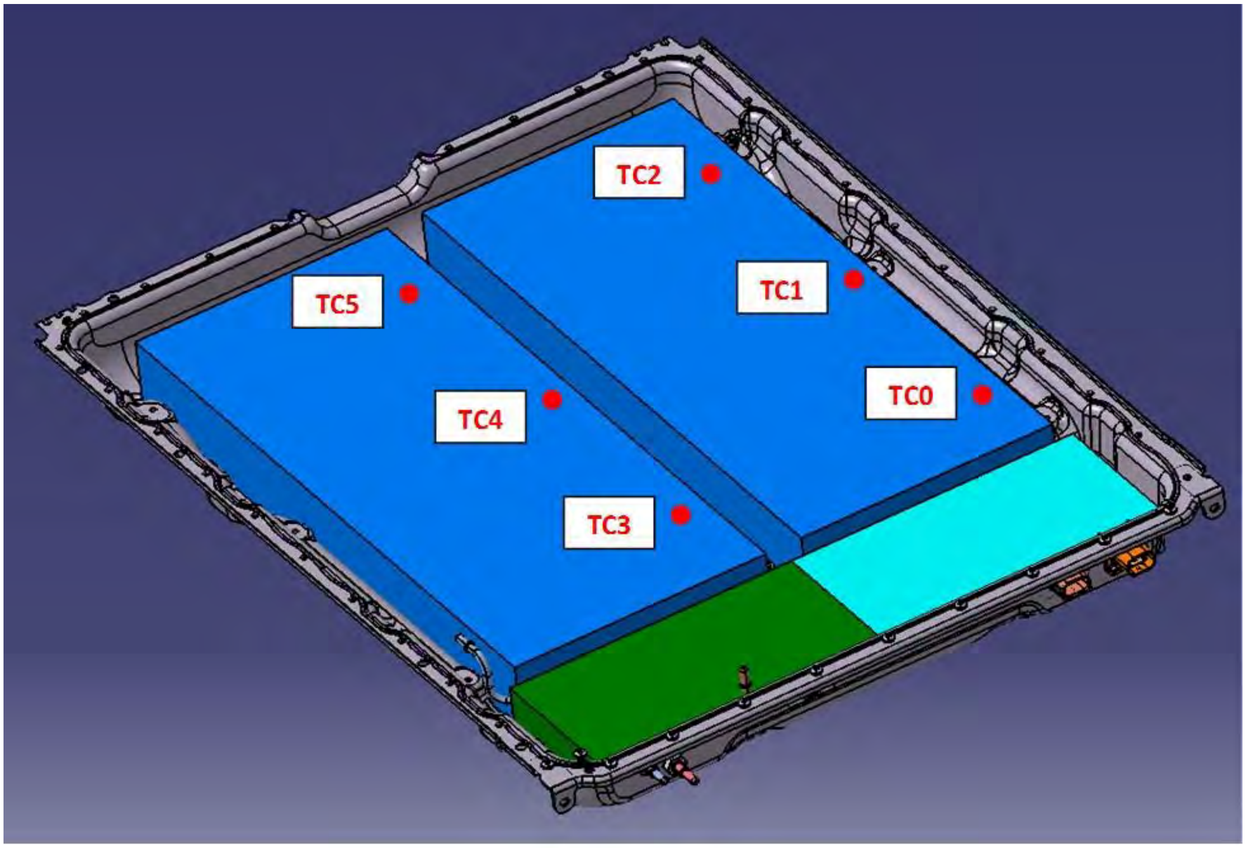

Figure 14 TC measurement locations within Pod 1; Pods 2 through 4 are similarly instrumented and labeled in the same numerical order

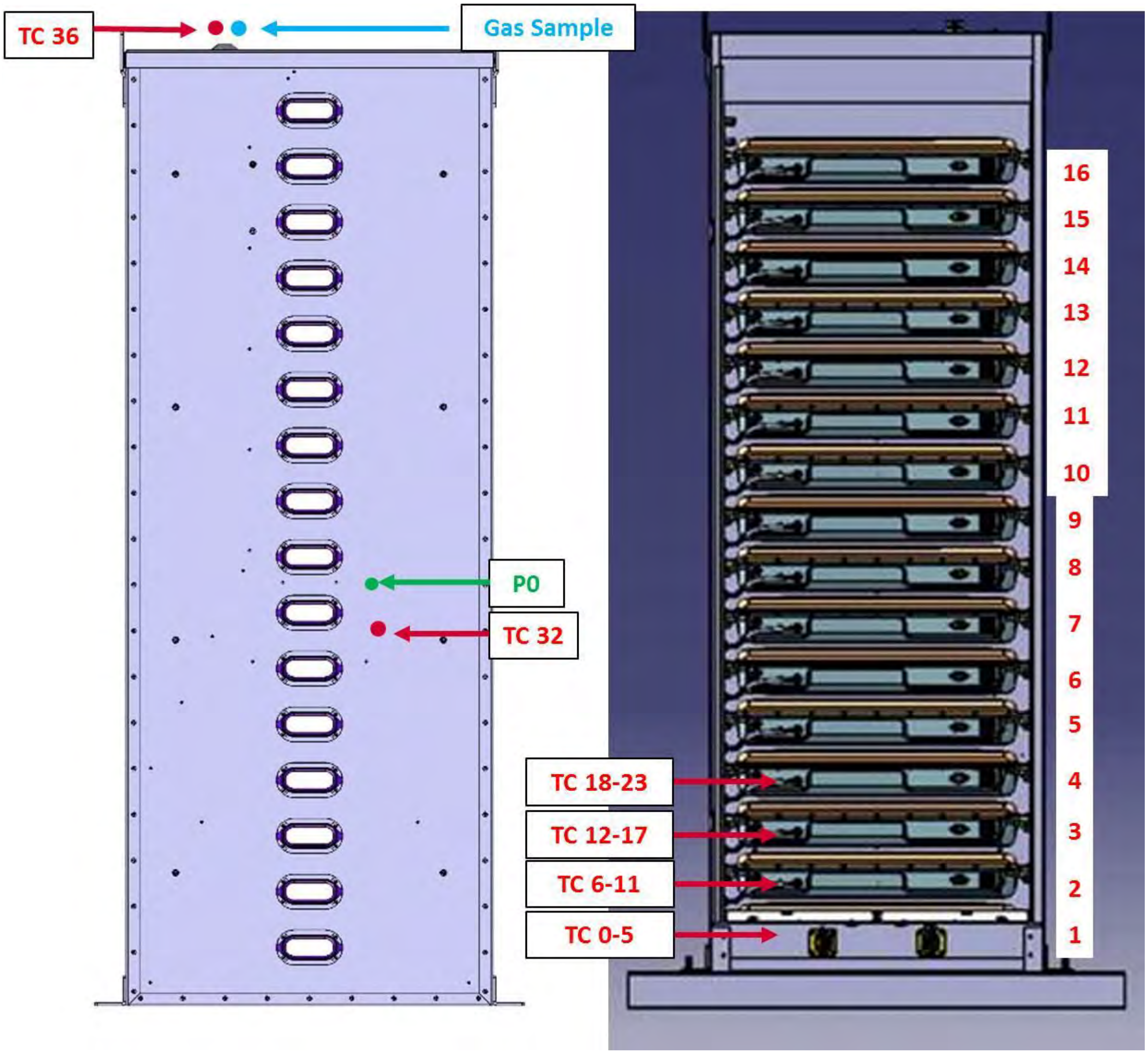

Figure 15 TC, gas sampling, and pressure measurement locations inside the Powerpack cabinet

5.1.4 Pressure Measurements

Pressures were monitored inside the Powerpack cabinet exhaust manifold using an Omega PX-309-015G5V pressure transducer capable of measuring up to 15 psi with an accuracy of ±0.25% full-scale. The transducer was positioned inside the Powerpack cabinet exhaust manifold to detect any overpressures inside the Powerpack cabinet during the test, as shown in Figure 15.

5.1.5 Products of Combustion Gas Sampling

Select products of combustion were monitored at the exhaust vent of the Powerpack cabinet as illustrated in Figure 15. The gas samples were analyzed with a MultiRAE Lite PGM-6208 and a calibrated PortaSens II portable gas leak detector; model C16, manufactured by Analytical Technology, Inc. Gases measured included CO, chlorine (Cl_2), methane (CH_4) (monitored by the MultiRAE Lite) and HF (monitored by the PortaSens II) at a range up to 2,000 ppm (±10 ppm), 50 ppm (±0.1 ppm), 0-100% volume/volume (±0.1%) and 100 ppm (±5%), respectively. Previous experience with Li-ion battery fires and information provided by Tesla focused the gas analysis to these four gasses during this test series. The two detectors were portable handheld units that contained their own built in pumps to draw a gas sample from the exhaust vent through tubing into the respective detector chamber.

5.1.6 Weather Meter

A Kestrel 4500 weather meter was utilized to monitor the ambient temperature, humidity, wind speed, and direction during testing. The Kestrel was positioned approximately 32 feet away from the Powerpack in an open space, away from any structures or objects that could affect the conditions being monitored, as illustrated in Figure 11.

5.1.7 Data Acquisition System

A National Instruments NI 9205 data acquisition unit was utilized to collect the heat flux and pressure measurements at a rate of 10 and 1,000 measurements per second, respectively, at a 16 bit resolution. A MeasurePoint DT9874 Isolation Temperature data acquisition unit was utilized to collect temperature measurements at a rate of 10 measurements per second at a 24 bit resolution. The gas analyzers and the weather meter utilized their own built in data acquisition and recording software to collect data.

5.1.8 Still Photography and High Definition Video

Still images and high definition videos were taken throughout the test. Video cameras were positioned around the Powerpack to get a 360-degree view of the Powerpack at all times, as illustrated in Figure 11. Still images were taken periodically during the test to capture the fire progression.

5.2 Internal Ignition Testing

The internal ignition test induced individual cells within the Powerpack to thermal runaway.

5.2.1 ESS Positioning

The Powerpack was positioned on a noncombustible surface similar to its intended end use installation on a concrete pad, as shown in Figure 5. The test instrumentation, including thermocouples (TCs), pressure transducers, gas sampling, data acquisition, weather meter, and cameras were positioned around the Powerpack as illustrated in Figure 16. In addition, heater cartridges utilized to force the individual batteries into thermal runaway, further described in Section 5.2.2, were positioned inside pod 6 (the initiator pod).

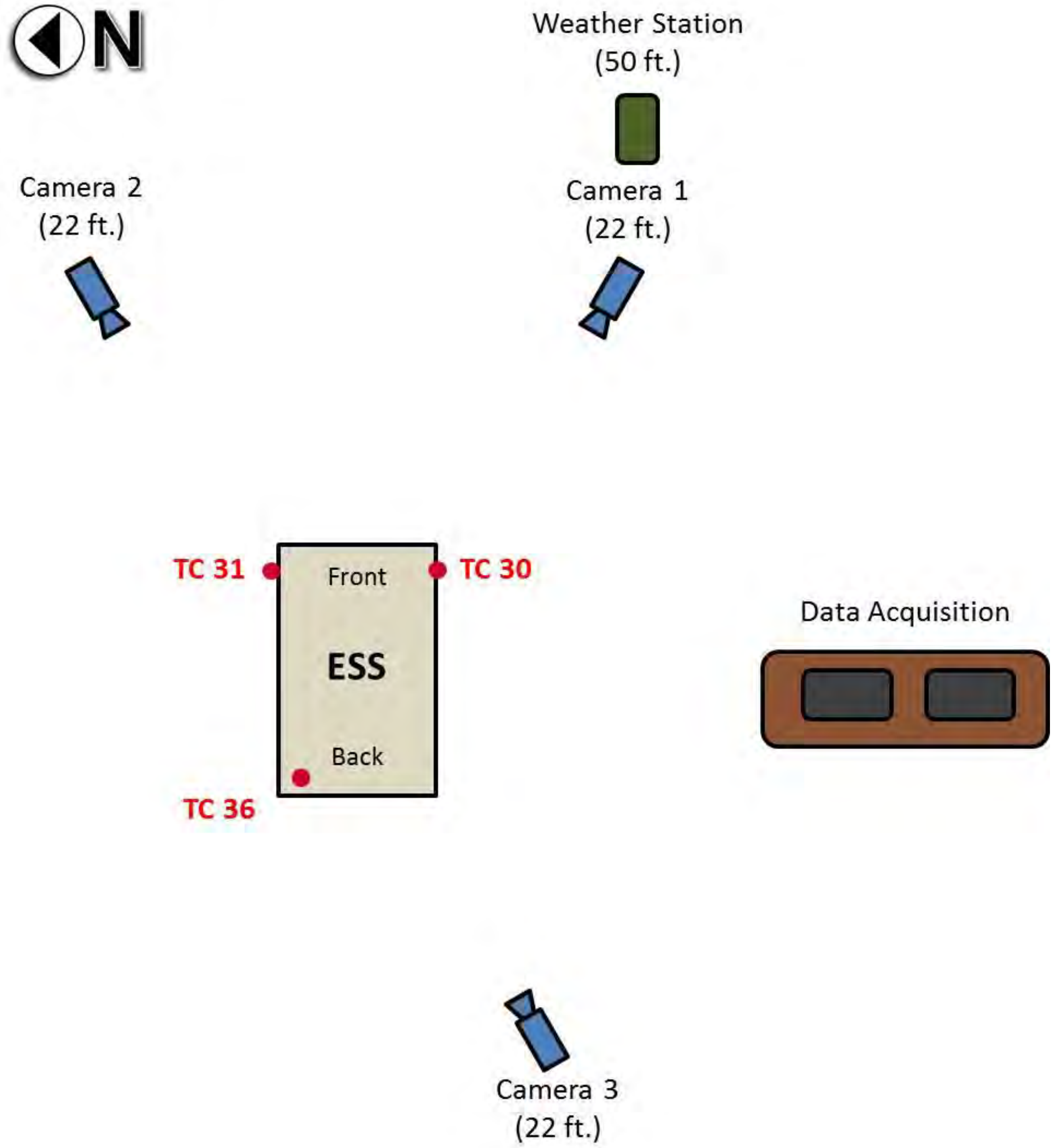

Figure 16 Internal ignition test setup and instrumentation

5.2.2 Internal Failure (Ignition Source)

The initiation method used in the internal ignition test consisted of using six (6) 1/8th-inch diameter 25-watt cartridge heaters, each placed in an interstitial space between the battery cells in Pod 6, as shown in Figure 18. All six heaters were clustered at the center of the module.

At the start of the test, current was applied to all six heaters simultaneously, resulting in an almost simultaneous thermal runaway of ten (10) cells. This method of inducing thermal runaway deliberately overwhelmed the passive propagation protection mechanisms of the Powerpack. After a minimum of ten cells had audibly undergone thermal runaway, the heaters were turned off.

5.2.3 Temperature Measurements

Temperatures were monitored with the same make and model 1/8th-inch diameter bare bead Type K Chromel-Alumel thermocouples as described in the external ignition testing. Thirty-seven (37) thermocouples were placed on the exterior surfaces of the Powerpack, at select battery pods inside the Powerpack, and within the Powerpack cabinet and exhaust manifold. Twelve (12) thermocouples were installed in the initiator pod (pod 6), as shown in Figure 17 and six (6) thermocouples were placed inside pod 5 and pod 7, the adjacent pods to the initiator pod, as shown in Figure 18 and Figure 19. In addition, two (2) thermocouples were placed on the top cover of pod 6, two (2) on the bottom of the cover of pod 7 and two (2) on the top of the cover of pod 5, to monitor the spread of fire, if any, outside of the initiator pod, as shown in Figure 20. Four (4) thermocouples were placed inside the Powerpack cabinet in the exhaust manifold and another thermocouple was placed at the exhaust vent, as shown in Figure 20. Two (2) final thermocouples were installed on the exterior surface of the Powerpack cabinet on the right and left sides of the Powerpack, as shown in Figure 16. The location of each thermocouple is provided in Table 4.

Table 4 Summary of Thermocouple Locations for Internal Ignition Testing

TC	Measurement Location	TC	Measurement Location	TC	Measurement Location
0	Interior Pod #6	12	Interior Pod #5	24	Pod #6 Cover
1	Interior Pod #6	13	Interior Pod #5	25	Pod #6 Cover
2	Interior Pod #6	14	Interior Pod #5	26	Pod #7 Cover
3	Interior Pod #6	15	Interior Pod #5	27	Pod #7 Cover
4	Interior Pod #6	16	Interior Pod #5	28	Pod #5 Cover
5	Interior Pod #6	17	Interior Pod #5	29	Pod #5 Cover
6	Interior Pod #6	18	Interior Pod #7	30	Exterior Left
7	Interior Pod #6	19	Interior Pod #7	31	Exterior Right
8	Interior Pod #6	20	Interior Pod #7	32	Exhaust Manifold
9	Interior Pod #6	21	Interior Pod #7	33	Exhaust Manifold
10	Interior Pod #6	22	Interior Pod #7	34	Exhaust Manifold
11	Interior Pod #6	23	Interior Pod #7	35	Exhaust Manifold
				36	Exhaust Vent

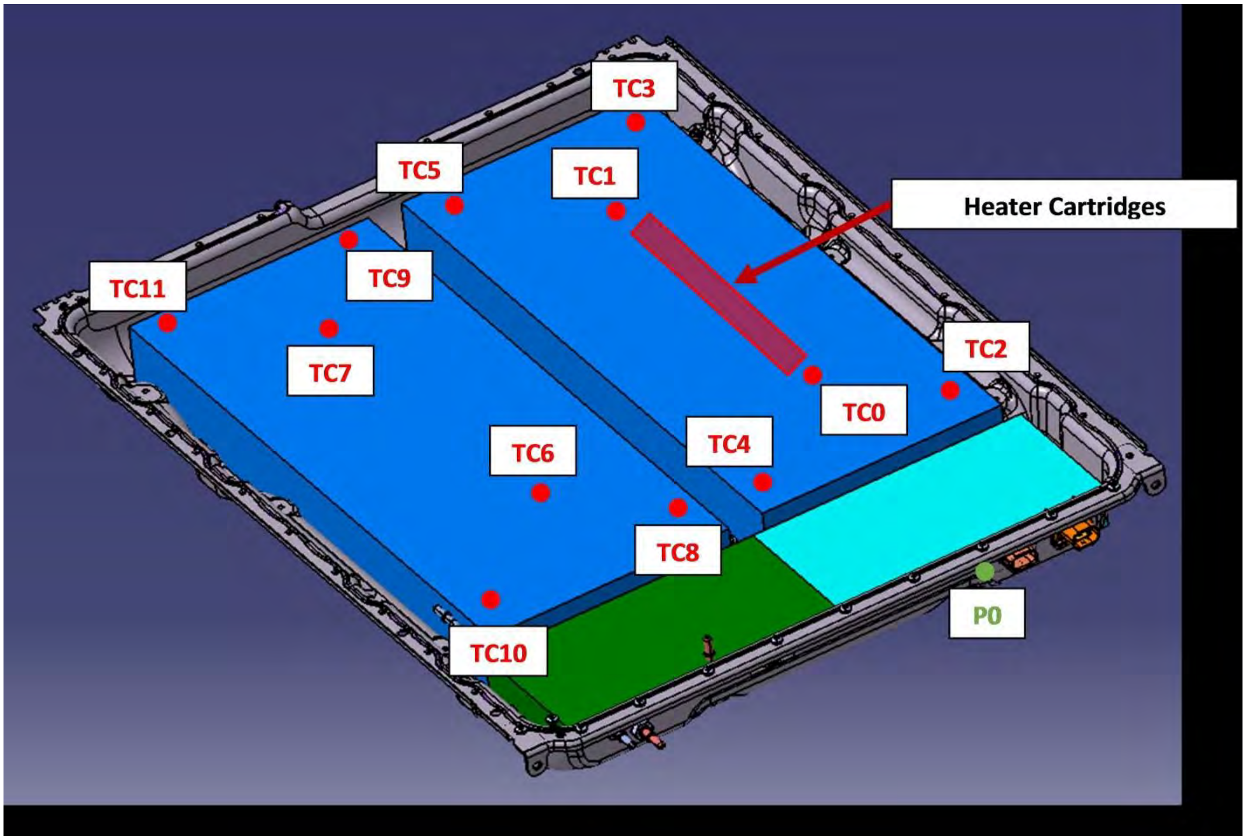

Figure 17 TC, pressure measurement and heater cartridge locations within Pod 6

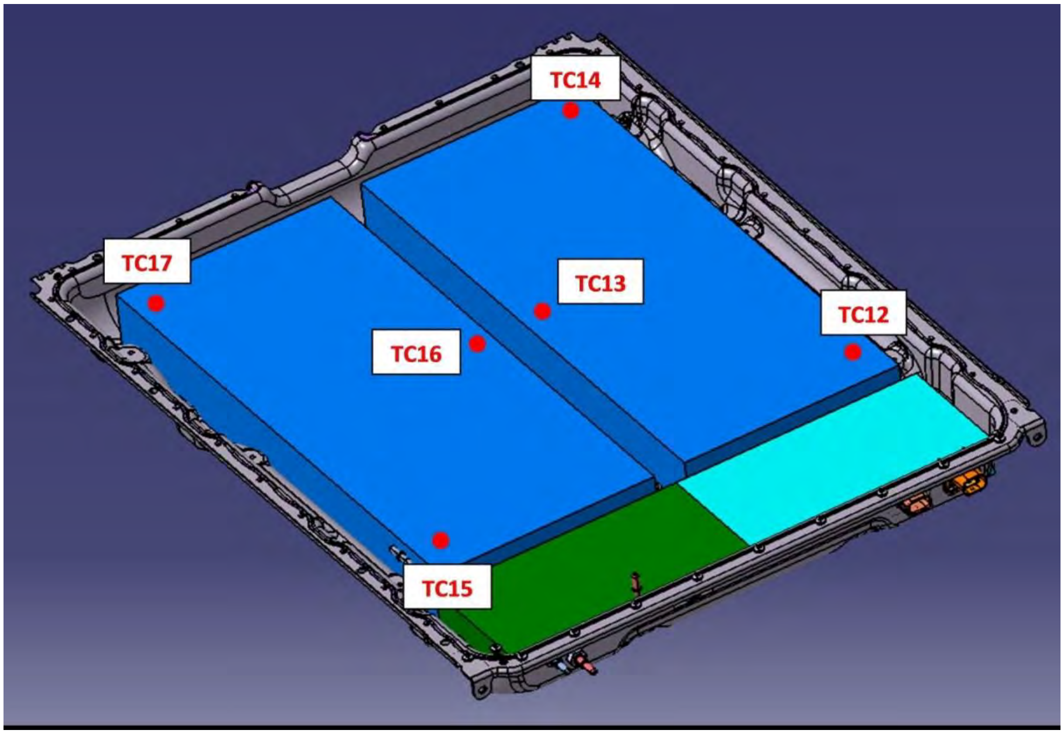

Figure 18 TC measurement locations within Pod 5

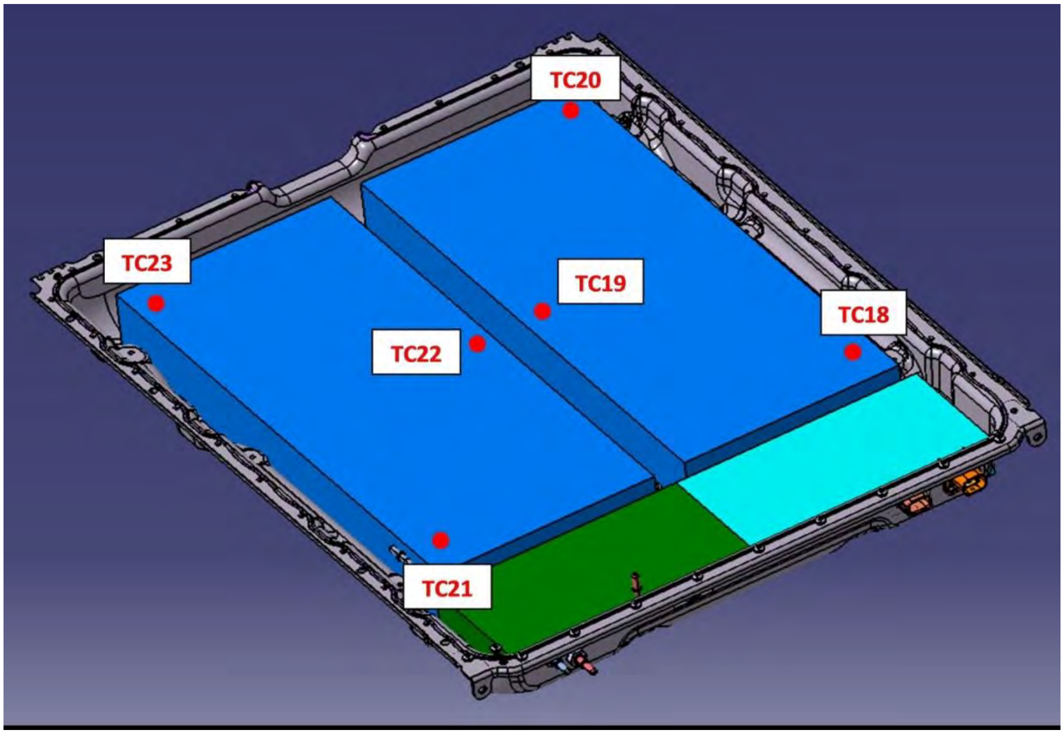

Figure 19 TC measurement locations within Pod 7

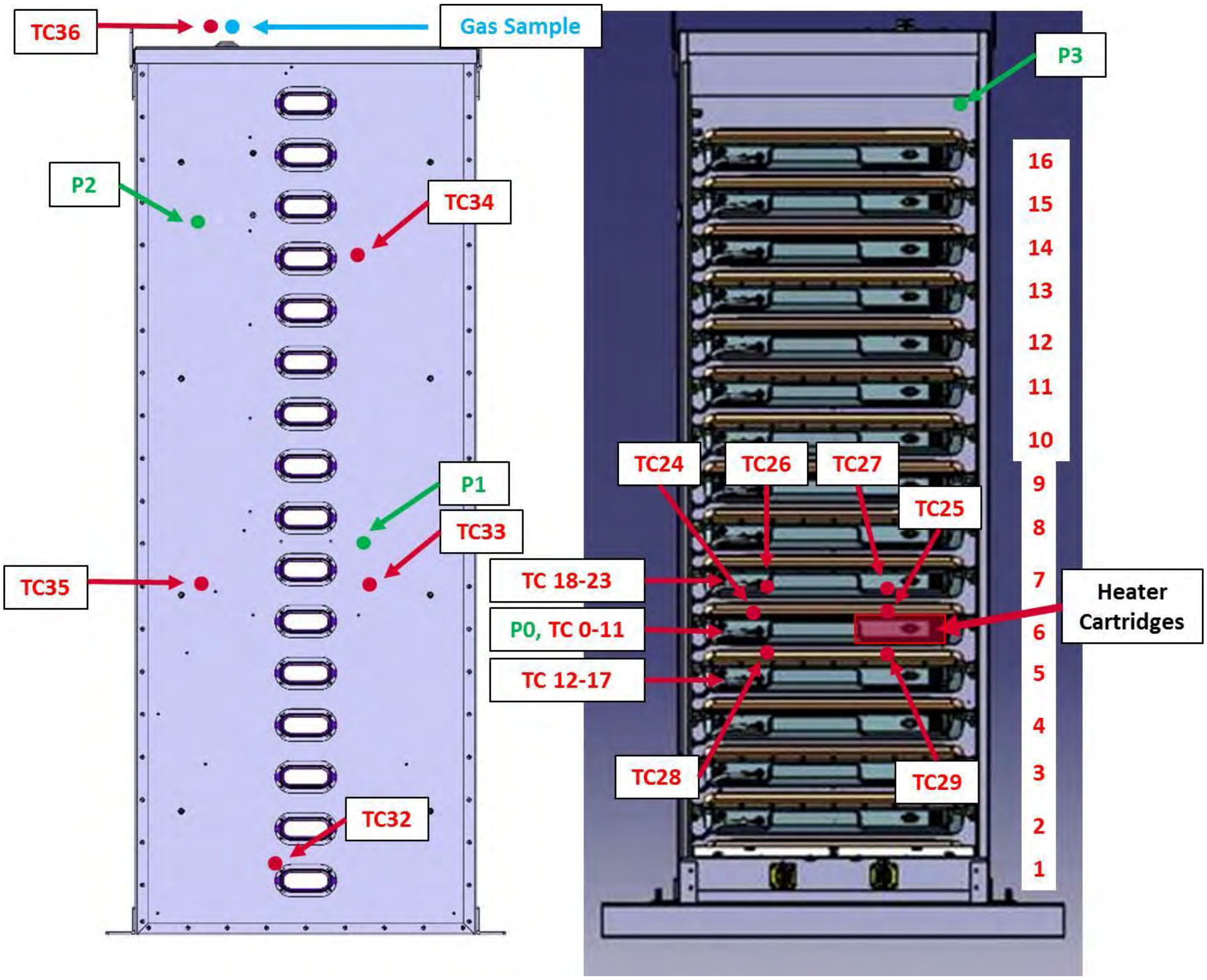

Figure 20 TC, gas sampling, and pressure measurement locations inside the Powerpack cabinet

5.2.4 Pressure Measurements

Pressures were monitored with the same make and model pressure transducers described in the external ignition testing. The transducers were positioned inside the Powerpack cabinet, as illustrated in Figure 20, as well as in the exhaust manifold and at the initiator pod to detect any overpressures in these locations during the test. The location of the pressure transducers is provided in Table 5.

Table 5 Summary of Pressure Measurement Locations for Internal Ignition Testing

Pressure Transducer	Measurement Location	Pressure Transducer	Measurement Location
0	Pod #6	2	Exhaust Manifold
1	Exhaust Manifold	3	Front Cabinet

5.2.5 Products of Combustion Gas Sampling

Select products of combustion were monitored at the exhaust vent of the Powerpack, as shown in Figure 20, with the same instrumentation as described in the external ignition test (see Section 5.1.5).

5.2.6 Weather Meter

Weather conditions were monitored with the same instrumentation as described in the external ignition test (see Section5.1.6). The weather meter was positioned approximately 50 feet away from the Powerpack, as shown in Figure 16.

5.2.7 Data Acquisition System

The same data acquisition unit described in the external ignition test (see Section 5.1.7) was utilized to collect the test data during the internal ignition test.

5.2.8 Still Photography and High Definition Video

Still images and high definition videos were recorded throughout the internal ignition test. Video cameras were positioned around the Powerpack to get a 360-degree view of the Powerpack at all times, as illustrated in Figure 16. Still images were taken periodically during the test to capture the test progression.

6 Test Results

Exponent witnessed the full-scale testing and reviewed the data collected to observe the behavior of the Powerpack when it is involved in a fire scenario. The tests were performed at the Tesla test facility on November 5, 2015, under the guidance and direction of FPRF and Exponent. Two tests were conducted; one external ignition test and one internal ignition test. For each test the Powerpack was positioned out in open air, on a noncombustible surface, as it would be typically installed in outdoor installations. The Powerpacks that were tested were 100 kWh units charged to 100% SOC, as described previously in Section 4.

6.1 External Ignition Testing

The external ignition test was conducted on November 5, 2015, at approximately 9:30 a.m. At the start of the test, the weather was overcast, with temperatures of approximately 35 °F and a relative humidity of approximately 65%. The wind was out of the west-southwest with a wind speed of 1.5 miles per hour (mph). Over the course of the three hour and forty-five minute test duration, the temperature slowly rose to 43 °F, the weather remained mostly overcast with no precipitation, the relative humidity dropped slowly to approximately 55%, and the wind remained calm out of the west or west-southwest, with speeds between 0 and 2.2 mph. The following sections summarize the data collected during the test.

6.1.1 Test Observations

Table 6 summarizes the key events observed by Exponent during the test. Images at significant test times are provided in Figure 21 through Figure 28. In general, the test demonstrated that an external heat source, such as a propane burner, could induce the Powerpack into thermal runaway and result in the ignition of electrolyte material and other combustibles within the Powerpack cabinet. Popping sounds from the interior of the Powerpack were heard throughout the test. White smoke was observed consistent with the release of flammable electrolyte material from individual cells. However, no violent projectiles, explosions, or bursts (other than an overpressure release of the thermal door refrigerant) were observed during the test while the Powerpack was exposed to the burners, while it was in a free burn state, or after flames were no longer visible. Flames remained mostly confined to the Powerpack itself. Weaker flames emanated from the exhaust vent of the Powerpack, the front thermal door grill, and around the front thermal door seal at varying times throughout the test.

Table 6 External Ignition Test: Key Observations

Time (hr:min:sec)	Event
- 0:03:00	Start data acquisition and video cameras
0:00:00	Ignite burner
0:35:12	First smoke (white and/or grey) observed from Powerpack
0:45:02	Pop sound heard from Powerpack cabinet (pops)
0:46:54	Sustained flames first observed at exhaust vent
0:47:09	Sustained flames first observed at back Powerpack panel
0:47:57	Sustained flames first observed at the front door
0:48:00	Steady pops heard from Powerpack starting at this time until 3:10:50 consistent with cell thermal runaway
1:00:00	Burners “OFF”, jet fire exiting exhaust vent, flames coming out of the front door grill
1:05:00 – 1:10:00	Material ejected from exhaust vent
1:08:00	Fire inside Powerpack only involving combustibles near the top; no burning of materials near the bottom of the Powerpack
1:11:00	Jet flame at exhaust vent weakens intermittently
1:14:30	Jet flame at exhaust vent increases in intensity
1:20:05	Overpressure sound consistent with refrigerant failure
1:27:00	Jet flame at exhaust vent weakens intermittently
1:27:45	Smoke from Powerpack turns darker
1:29:45	Flames inside Powerpack moving lower
1:32:05	Fire inside Powerpack intensifying
2:00:00	Fire inside Powerpack intensifying
2:30:00	Fire inside Powerpack steady
2:33:30	Fire inside Powerpack decreasing in intensity
3:00:00	Fire insides subsiding, weak flames observed out the front door and exhaust vent
3:10:50	Last pop heard from Powerpack
3:30:00	Fire continues to decrease in intensity
3:41:10	Last visible flame out
3:45:00	Cameras and data acquisition off

[redacted]

Figure 21 External test screenshot: start of test, burners “ON”

Figure 22 External test screenshot: test time = 1 hour, fire emanating from the front door and exhaust vent, pops consistent with battery cell thermal runaway heard steadily, burners turned “OFF”

[redacted] [redacted]

Figure 23 External test screenshot: test time = 1 hour 30 minutes, flames at front door and exhaust vent intermittently decreasing in intensity

[redacted]

Figure 24 External test screenshot: test time = 2 hours, fire inside the Powerpack intensifying

[redacted]

[redacted]

[redacted]

Figure 25 External test screenshot: test time = 2 hours 30 minutes, fire inside the Powerpack intensifying

Figure 26 External test screenshot: test time = 3 hours, fire inside the Powerpack subsiding

Figure 27 External test screenshot: test time = 3 hours 30 minutes, fire inside the Powerpack burning itself out

Figure 28 External test screenshot: end of test, fire is out.

6.1.2 Temperatures and Heat Flux Measurements

Temperature and heat flux measurements were collected during the external ignition test and plots for each as a function of time are provided in Appendix A.

The maximum temperatures measured on the interior thermocouples installed within pods 1, 2, 3, and 4 were all consistent with direct flame contact, with temperatures in excess of 2,000 °F. The maximum temperatures measured on the exterior of the Powerpack cabinet were much lower. TC30, positioned on the left side of the Powerpack opposite of the burner, measured a maximum surface temperature of approximately 150 °F and TC33, positioned on the front door measured a maximum temperature of approximately 460 °F.

An analysis of the heat flux measurements yielded values inconsistent with observations of the test, the fire progression and its severity. As such, the data collected for heat fluxes was not considered in this fire hazard assessment.

6.1.3 Pressure Measurements

Pressure was monitored at the Powerpack exhaust manifold throughout the test and a plot of the pressure as a function of time is provided in Appendix B. No pressure build-up or release consistent with an overpressure event occurring inside the Powerpack cabinet was observed in the data or during the test.

6.1.4 Gas Sampling Measurements

Select products of combustion were monitored at the Powerpack exhaust vent throughout the test and a plot of CO and HF levels as a function of time are provided in Appendix C.

CO was first detected approximately 2.5 minutes after the burners were turned on at 10 ppm. The value steadily rose to its maximum value of 50 ppm approximately four minutes after the burners were turned on. The CO detected then slowly decreased to 0 ppm approximately 30 minutes after the burners were turned on and remained at 0 ppm for the remainder of the test. As such, the production of CO, as detected at the exhaust vent, only occurred while the external burner was on and CO was not detected while the Powerpack underwent self-sustaining combustion (i.e., the external burner was off).

No Cl_2 or CH_4 were detected in any quantities during the test.

HF was detected two minutes after the burners were turned on at 2 ppm. The value of HF steadily rose from 2 ppm to its maximum value of 100 ppm approximately 30 minutes after the burners were turned on. The maximum range of the HF detector was 100 ppm. All HF data after 30 minutes was "over range" of the HF detector, indicating HF levels were greater than 100 ppm for the duration of the test.

6.1.5 Post Test

Following the test, it was determined that all of the energy pods were damaged and there was no stranded energy within the Powerpack.

6.2 Internal Ignition Testing

The internal ignition test was conducted on November 5, 2015, at approximately 2:45 p.m. At the start of the test, the weather was sunny, with temperatures of approximately 49 °F and a relative humidity of approximately 32%. The wind was out of the west with a wind speed of 1.3 mph. Over the course of the hour and a half test duration, the temperatures fluctuated between approximately 45 and 54 °F, the weather remained mostly sunny with no precipitation, the relative humidity remained between 30 and 32%, and the wind remained calm out of the west or west-southwest, with speeds between 0.1 and 2.5 mph. The following sections summarize the data collected during the test.

6.2.1 Test Observations

Table 7 summarizes the key events observed during the test. Images at significant test times are provided in Figure 29 through Figure 31. In general, the internal ignition test demonstrated that heater cartridges installed within the battery pack could induce multiple battery cells into thermal runaway; however, the failures did not result in thermal runaway of battery cells outside of the initiator pod. Popping sounds from the interior of the Powerpack were heard sporadically throughout the test, and steadily for approximately 15 minutes. White smoke was observed consistent with the release of flammable electrolyte material from individual cells. However, no violent projectiles, explosions, or bursts were observed during the test. In addition, no flames or other signs of fire, other than smoke production, were observed. The event stopped on its own without thermal runaway occurring outside of the initiator pod.

Table 7 Internal Ignition Test: Key Observations

Time (hr:min:sec)	Event
- 0:01:30	Start data acquisition and video cameras
0:00:00	Turn on heater cartridges
0:12:35	Pop sound heard from Powerpack cabinet (pops)
0:15:10	First smoke (white and/or light grey) observed at exhaust vent
0:27:13	Light smoke continues at exhaust vent
0:29:35	Smoke at exhaust vent increasing
0:33:07	Pop heard from Powerpack cabinet
0:34:28	Smoke at exhaust vent increasing, getting darker (grey)
0:34:56	Pop heard from Powerpack cabinet
0:35:30	Smoke at exhaust vent increasing, getting darker (grey)
0:36:22	Steady pops heard from Powerpack starting at this time until 0:45:01 consistent with cell thermal runaway
0:38:34	Heater cartridges turned off.
0:45:01	Last pop heard from Powerpack
0:49:30	Smoke production at exhaust vent subsiding
1:00:00	Smoke production at exhaust vent subsiding
1:15:00	Smoke production at exhaust vent subsiding
1:30:00	Smoke production at exhaust vent barely visible, cameras and data acquisition turned off, test terminated

[redacted]

Figure 29 Internal test screenshot: start of test, heater cartridges “ON”

[redacted] [redacted]

Figure 30 Internal test screenshot: peak smoke production approximately 35 to 40 minutes after the heater cartridges were turned “ON”

[redacted]

Figure 31 Internal test screenshot: end of test

6.2.2 Temperatures

Temperatures were collected during the internal ignition test and plots of the temperatures as a function of time are provided in Appendix D.

The maximum temperatures were measured in the initiator pod, Pod 6. In the module with the heater cartridge, maximum temperatures were recorded in excess of 2,000 °F for approximately two seconds at TC1 , which was one of the thermocouples installed closest to the heater cartridges and may have come in contact with a brief (2 second) flame as the cell underwent thermal runaway. The rest of the thermocouples within the module recorded temperatures up to approximately 1,550 °F. In the second module within pod 6, the temperatures were lower, with the maximum temperatures between 200 and 400 °F for the six thermocouples installed within that module. The maximum temperatures measured on the adjacent pods, pod 5 and pod 7, were much lower as well. Pod 5 recorded maximum temperatures between 80 and 125 °F and pod 7 recorded maximum temperatures between 80 and 180 °F. TC30, positioned on the left side of the Powerpack cabinet exterior, measured a maximum surface temperature of 70 °F and TC31, positioned on the right side of the Powerpack cabinet exterior, measured a maximum temperature of 60 °F.

6.2.3 Pressure Measurements

Pressure was monitored inside the Powerpack cabinet, exhaust manifold and at the initiator pod throughout the test and a plot of the pressure as a function of time is provided in Appendix E. No pressure build-up or release consistent with an overpressure event occurring inside the Powerpack cabinet or the initiator pod was observed in the data or during the test.

6.2.4 Gas Sampling Measurements

Select products of combustion were monitored at the Powerpack exhaust vent throughout the test and a plot of CO, CH_4, and HF levels as a function of time is provided in Appendix F.

CO was first detected approximately 10.5 minutes after the heaters were turned on at 10 ppm. The value steadily rose to its maximum value of 2,000 ppm approximately 12 minutes after the heaters were turned on, which is the maximum range for the CO detector. The value of CO remained at its maximum detection level of 2,000 ppm from the 12 minute mark until 63.5 minutes after the heaters were turned on. It then slowly decreased for the remaining 30 minutes of the test.

No Cl_2 was detected in any quantities during the test.

CH_4 was first detected approximately 12 minutes after the heaters were turned on. The detector measured CH_4 in percent volume fraction and steadily rose until approximately 36 minutes after the heaters were turned on, to a recorded a maximum percentage of 96.9. This time correlates with when the most cell runaways were observed in the test, as described in Section 6.2.1. It then slowly decreased for the remaining 54 minutes of the test.[82] The elevated CO and CH_4 levels detected after the heater cartridges were turned off and after thermal runaway of the cells had ceased indicates that CO and CH_4 can still be vented from the cells as they are cooling and obvious signs of thermal runaway (i.e., popping) are no longer observed.

HF was detected approximately 21 minutes after the heater cartridges were turned on at 1 ppm. The value of HF steadily rose from 1 ppm to its maximum value of 26 ppm approximately 46 minutes after the heater cartridges were turned on. The value plateaued at 26 ppm for 2 additional minutes (minute 47 and 48), then steadily declined back down to a value of 2 ppm by the end of the test.

6.2.5 Post Test

Following the test, it was determined that only one of the energy pods (the initiator pod) was damaged. The other 15 pods remained operational and had a full SOC. The energy pods were discharged and the Powerpack was recycled.

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[82] During thermal runaway of the battery cell methane can be released. During the external ignition test no methane was detected at the exhaust vent, likely a result of the fire inside the ESS igniting any off gassing methane from the cells. However during the internal ignition test, no flames were observed and the released methane vented into the exhaust manifold and out the exhaust vent. Methane was also detected in previous testing programs, such as during the FAA's fire tests of cylindrical battery cells.

7 Key Findings

The following section is a discussion of the data and observations collected during the literature review and full-scale testing and supplements the presentation of the data in Sections 2 and 6.

7.1 Literature Review Summary

Li-ion ESSs are becoming more popular and are posed to be installed in many occupancies across the country, including commercial and residential buildings. However, little public knowledge is known about the fire hazards they pose to those buildings and their occupants.

7.1.1 Electrical, Fire, and Building Codes

Several gaps were identified in a review of electrical, fire, and building codes typically adopted in the United States as they relate to ESSs. These gaps are predominantly related to sections of the codes categorizing battery systems based on the volume of liquid electrolyte, which is not appropriate for assessing Li-ion ESS hazards. In addition, NFPA 1 provides contradictory guidance regarding thermal runaway protection for Li-ion battery systems, while the IFC does not require it at all. These gaps can be corrected with changes to the sections identified at the ICC code action hearings and NFPA technical committee meetings, some of which are currently being undertaken. In addition, the next edition of the NEC, the 2017 edition, is proposed to have a new article (Article 706) dedicated to ESSs. This addition should further assist installers, AHJs, and manufacturers with navigating the electrical installation requirements for these systems. However, it should also be noted that guidance for Li-ion battery system installations is currently within the codes and has been since 2006, most notably Section 608 of the IFC and since 2009, Chapter 52 of NFPA 1. Many of the concerns over the installation of battery systems could be addressed by local jurisdictions adopting more current editions of the ICC codes.

7.1.2 Design Standards

The ESS assessed in this testing program was listed to UL 1741, UL 1973, and IEC 62109 and was designed to be compliant with UL 9540 and IEC 62619, currently under development. UL

1973 requires stationary battery systems to meet two fire tests: one originating internally at the battery cell level and one externally by means of a hydrocarbon pool fire.

7.1.3 ESS Fires

Real world experience with Li-ion ESS fire incidents are limited, likely stemming from the early stage of adoption that these systems are currently in. Only one case was identified in the public records where a Li-ion ESS was involved in a fire; however, the details of that fire are not known, as requests for more information for public sources have not yielded any additional details. Previous research on other large format Li-ion batteries had demonstrated that the batteries did not significantly add to the HRR of the fire, that the fires can be extinguished with large amounts of water, the batteries can pose a projectile hazard when designed with cylindrical 18650 cells, but do not pose that hazard with polymer or pouch style cells, that toxic compounds such as CO_2, NO_x, HCN, HCl, CO, and HF can be produced during the fires, water samples collected after extinguishing Li-ion battery fires can contain concentrations of fluoride and chloride, and that no electrical hazards exist for personnel suppressing a battery fire from current leakage through the hose stream provided they are standing at specified standoff distances.

7.1.4 Knowledge Gaps

As stated in Section 2, the following gaps in the knowledge base for commercial and residential Li-ion ESSs have been identified:

1. No public fire test data demonstrating the fire behavior of ESSs.
2. Limited public fire test data related to large format battery packs with cylindrical design utilized either in vehicles or storage systems.
3. No fire test data or real world fire incidents involving residential or commercial Li-ion ESSs illustrating the hazards (projectiles, heat release, toxic gas production) to first responders and/or the best practices for fire department operations.
4. No Li-ion ESS guidance in the IRC.
5. Limited real world fire incidents involving large-scale (grid size) ESSs.

6. Some sections of the IBC, IFC, and NFPA 1 are confusing, as only the volume of the electrolyte (a requirement for older battery chemistries such as lead acid) and not the weight of the Li-ion battery system, is used as a threshold for when certain building or fire code requirements are necessary. In addition, other agencies, such as the United Nations and DOT, have other methods for defining and categorizing batteries. Many of these code sections are presently being revised and could be addressed by the next published code set.

7. NFPA 1 provides contradictory guidance regarding thermal runway protection for Li-ion battery systems, while the IFC does not require thermal runaway protection for Li-ion battery systems at all. Many of these code sections are presently being addressed and could be resolved by the next published code set.

8. No post-fire incident response and recovery (i.e., overhaul) procedures.

9. No stationary battery system or ESS fire reporting code in NFIRS to assist in analyzing fire incidents and differentiate battery systems from household batteries.

7.2 Test Summary

The following sections highlight the key findings from the full-scale fire tests.

7.2.1 Overall Test Observations

A 400 kW propane burner impinging directly on the side of the Powerpack for approximately 60 minutes was required to achieve self-sustaining thermal runaway in the Powerpack battery pack and ignite interior components within the Powerpack cabinet. The test had a duration of approximately 3 hours and 45 minutes until the fire burned itself out. Flames were observed breaching the cabinet at the front door of the Powerpack and out the top of the Powerpack at the exhaust vent. No projectiles or explosions were observed at any time during either test.

During the internal ignition test, individual battery cells were forced into thermal runaway; however, no flames were observed at any time. Smoke was observed emanating from the Powerpack at the exhaust vent, however, within 1 hour and 30 minutes the smoke had dissipated and the thermal event was over. The Powerpack was designed to stop a single battery cell failure from cascading into a series of thermal runaways of adjacent battery cells, a design safety feature deliberately overwhelmed in this test through the use of multiple heater cartridges. However, the event was still contained within the Powerpack and did not propagate outside of the initial pod where the heaters were installed.

7.2.2 Flame Spread Hazards

Temperature measurements in the external ignition test demonstrated that a fire inside the Powerpack can reach elevated temperatures in excess of 2,000 °F. Exterior temperatures at the Powerpack cabinet were much lower and would not pose a fire spread hazard if the manufacturer recommended clearance distances to combustibles, as specified by the installation manual, are followed. Flames did breach the front door; however, the recommended clearance distance of six feet would likely eliminate any direct flame spread from the front door to nearby combustibles. Given that the unit tested can be installed outdoors, wind conditions could affect any flames emanating from the Powerpack. During these tests, the wind was calm with speeds at or less than 2 mph. As such, the hazard that a high wind scenario could inflict on the flame spread was not directly assessed during these two tests and may warrant further investigation. In addition, a standalone Powerpack was tested in this test program, not a large installation with many Powerpacks installed in an array. As such, the effects, if any, of additional Powerpacks installed within close proximity to one another was not directly assessed during these two tests and may warrant further investigation.

Flames several feet high were observed from the exhaust vent at the top of the Powerpack. The installation manual recommends at least five feet of clearance above the Powerpack. This clearance may not be sufficient if combustible materials are installed above the Powerpack, such as a building canopy or awning. It is recommended that this clearance distance be evaluated when a system is being installed, especially if the installed system is adjacent to a building or structure that has or could have combustibles installed above the Powerpack.

During the internal ignition test the temperatures recorded were much lower, with exterior cabinet surface temperatures only slightly higher than ambient and no observed flames emanating from inside the Powerpack. Based on this test, the flame spread hazard from an internal cell failure for combustibles positioned at the recommended clearance distances away from the Powerpack is negligible.

7.2.3 Products of Combustion Hazards

The release of HF during Li-ion fires is well known and HF was detected in both fire tests. The maximum range for the portable detector utilized in testing was 100 ppm, which was exceeded during the external ignition test after 30 minutes of burner exposure to the Powerpack. During the internal ignition test, the maximum recorded HF was 26 ppm, as less battery cells were involved compared to the external ignition test. Both of these measurements are greater than the recommended exposure levels over an 8 hour period as specified by the Occupational Safety & Health Administration (OSHA). It is recommended that first responders don typical firefighting self-contained breathing apparatus (SCBA) equipment when responding to an outdoor Li-ion battery fire. CO was also detected in both fire tests, though more significantly in the internal ignition fire test. Based on these test results, if installed indoors, additional ventilation of the Powerpack and/or for the room in which it is installed may be required. In addition, this test series only assessed select products of combustion produced during the Powerpack fires, namely HF. Additional testing accounting for other toxic products of combustion may warrant further investigation.

8 Recommendations and Future Work

The following recommendations and possible future work are suggested (Phase II) to further identify and understand the fire hazards of Li-ion ESSs:

- Research studying first responder tactics and suppression for Li-ion ESS fires.
- Research studying post fire incident response and recovery (i.e., overhaul) procedures.
- Heat release rate testing of ESSs.
- Testing to study what effect, if any, severe wind conditions may have on the spread of flames from one ESS to another or to other nearby combustibles.
- Testing to study what effect, if any, an array of ESSs installed within close proximity to one another would have on the spread of flames from one ESS to another or to other nearby combustibles.
- Testing of ESSs inside a compartment to study what effect, if any, a room will have on the fire behavior and potential toxic gas hazards within an enclosure.
- Testing to study different ESS manufacturers' products, battery chemistries, and/or sizes under similar conditions to verify the performance of other ESSs under these fire conditions.
- The addition of a stationary battery or ESS code in NFIRS such that fires in these systems can be differentiated from other battery fires, such as household batteries.
- Resolve the conflicting code sections relating to ESSs.

9 Acknowledgements

The authors would like to thank Tesla for donating the Powerpacks and for their significant efforts during this project.

The authors further thank Kathleen Almand, Executive Director of FPRF, Daniel Gorham, Research Project Manager, and everyone on the FPRF Advisory Panel.

Appendix A: External Ignition Test: Temperature and Heat Flux Plots

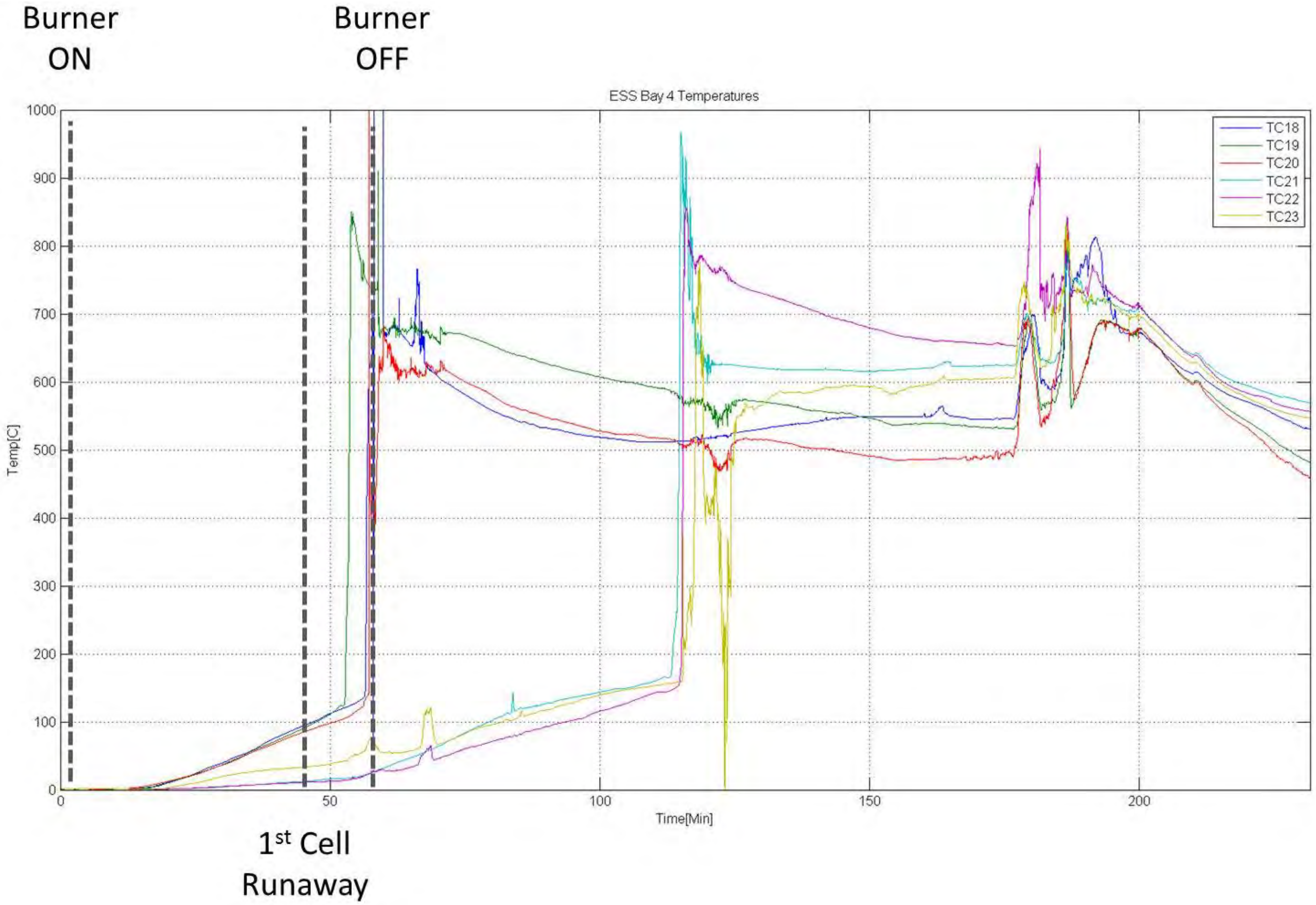

Figure 32 Powerpack Pod 4 temperatures (noise observed in the data is consistent with electrical interference that occurs during voltage leakage from the damaged batteries after thermal runaway)

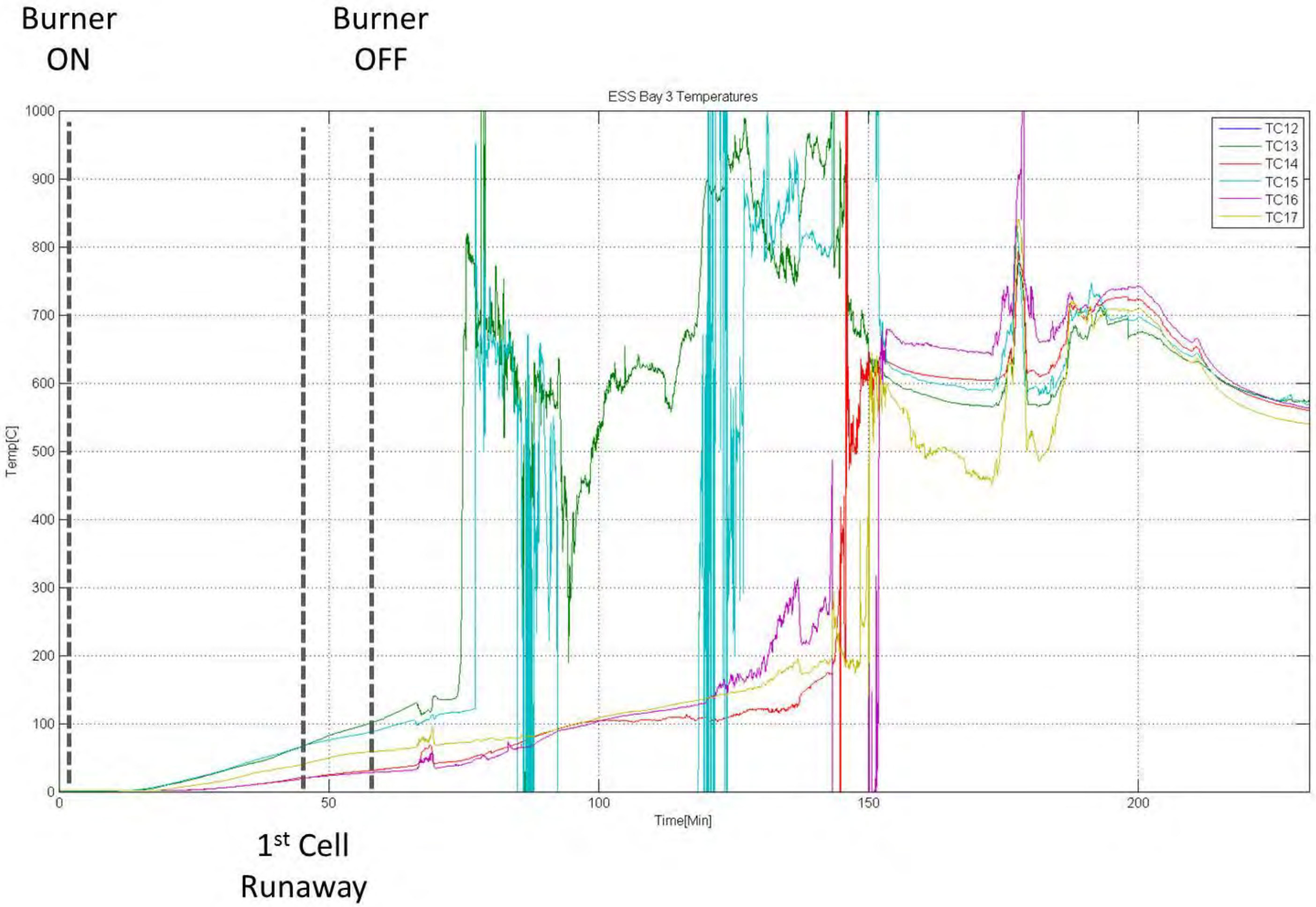

Figure 33 Powerpack Pod 3 temperatures (noise observed in the data is consistent with electrical interference that occurs during voltage leakage from the damaged batteries after thermal runaway)

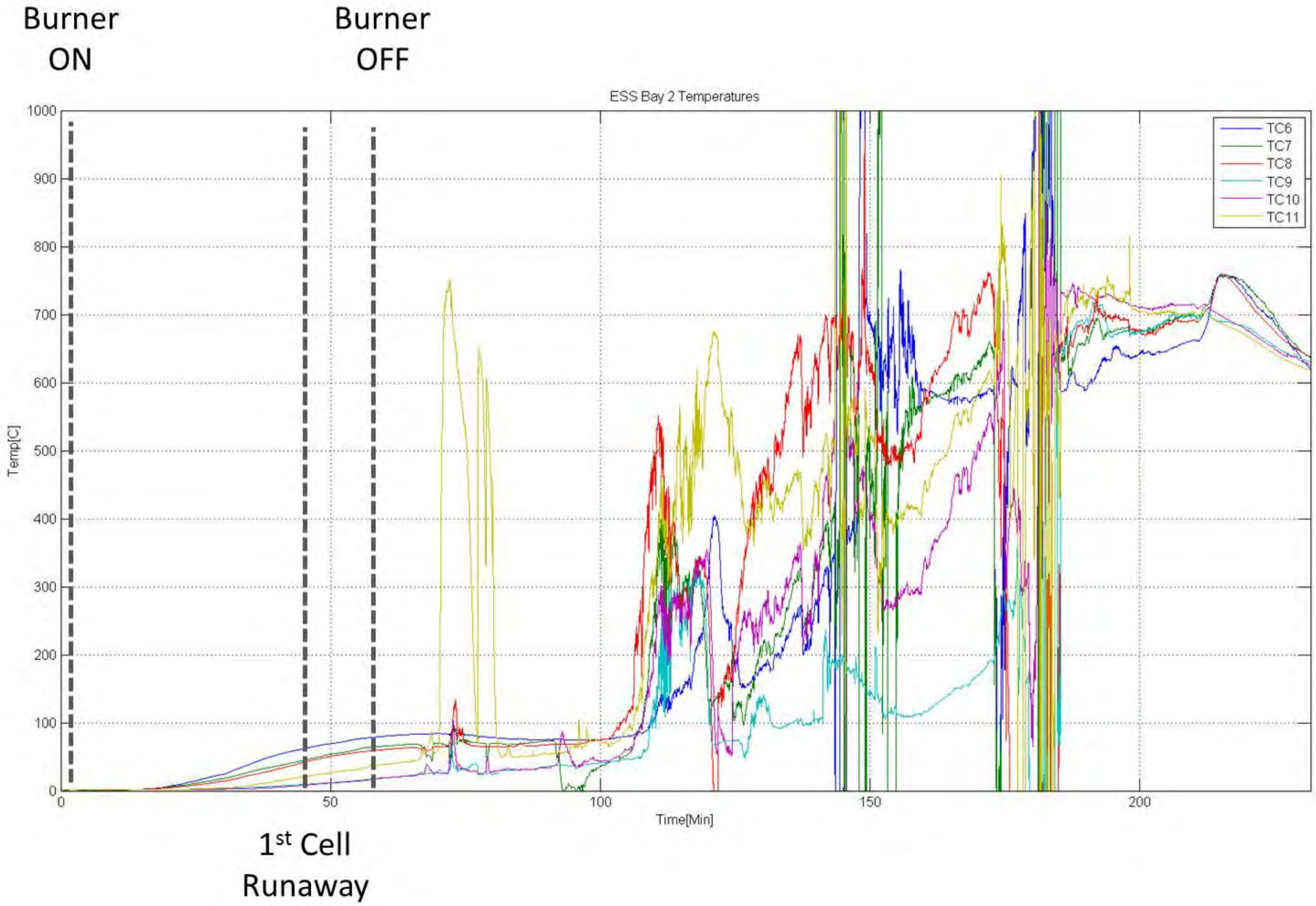

Figure 34 Powerpack Pod 2 temperatures (noise observed in the data is consistent with electrical interference that occurs during voltage leakage from the damaged batteries after thermal runaway)

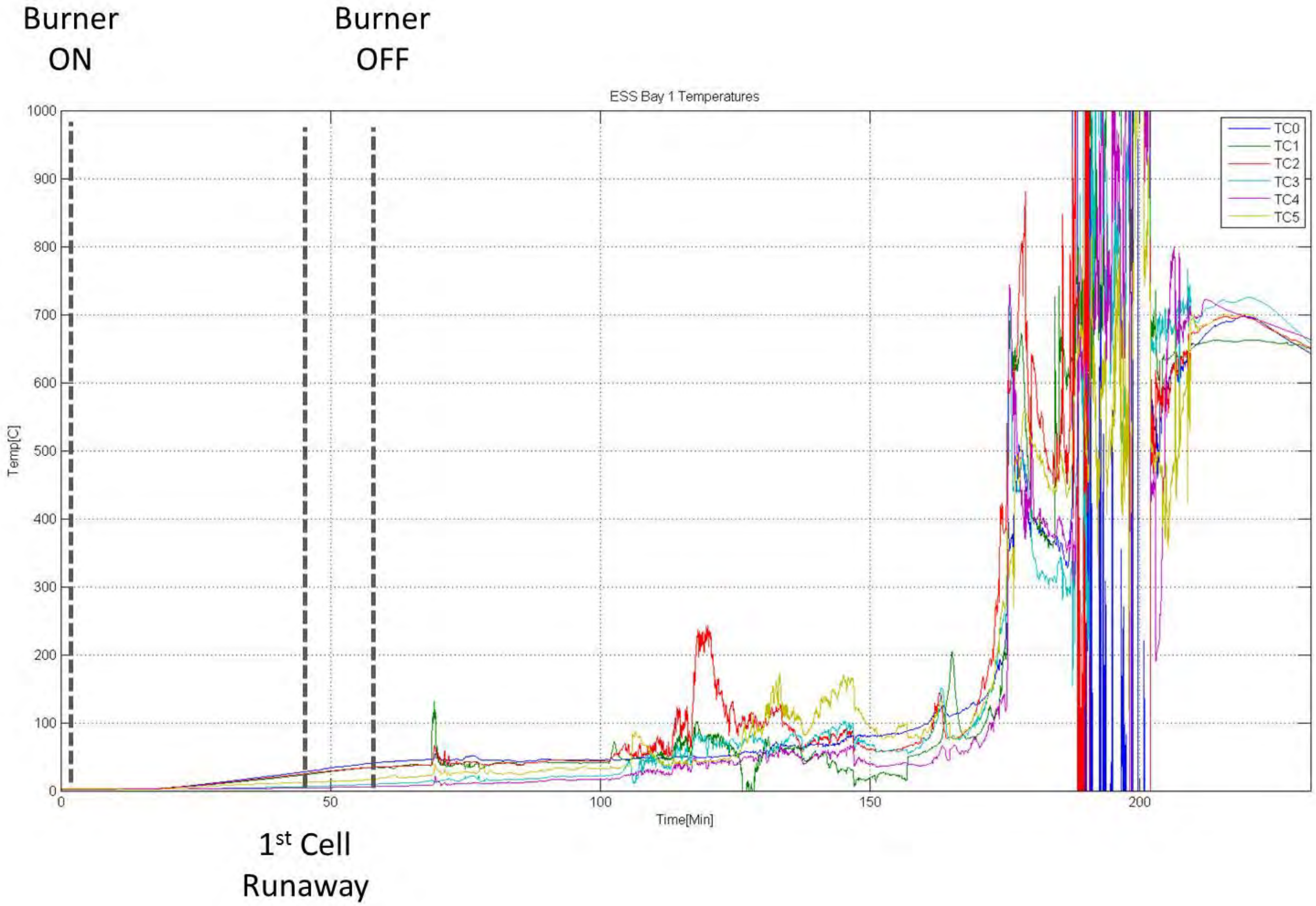

Figure 35 Powerpack Pod 1 temperatures (noise observed in the data is consistent with electrical interference that occurs during voltage leakage from the damaged batteries after thermal runaway)

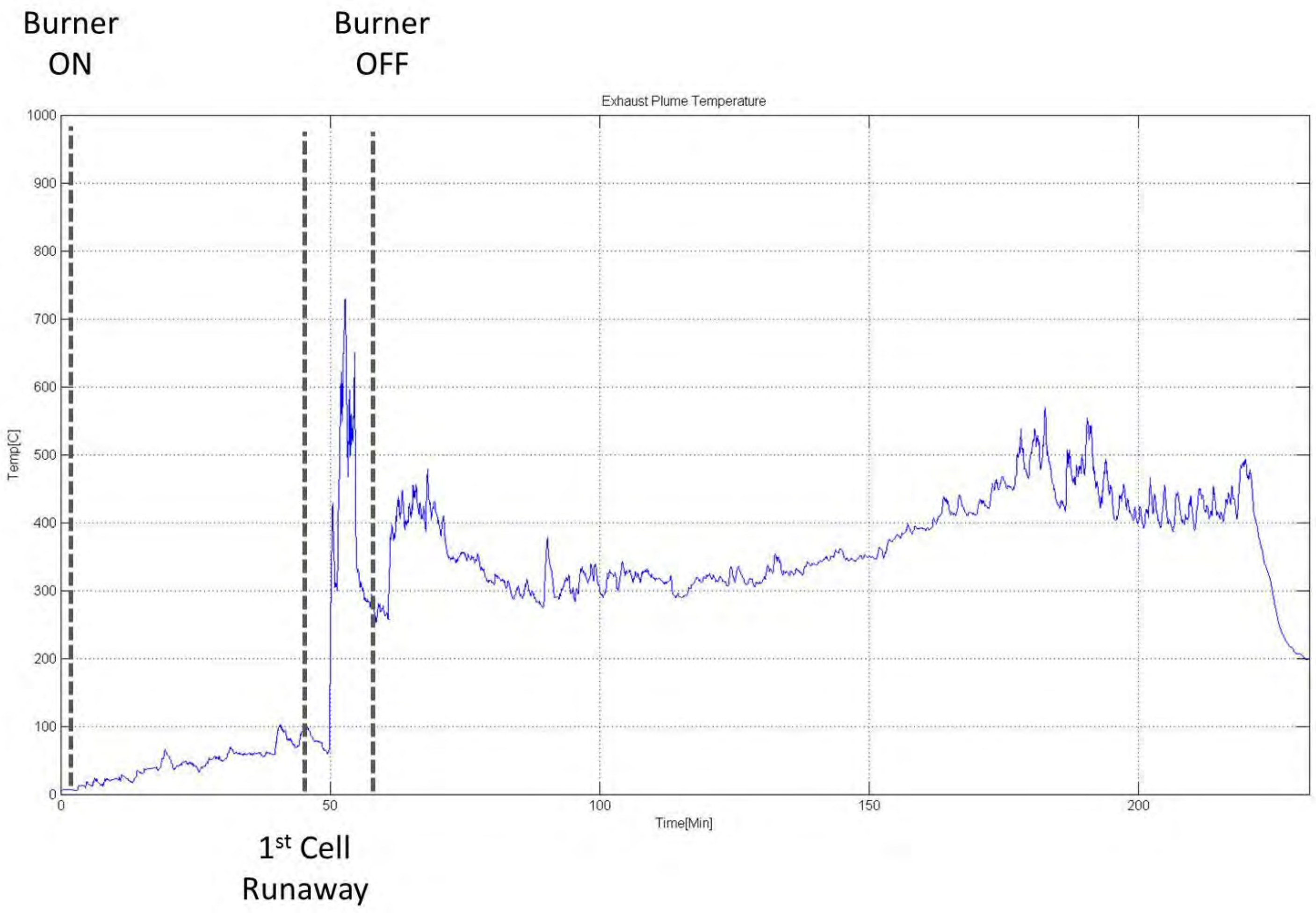

Figure 36 Powerpack exhaust vent temperature

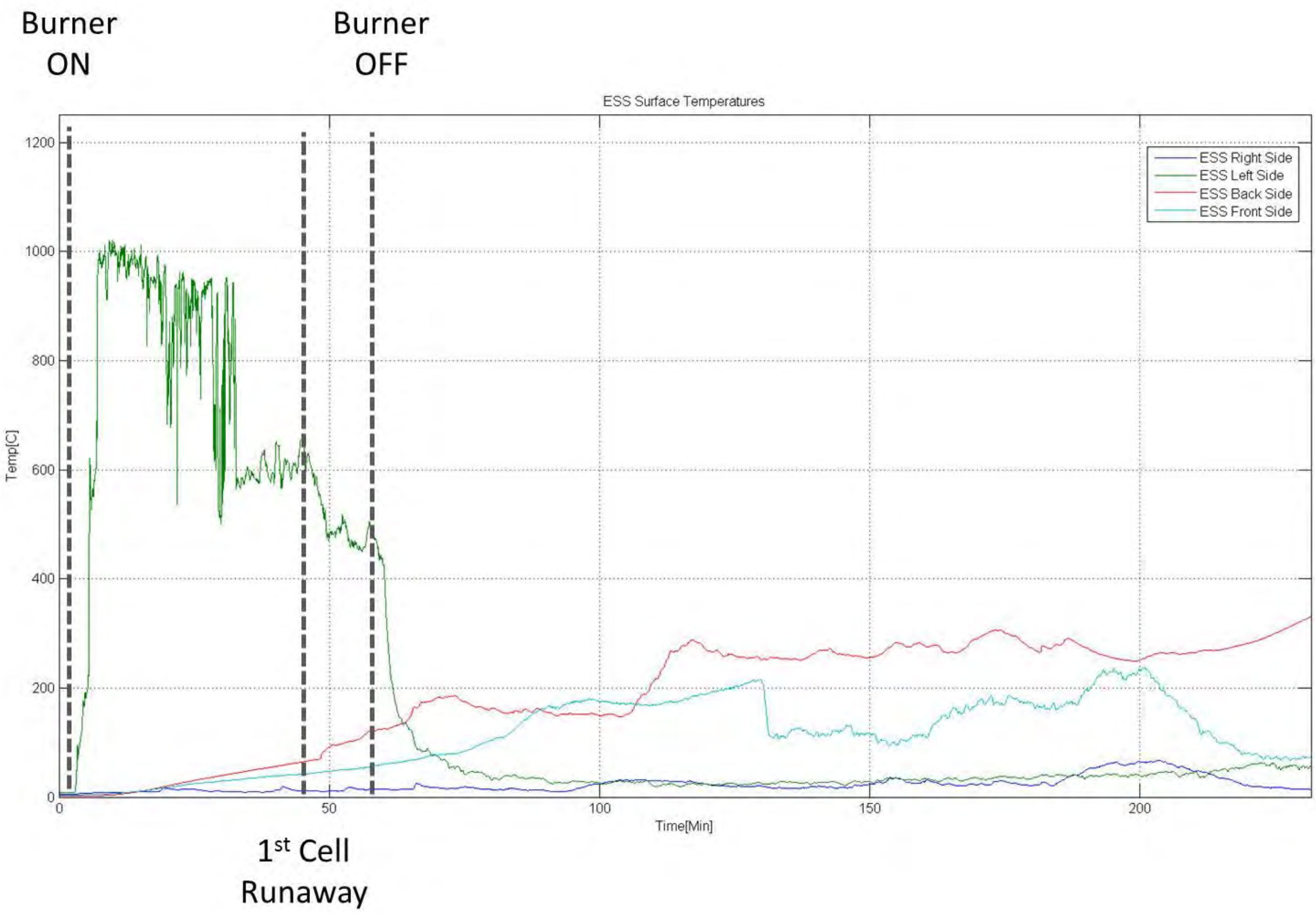

Figure 37 Powerpack external surface temperatures

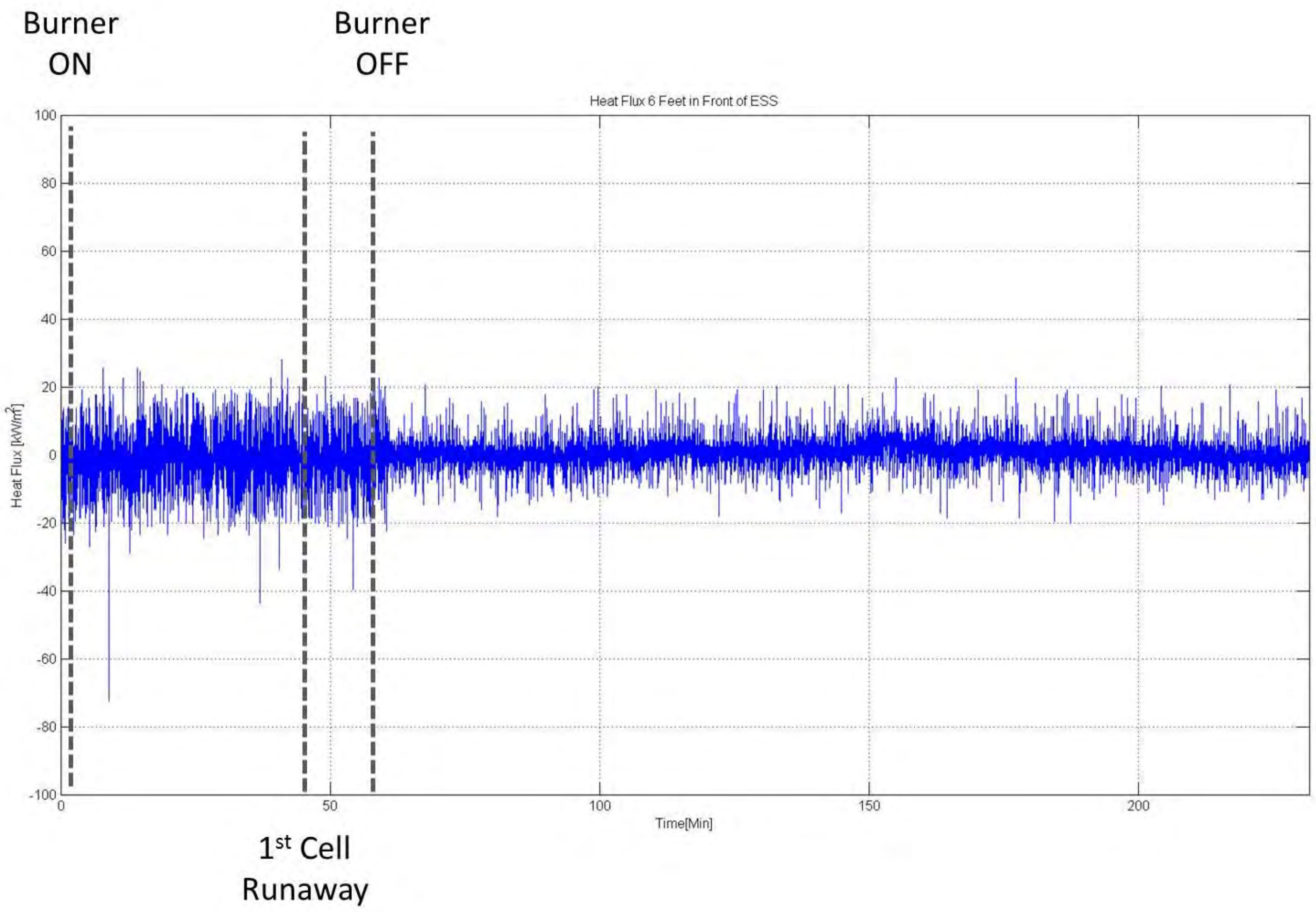

Figure 38 Heat flux measurements at HFG1, 6 feet from the front of the Powerpack

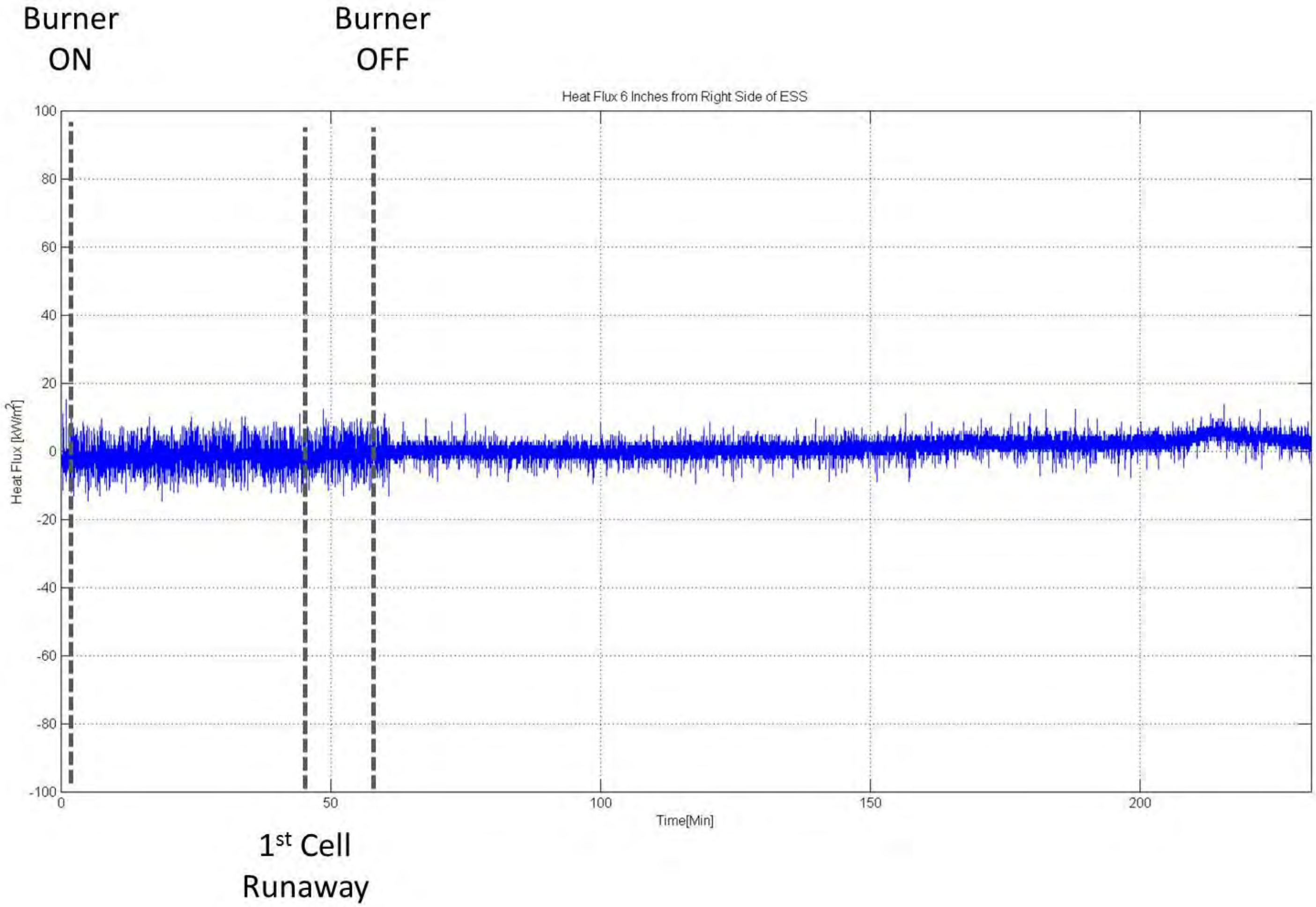

Figure 39 Heat flux measurements at HFG2, 6 inches from the side of the Powerpack

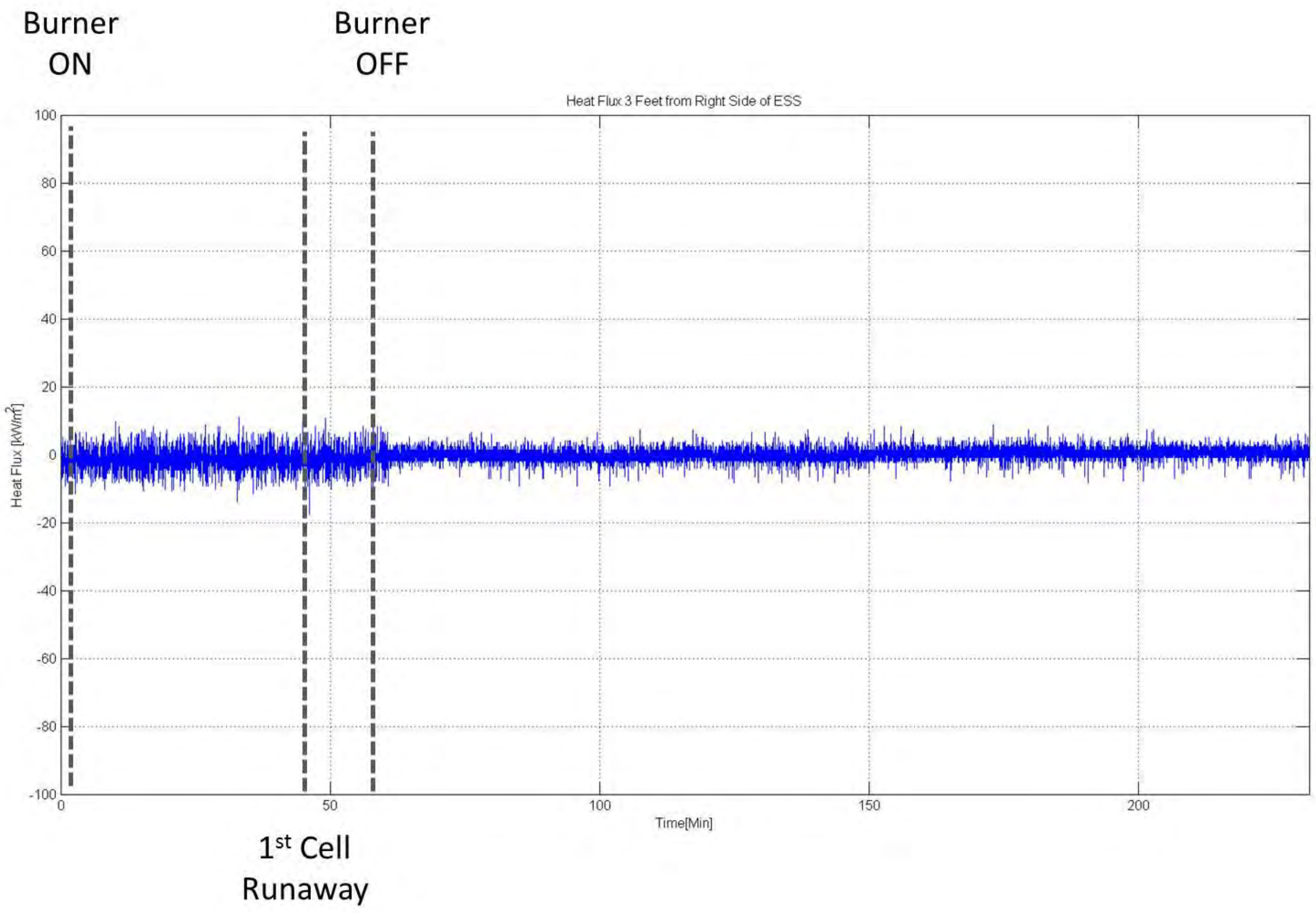

Figure 40 Heat flux measurements at HFG3, 3 feet from the back of the Powerpack

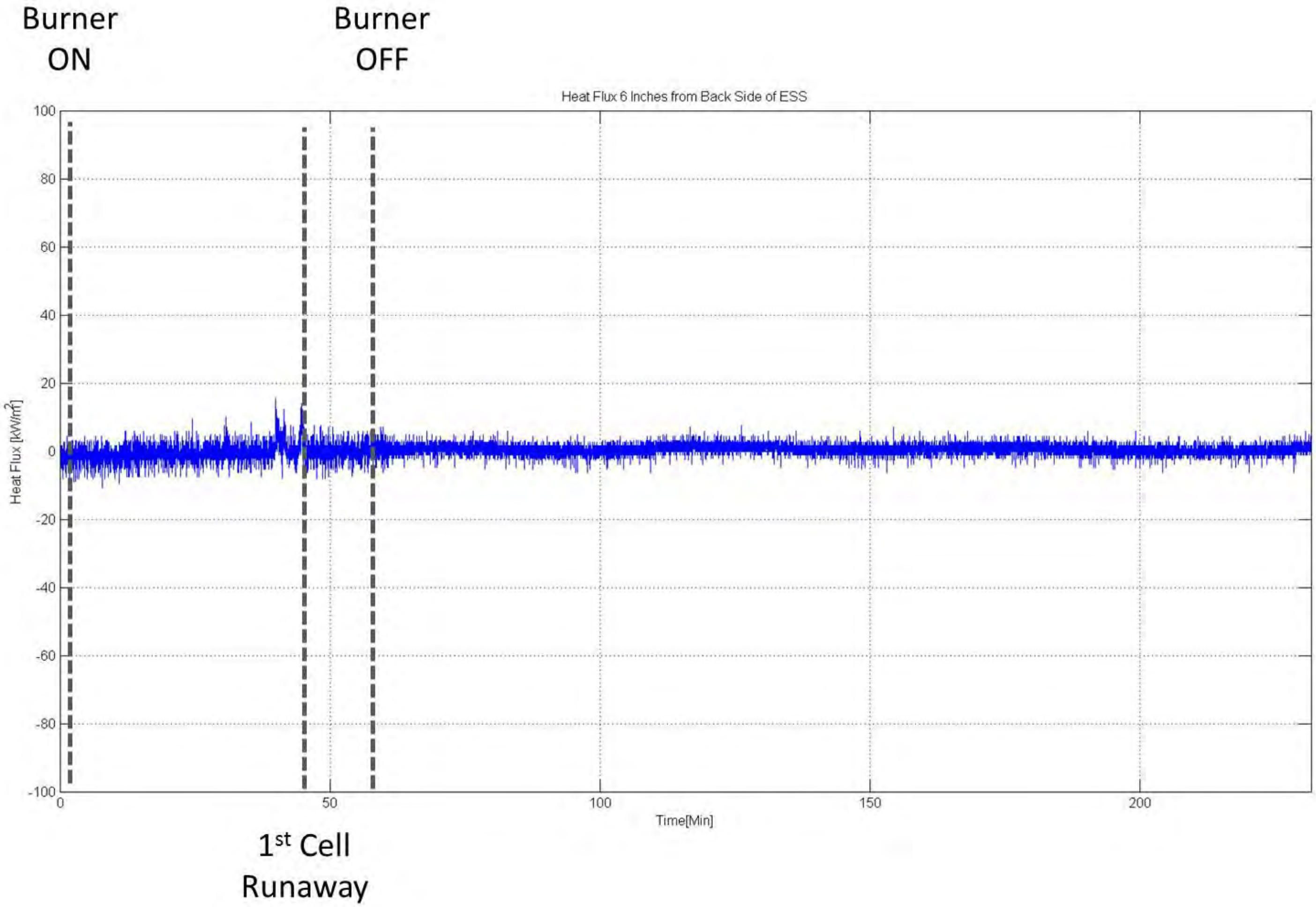

Figure 41 Heat flux measurements at HFG4, 6 inches from the side of the Powerpack

Appendix B: External Ignition Test: Pressure Plot

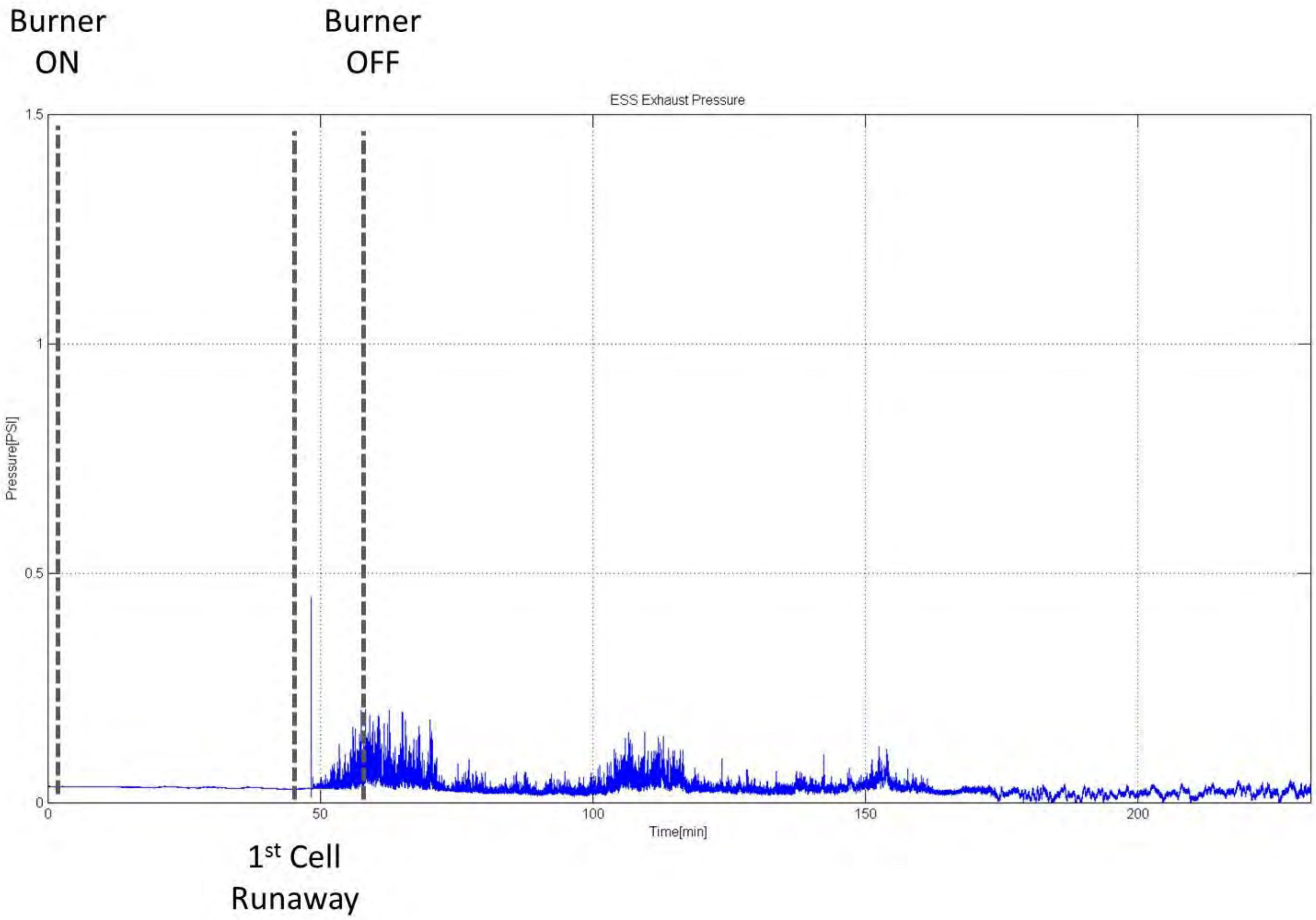

Figure 42 Exhaust manifold pressure

Appendix C: External Ignition Test: Gas Sampling Plot

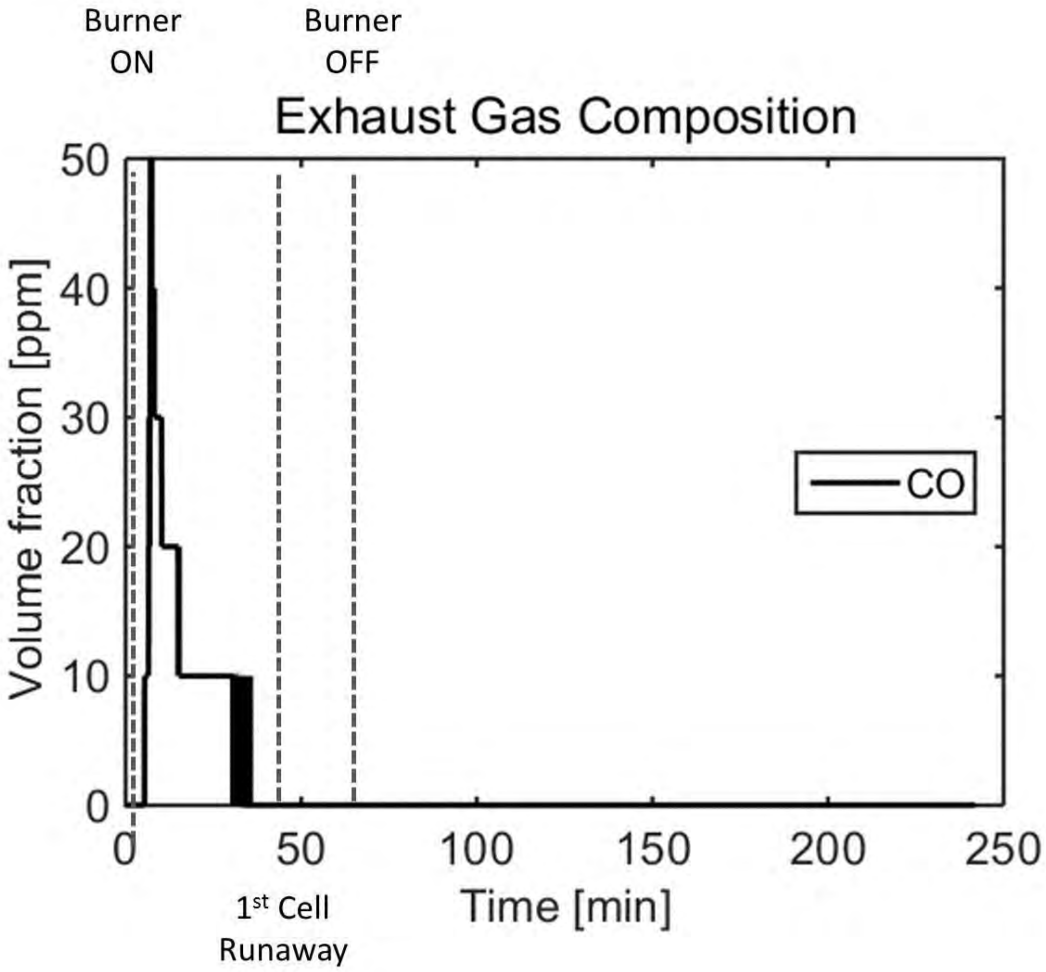

Figure 43 CO detected at the exhaust vent

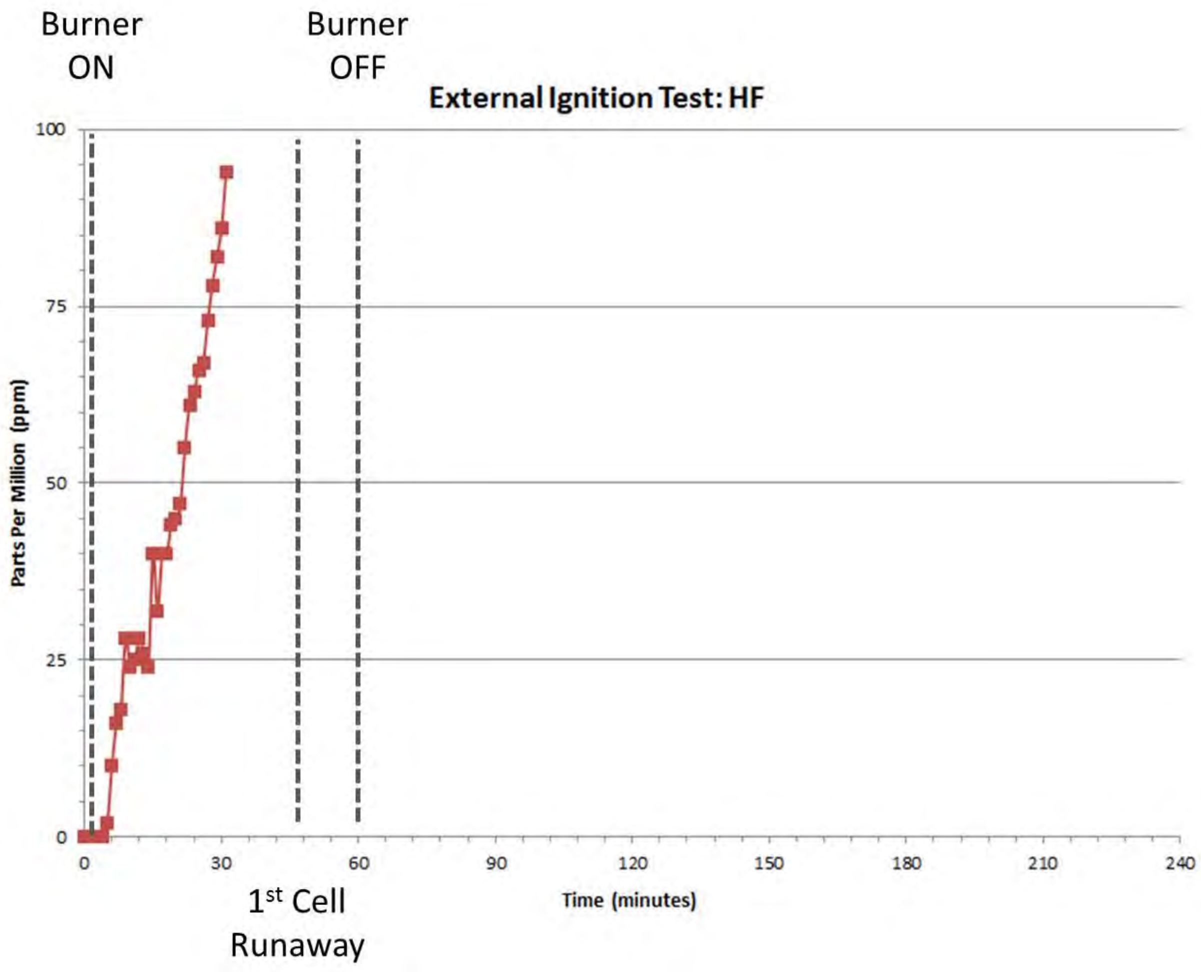

Figure 44 HF detected at the exhaust vent (detector maximum range was 100 ppm; all measurements after minute 30 were "over range," indicating the HF values were greater than 100 ppm for the remainder of the test

Appendix D: Internal Ignition Test: Temperature Plots

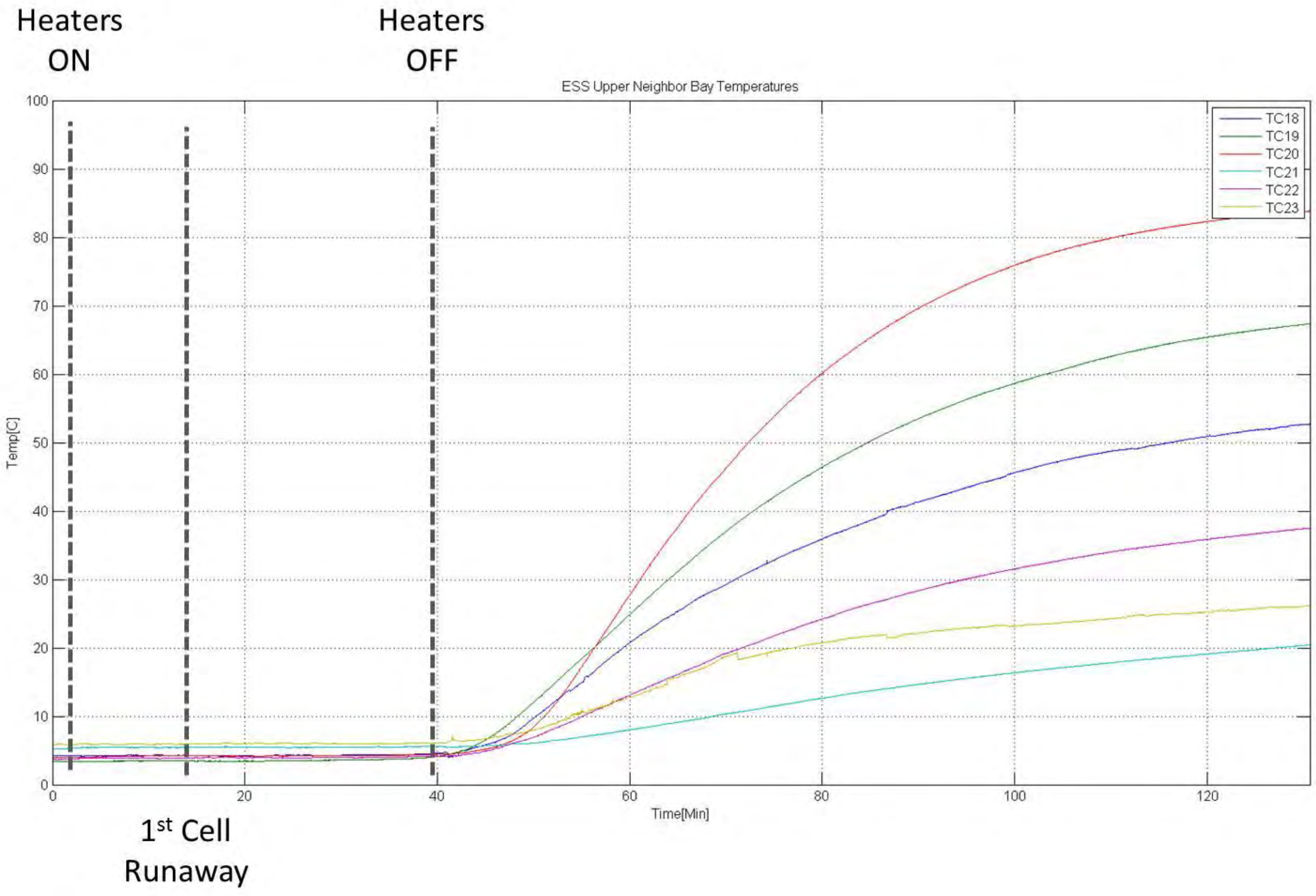

Figure 45 Pod 7 temperatures

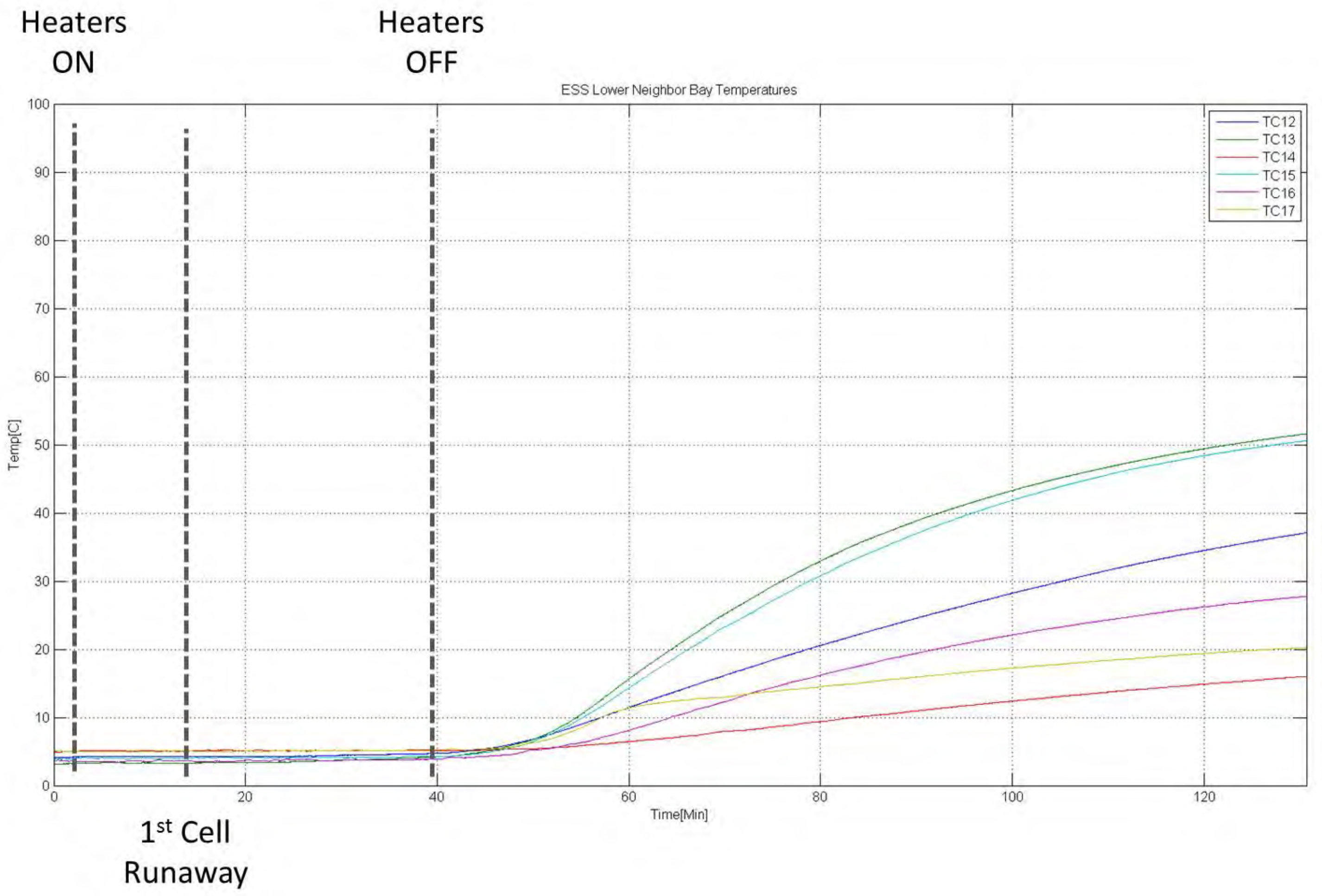

Figure 46 Pod 5 temperatures

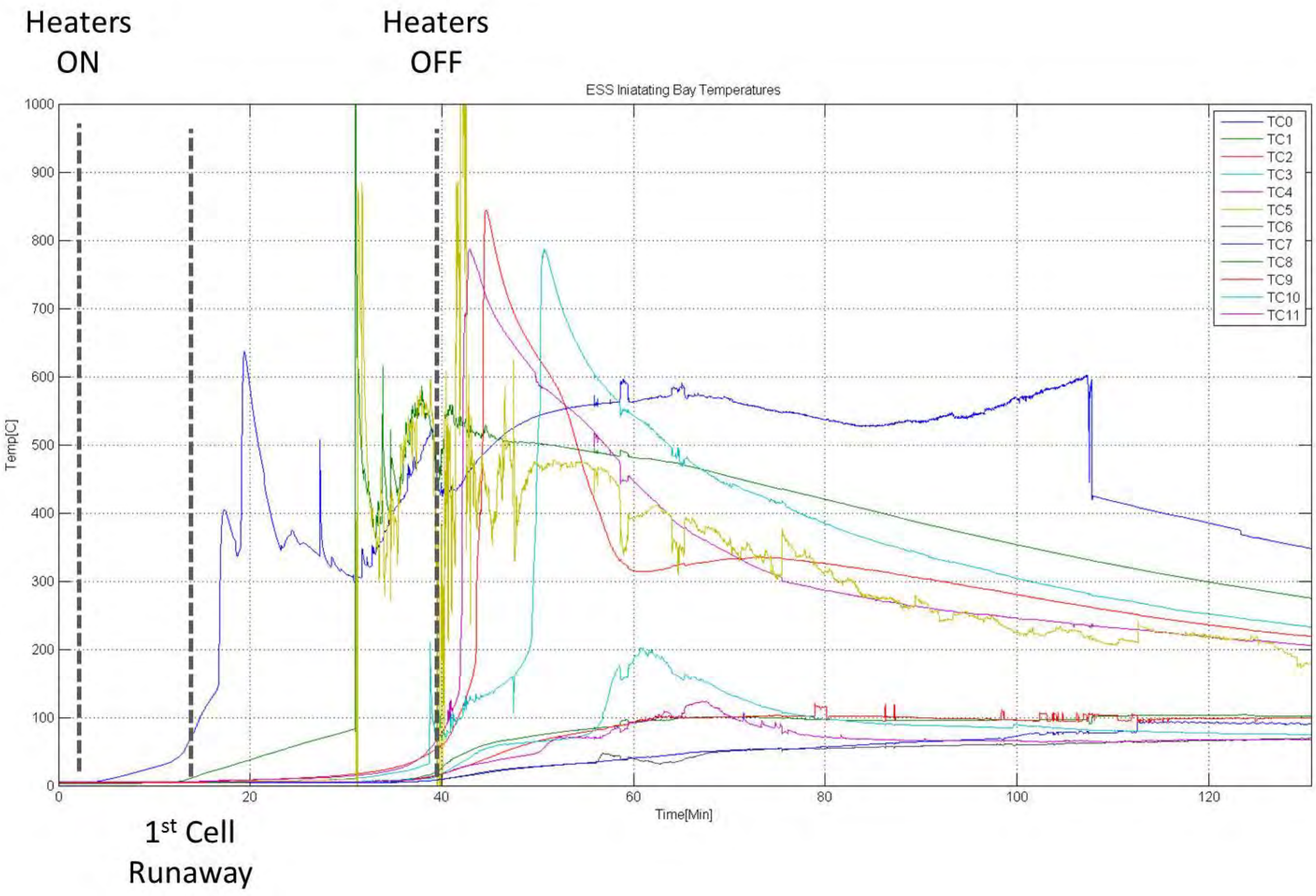

Figure 47 Pod 6 (initiator pod) temperatures (noise observed in the data is consistent with electrical interference that occurs during voltage leakage from the damaged batteries after thermal runaway)

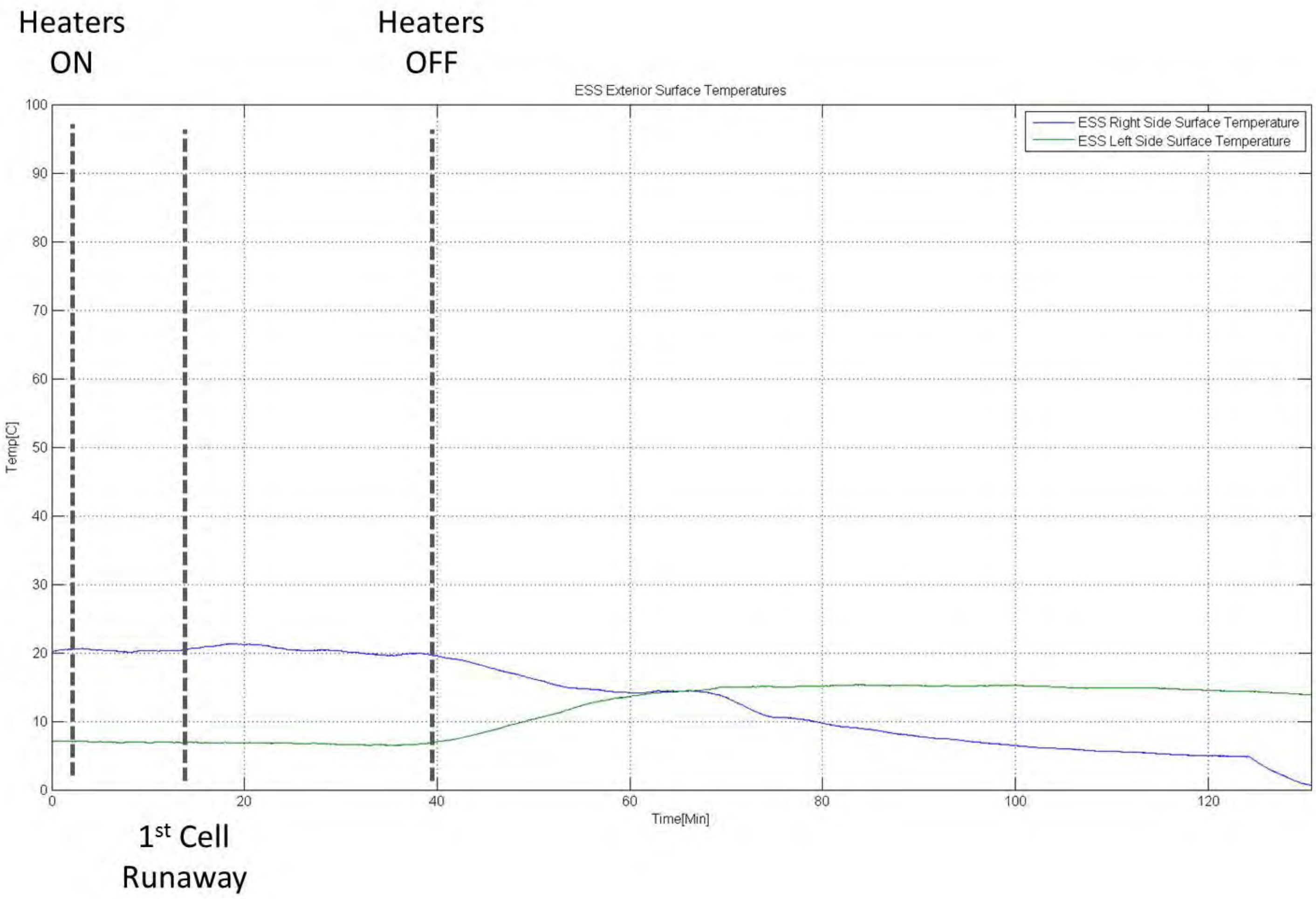

Figure 48 Exterior Powerpack surface temperatures

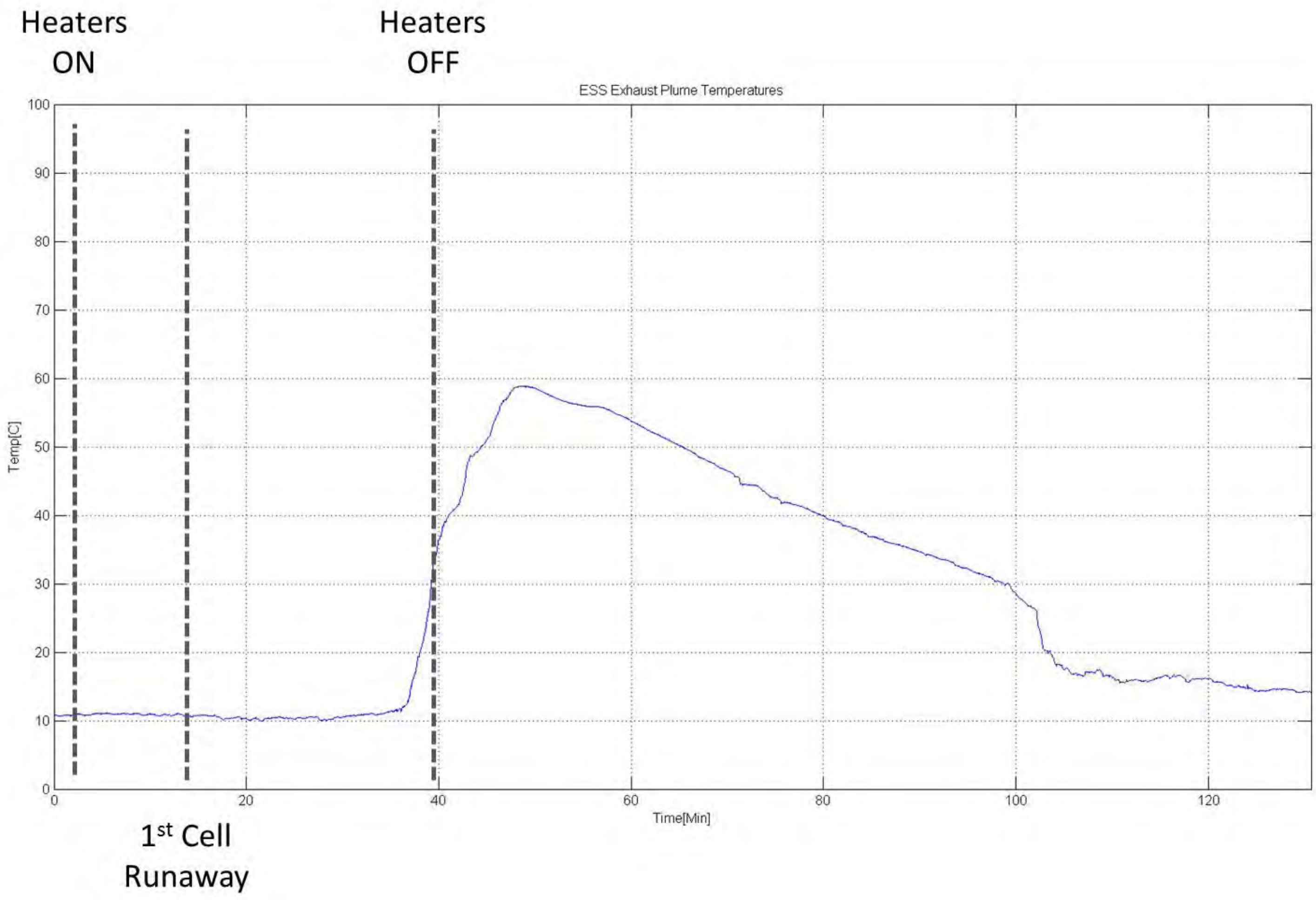

Figure 49 Exhaust vent temperature

Appendix E: Internal Ignition Test: Pressure Plots

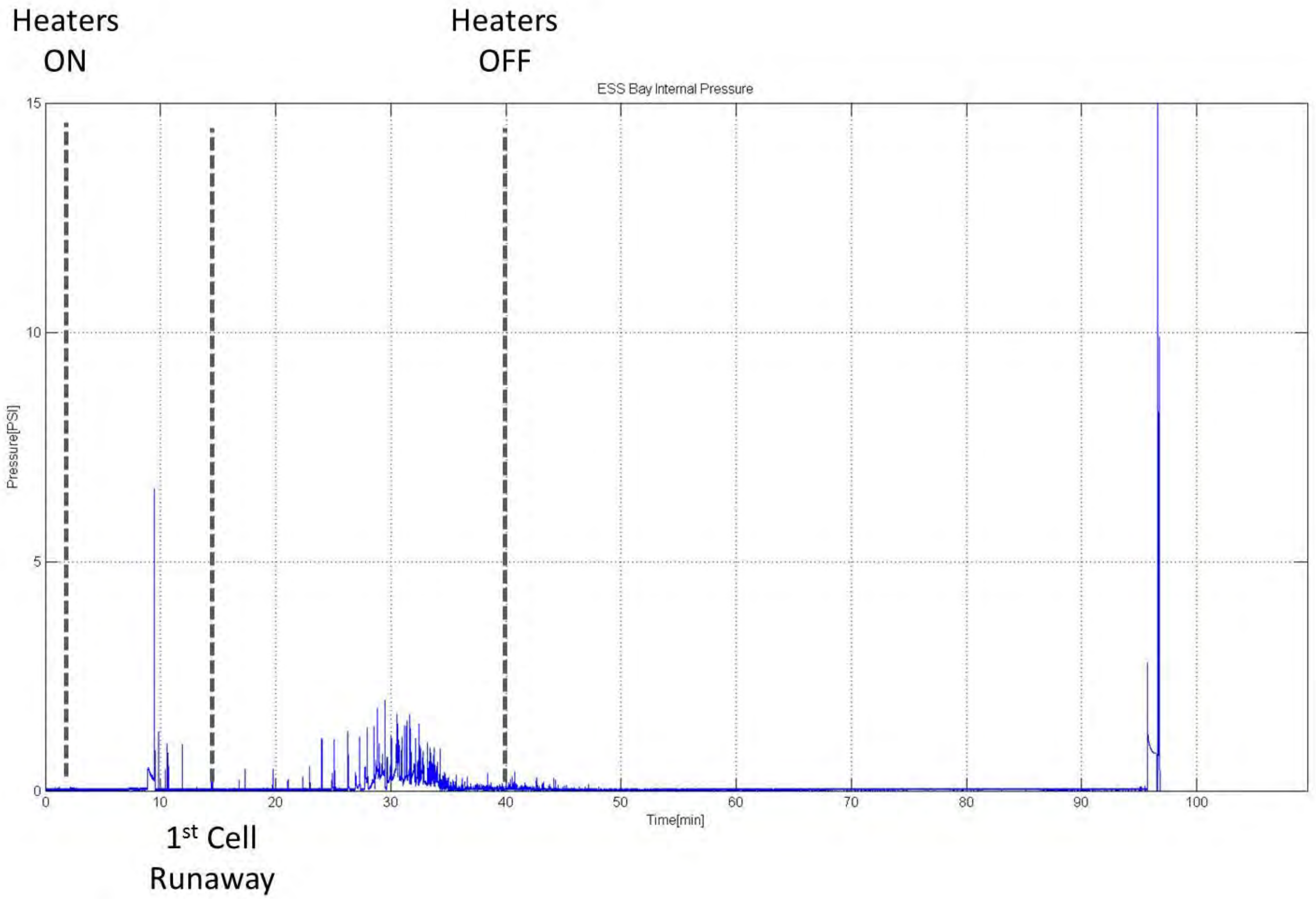

Figure 50 Pod 6 (initiator pod) pressure

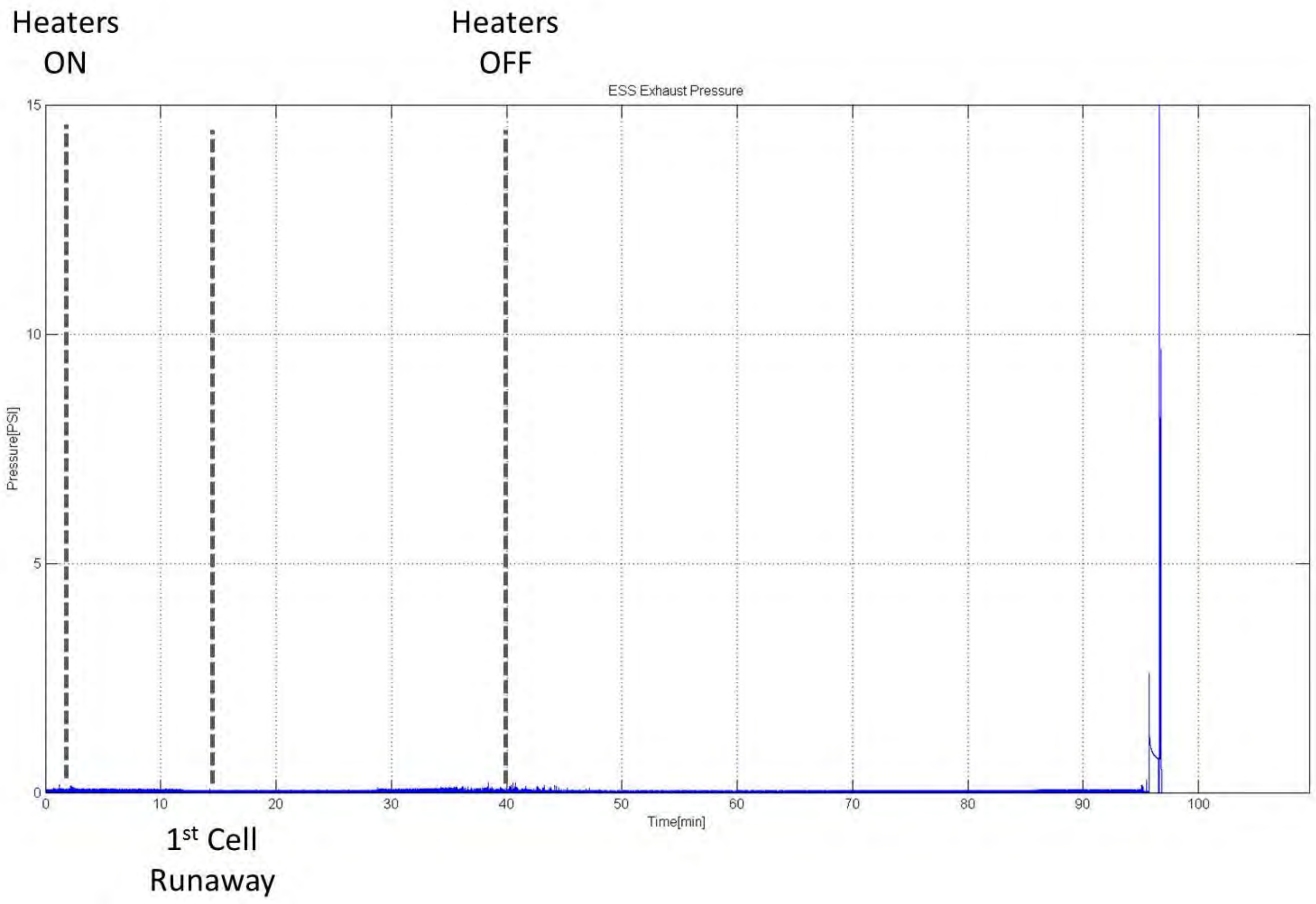

Figure 51 Powerpack exhaust manifold pressure

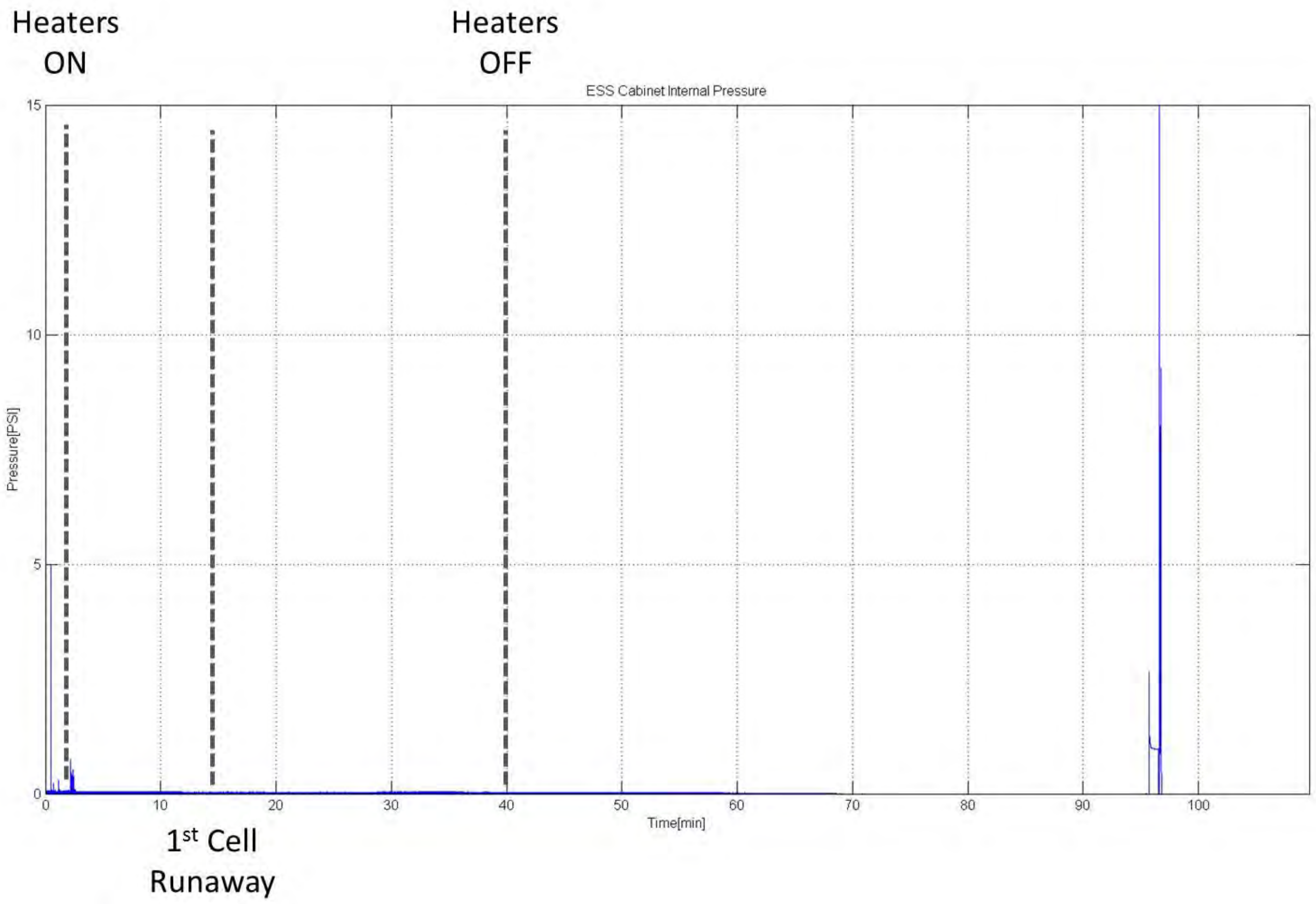

Figure 52 Powerpack cabinet pressure

Appendix F: Internal Ignition Test: Gas Sampling Plot

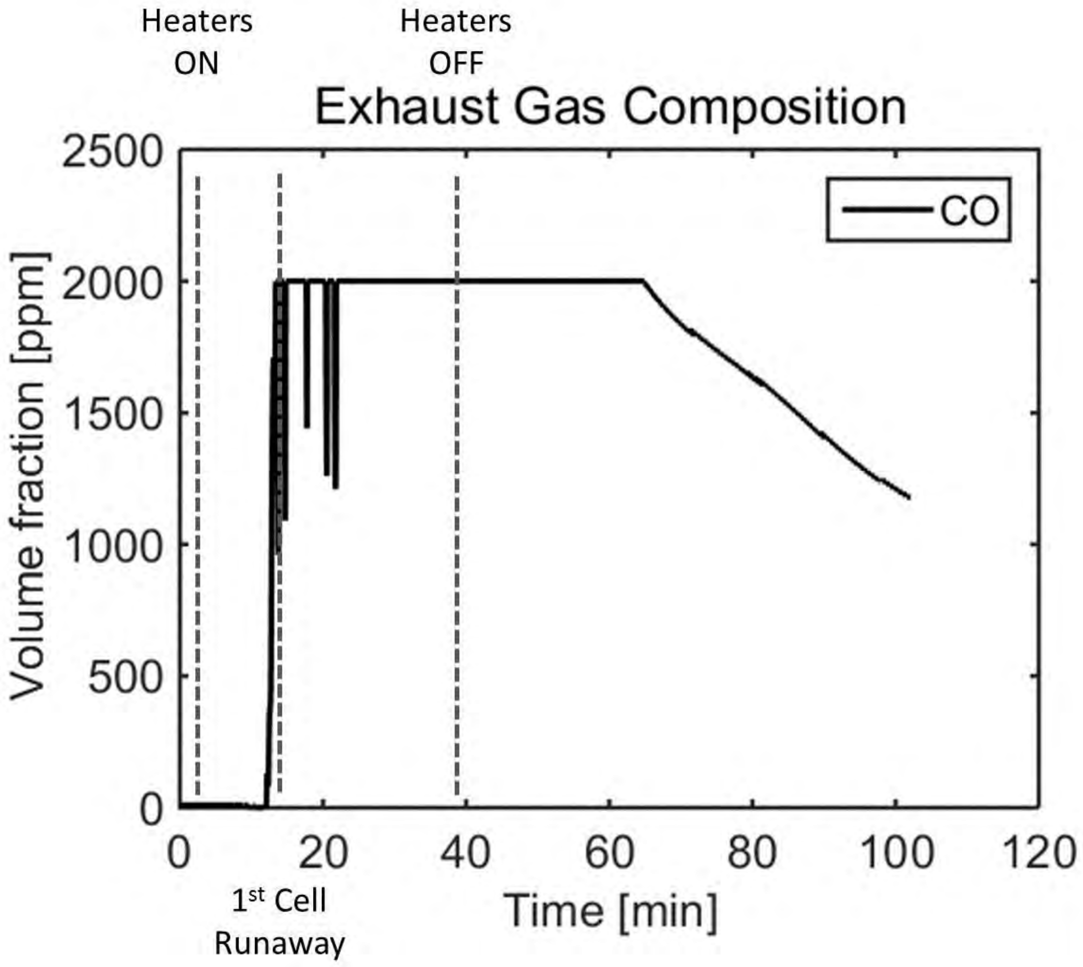

Figure 53 CO detected at exhaust vent

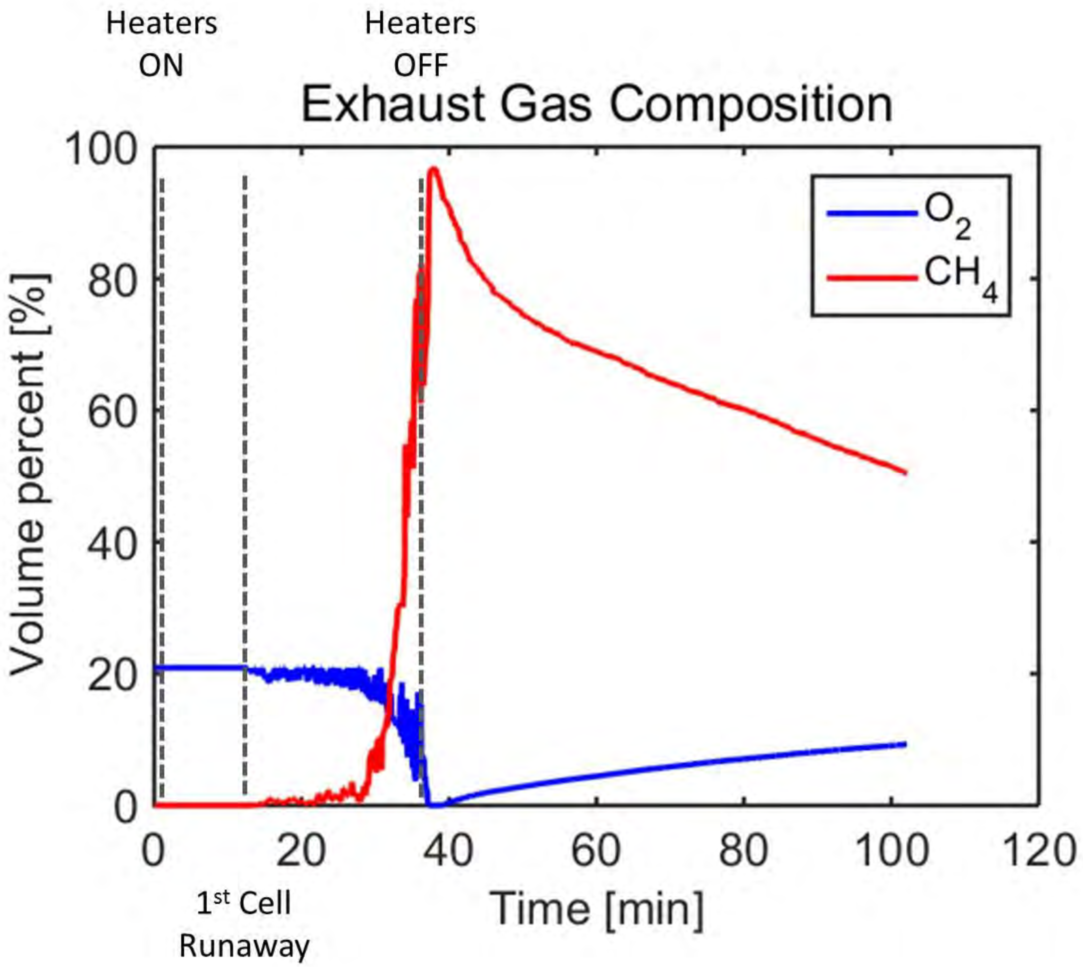

Figure 54 CH_4 detected at exhaust vent

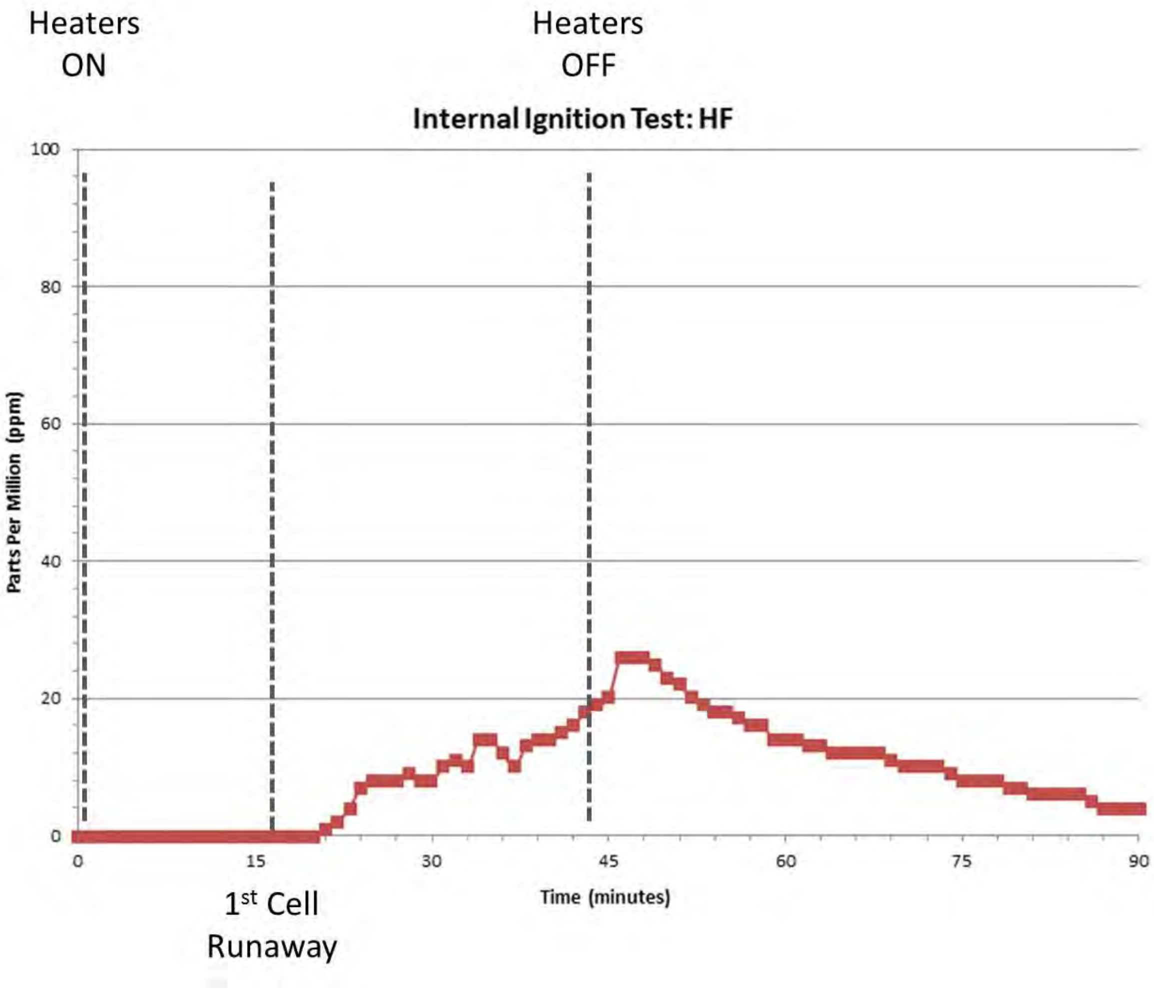

Figure 55 HF detected at the exhaust vent

Appendix 5

Andersen et al. (2013) Investigation of fire emissions from Li-ion batteries

Investigation of fire emissions from Li-ion batteries

Petra Andersson, Per Blomqvist, Anders Lorén and Fredrik Larsson

SP Technical Research Institute of Sweden

Fire Technology

SP Report 2013:15

Investigation of fire emissions from Li-ion batteries

Petra Andersson, Per Blomqvist, Anders Lorén and Fredrik Larsson

Abstract

Investigation of fire emissions from Li-ion batteries

This report presents an investigation on gases emitted during Lithium-ion battery fires. Details of the calibration of an FTIR instrument to measure HF, POF_3 and PF_5 gases are provided as background to the minimum detection limits for each species. The use of FTIR in tests has been verified by repeating experiments reported in the literature. The study reports on gases emitted both after evaporation and after ignition of the electrolyte fumes. Tests were conducted where electrolyte is injected into a propane flame and the influence of the addition of water is studied. Finally three types of battery cells were burnt and emission of fluorine and/or phosphorous containing species quantified.

Key words: Lithium-ion battery fires, toxic gases, FTIR

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Contents

Förord / Preface

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Several persons have contributed to the work including technical staff at Fire technology, Sven Ove Vendel and Brith Månsson.

Input from the reference group consisting of Ulf Lundström, Trafikverket, Thomas Mohlen, Scania, Bengt-Erik Mellander, Chalmers and Patrik Roth, Atlas Copco is also acknowledged.

Sammanfattning

Rapporten beskriver tests som har gjorts på elektrolyt i Litium-jon batterier. Elektrolyten blandades till baserat på litteraturdata och injicerades i en propanflamma. Olika blandningsförhållanden användes och även vatten sprutades in. Gaser från branden samlades in och analyserades med hjälp av en FTIR. Projektet inleddes med att FTIRen kalibrerades upp för att kunna mäta HF, POF_3 och PF_5.

Försöken visade att det var möjligt att använda FTIR för att mäta dessa gaser. Dock visade det sig i ett tidigt skede av projektet att PF_5 är så pass reaktiv att den inte finns tillräckligt länge för att detekteras. Däremot visade sig POF_3 finnas med i samtliga försök. POF_3 är en gas som potentiellt är mycket giftig, eventuellt giftigare än HF. Influensen av vatten som sprutades in i flammorna med avseende på emitterade gaser undersöktes .Det gick dock inte att påvisa någon effekt på vilka gaser som emitteras av att spruta in vatten.

Projektet avslutades med att battericeller som kan finnas i elhybrider eldades och gaserna analyserades. I dessa försök mättes HF men ingen POF_3. Detta berodde dock sannolikt på att vi hamnade under detektionsgränsen för POF_3 i dessa försöken.

Samtliga resultat extrapoleras och jämfördes med rapporterade emissionsdata från mätningar gjord på en helbilsbrand. Extrapolationen gav värden i samma storleksordning som de storskaliga bränderna.

1 Introduction

Batteries are used in more and more applications and are seen as an important solution to meet the climate goals for the automotive sector. Several types of batteries are used today and more are developed over time.

One of the most common types of batteries today is lithium-ion (Li-ion) batteries due to their high energy and power densities. Li-ion also offers long life time. Li-ion batteries have, however, some safety drawbacks. Compared to many other battery technologies, Li-ion batteries have a smaller region of stability, regarding temperatures and cell voltage. Li-ion batteries can undergo a thermal runaway resulting in gassing and fire, and potentially even explosion. A thermal runaway can be the result if a Li-ion cell is exposed to increased temperatures, typically starting from 120-150 °C. Other types of abusive conditions, e.g. overcharge or deformation can also results in venting of gasses and thermal runaway reactions. The Li-ion cell has an organic based electrolyte which enables its high energy and power densities, but it is also flammable.

Another feature of Li-ion batteries is the potential for emitting toxic gases. So far it is HF (Hydrogen Fluoride) that has gained most interest as this is a very toxic gas. Other gases that can pose a danger include the chemical species in the oxidation and thermal breakdown of the initial $LiPF_6$ salt solution. Most likely PF_5, POF_3 and HF are of greatest concern but also the fluorinated phosphoric acids can be of interest since they will give HF and phosphoric acid when completely reacted with water. The toxicity of all these gases is not fully established. The Swedish Work Environment Authority has exposure limits for total fluorides, HF and phosphoric acid but lacks data for the rest of the substances[1].

The NGV[i] for total fluorides are 2 mg/m^3 and HF has a TGV[ii] of 2 ppm. NIOSH (National Institute for Occupational Safety and Health, USA) states that HF has a IDLH (Immediately Dangerous to Life and health) value of 30 ppm. No exposure linits are given for PF_5 and POF_3 , however their chlorine analogues, PCl_5 and $POCl_3$ have NGV values of 0.1 ppm. The toxicity might, however, differ between the chlorine and fluorine species and there is no general rule like “fluorine is always more toxic”. But, still, the limits are low and gases evolved from battery fires are certainly of great concern to both the fire fighters, people in the vehicles and in the close vicinity of the fire. Both of these gases are very reactive and very few measurements have been performed on these gases in the literature. Yang, Zhuang and Ross[2] report measurements conducted using TGA (Thermal Gravimetry Analysis) and FTIR (Fourier transform Infra Red) on pure $LiPF_6$ salt and salt solved in EC, PC, DMC and EMC but so far little or none work has been published on emissions of these gases from fire scenarios.

One important aspect for Li-ion batteries is the possibility to extinguish a fire in them. Several different types of advice are available such as using copious amounts of water or sand or letting the battery burn. There are, however, several situations when it is not possible to allow a battery fire to continue, e.g. if someone is trapped in a car. It is, therefore, important to investigate different extinguishing means together with the toxic gases emitted during extinguishment.

The work presented in this report includes calibration of an FTIR equipment to be used to measure HF, POF_3 and PF_5 to analyse smoke from fire tests. The technique developed is

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[i] ”Nivågränsvärde” Mean value threshold in a working environment

[ii] ”Takgränsvärde” Maximum allowed concentration in a working environment

then used in different heating and combustion conditions in different scales. The impact of water on the combustion gases is also investigated.

2 FTIR instrumentation

The instrument used for analysis of the emission products in the fire tests reported here was an FTIR spectrometer. Fourier transform infrared spectroscopy (FTIR) is a general technique used to obtain an infrared spectrum of absorption from a solid, liquid or gas. An FTIR spectrophotometer uses an interferometer to simultaneously collect spectral data over a wide spectral range, in the form of an interferogram, which is different from classical dispersive spectroscopy, which sequentially collects data at each wavelength. A Fourier transform is a mathematical algorithm used to convert the raw data into a spectrum, corresponding to the spectrum resulting from a classical scanning dispersive spectrometer. The use of an interferometer gives two main advantages in comparison with the traditional dispersive spectroscopy: First, all wavelengths are collected in principal simultaneously. Second, the interferometer throughput is higher compared to dispersive methods which gives a higher signal.

The measurement system used here consisted of an FTIR spectrometer, a gas cell, sampling lines, filters for removing particulates before the gas cell and a pump that continuously drew sample gas through the cell. The system is specified in Table 1.

Table 1 Specification of the FTIR measurement system.

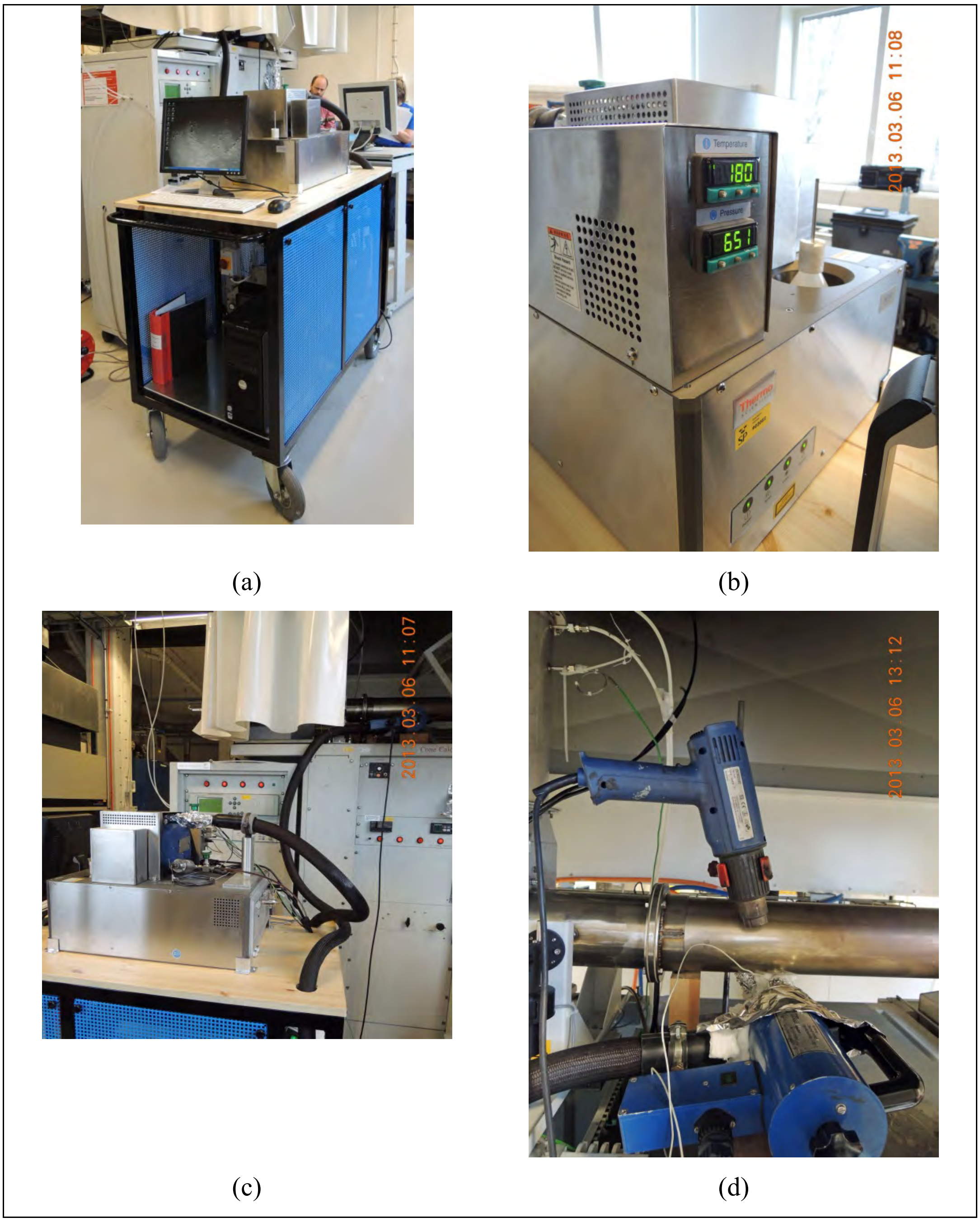
Instrumentation	**Specification**
Spectrometer	Thermo Scientific Antaris IGS analyzer (Nicolet)
Spectrometer parameters	Resolution: 0.5 cm-1 Spectral range: 4800 cm^{-1} – 650 cm^{-1} * Scans/spectrum: 10 Time/spectrum: 12 seconds Detector: MCT
Gas cell	Volume: 0.2 litres Path length: 2.0 m Temperature: 180°C** Cell pressure: 650 Torr**
Primary filter	M&C ceramic filter heated to 180 °C
Secondary filter	M&C sintered steel filter heated to 180°C***
Sampling tubing	4/6 mm diameter PTFE tubing heated to 180°C. The length of the tubing was 1.5 m in the Cone calorimeter tests and 8.5 m in the battery tests.
Pump	Sampling flow: 3.5 l/min

* The spectral range used in the initial pre-study was 4000 cm^{-1} – 650 cm^{-1}.

** In the initial pre-study and calibration the cell temperature was 170 °C and the pressure was ~740 Torr.

*** A 37 mm diameter planar filter (PTFE) heated to 130°C was used in the initial pre-study.

Photos of the FTIR measurement system connected to the Cone calorimeter are shown in Figure 1.



(a) (b)

(c) (d)

Figure 1 Photos of the FTIR instrumentation. (a) Overview of the measurement set-up. (b) The Antaris FTIR spectrometer. (c) The connection of the incoming sample gas to the measurement cell. (d) The primary filter with the heating device (blue in front) and heating of incoming connection with a heating gun.

3 Fundamental Chemistry of $LiPF_6$

When heated in a dry and inert environment $LiPF_6$ decomposes to lithiumfluoride (LiF) and phosphorouspentafluoride ($PF_5(g)$)^2.

$$LiPF_6 \rightarrow LiF + PF_5 \qquad (1)$$

In contact with moisture/water PF_5 reacts to form phosphorous oxyfluoride and hydrogenfluoride. ^{2}

$$PF_5 + H_2O \rightarrow POF_3 + 2HF \qquad (2)$$

When heated in moisture/water $LiPF_6$ can directly form LiF, POF_3 and HF.^{2}

$$LiPF_6 + H_2O \rightarrow LiF + POF_3 + 2HF \qquad (3)$$

PF_5 also react with HF to form hexafluorophosphoric acid (HPF_6)^3:

$$PF_5 + HF \rightarrow HPF_6 \qquad (4)$$

Phosphorous oxyfluoride (POF_3) can react to form several fluorinated phosphoric acids, monofluorophosphoric acid (H_2PO_3F), difluor-phosphoric acid (HPO_2F_2) hexafluorphosphoric acid (HPF_6), and phosphoric acid (H_3PO_4)^4. The fluorinated phosphoric acids can react with water and yield HF and form phosphoric acid as a final product. [4]:

$$H_3PO_4 \underset{H_2O}{\overset{HF}{\rightleftharpoons}} H_2PO_3F \underset{H_2O}{\overset{HF}{\rightleftharpoons}} HPO_2F_2 \underset{H_2O}{\overset{HF}{\rightleftharpoons}} HPF_6 \qquad (5)$$

4 Pre-study of fluorinated emission products

In order to be able to study the fluorinated emission products emitted during a potential battery fire the FTIR to be used in the experiments had to be calibrated. The measuring method was then also verified by conducting experiments on electrolyte and salt solutions that were heated. The full calibration methodology is described below.

4.1 Production of calibration gases

The FTIR instrument contained a basic factory calibration for HF. This calibration was, however, improved during the project to include more spectral information and a wider concentration range. The calibration of HF was made using a dynamic dilution system where a water solution of HF was injected into a heated stream of nitrogen.

In addition was the FTIR calibrated for PF_5 and POF_3. Calibration gas mixtures were prepared for this purpose by dilution of PF_5 (99%, ABCR) and POF_3 (99%, ABCR) in nitrogen atmosphere using gasbags (Flexfoil, SKC). Extra effort was put into pre-conditioning the bags so they were free of water adsorbed to the walls. This was necessary to be able the prepare the highly reactive PF_5 mixture. The concentrations produced for the POF_3 calibration were: 25 ppm, 100 ppm, 200 ppm, 300 ppm and 416 ppm. While the PF_5 concentrations were 108 and 200 ppm, respectively.

4.2 Calibration of FTIR

The FTIR used had a calibration for a number of components when delivered from factory. These components included *e.g.* CO_2, CO and HF. It was seen that the factory calibration was not sufficiently accurate for the intended use of the instrument and the instrument was recalibrated during the course of this project. The settings of the FTIR instrument were changed somewhat (see Table 1) for the recalibration, which meant that measurements made before the recalibration could only be evaluated semi-quantitatively using recalibration data. This was not a problem, however, as the new calibration data was used in the evaluation of the project data.

4.2.1 HF

The instrument was recalibrated for HF during the project to include the full spectral band of HF and to include a wide concentration range i.e. 18 ppm to 1245 ppm. The quantification limit (LOQ) for HF was calculated to 2 ppm.

The spectral band at 520 ppm for HF (together with water) in nitrogen is seen in Figure 2. There are two branches of peaks for HF. The branch at the higher wavenumbers is clearly seen in the figure whereas the branch at lower wavenumbers contains interference from water bands.

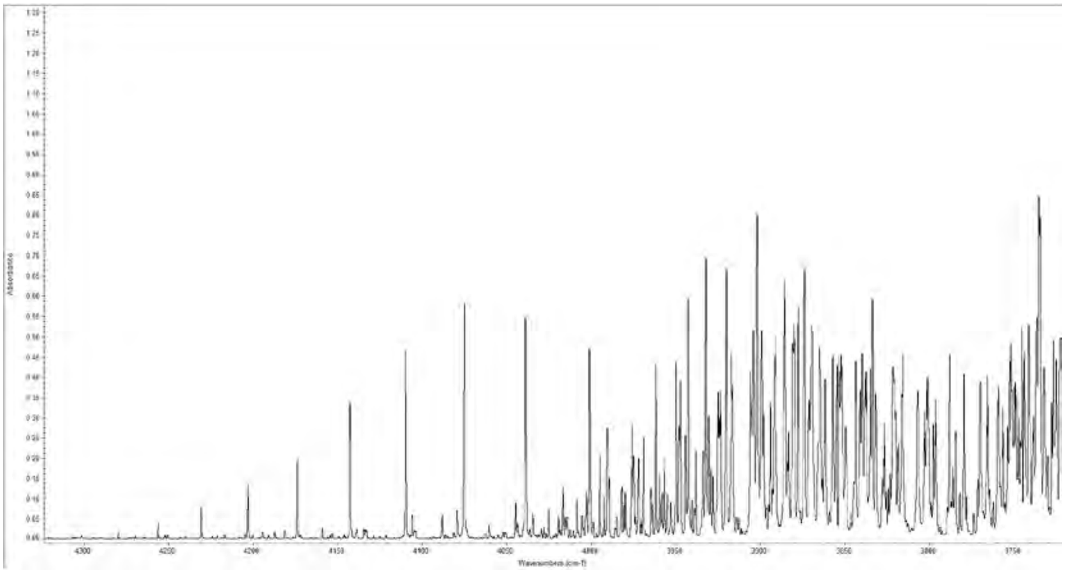


Figure 2 **Spectra of 520 ppm HF and 2.9 % H_2O in N_2.**

4.2.2 POF_3

Tests were conducted to record the spectral bands of POF_3 as a basis for calibration of the FTIR. An important part of the calibration work was further to investigate the stability of POF_3 under the conditions used for calibration (see section 4.3). This initial work was conducted before the FTIR was recalibrated.

A spectrum of POF_3 (116 ppm) is shown in Figure 3. Several distinctive absorption bands can be seen (together with some water that was present in the bag). These bands can be seen more clearly in Figure 4, where the spectral range of interest is shown.

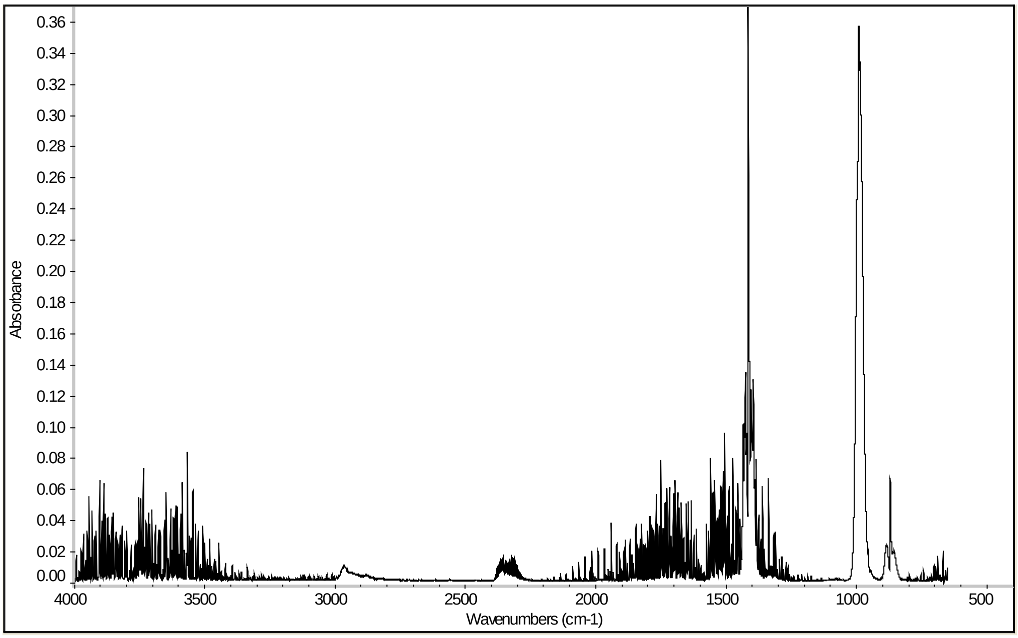


Figure 3 **Spectra of 116 ppm POF_3 in N_2.**

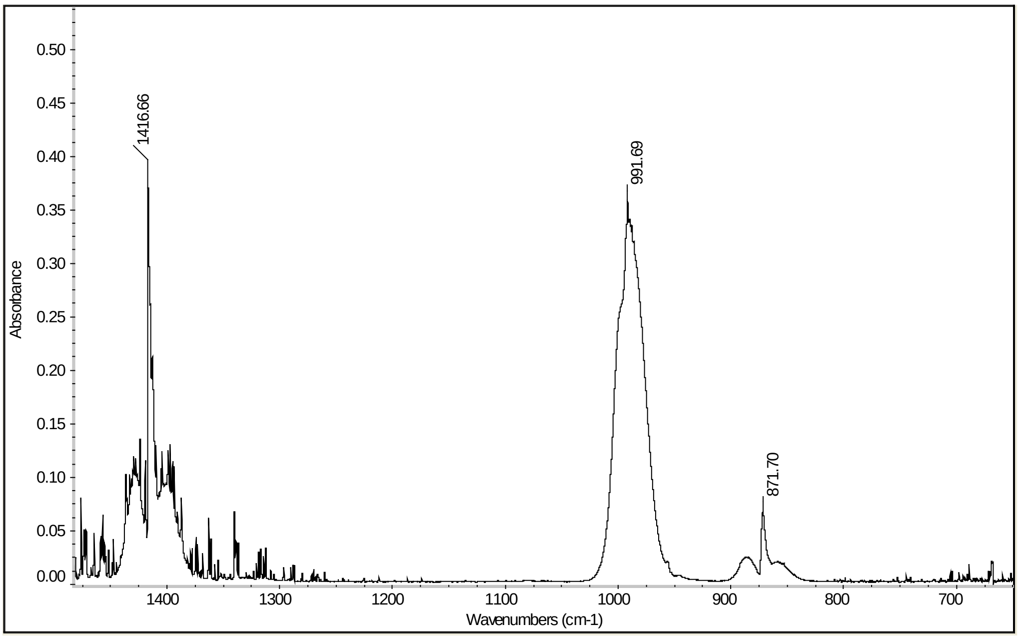


Figure 4 Spectral bands of POF_3 (from 116 ppm POF_3 in N_2).

Three spectral bands are shown centred around the wavenumbers 871 cm^{-1}, 991 cm^{-1} and 1416 cm^{-1}. These bands are from P-F symmetrical stretches, P-F asymmetrical stretches and P-O stretches. The two latter vibrations are the strongest. The spectral information of POF_3 is summarized in Table 2.

Table 2 Spectral band positions for POF_3.

Band position (cm^{-1})	Absorptivity (abs/ppm.m)	Type of band [2]
1416	0.00159	P-O stretch
991	0.00154	P-F asymmetrical stretch
871	0.00029	P-F symmetrical stretch

A quantitative calibration was made for POF_3 using flushed gas bags where known volumes of POF_3 gas were injected into a known volume of nitrogen gas. The concentrations produced for the calibration were: 25 ppm, 100 ppm, 200 ppm, 300 ppm and 416 ppm. Spectral regions around 871 cm^{-1} and 1416 cm^{-1} were used for a CLS (classical least squares) calibration and water was included as an interfering component. The quantification limit (LOQ) for POF_3 was calculated to 6 ppm.

4.2.3 PF_5

It was found that the gas bags used needed to be dried by flushing with N_2 in order to remove any remaining water. Water was unwanted as hydrolysis of PF_5 could be expected. Figure 5 shows the FTIR spectrum of a non-flushed gas bag where the nominal concentration of PF_5 was 108 ppm. This spectrum shows, however, no significant spectral bands apart from those of POF_3 and HF. (Spectral bands of water, some CO_2 and a small contamination of HCl are additionally shown.)

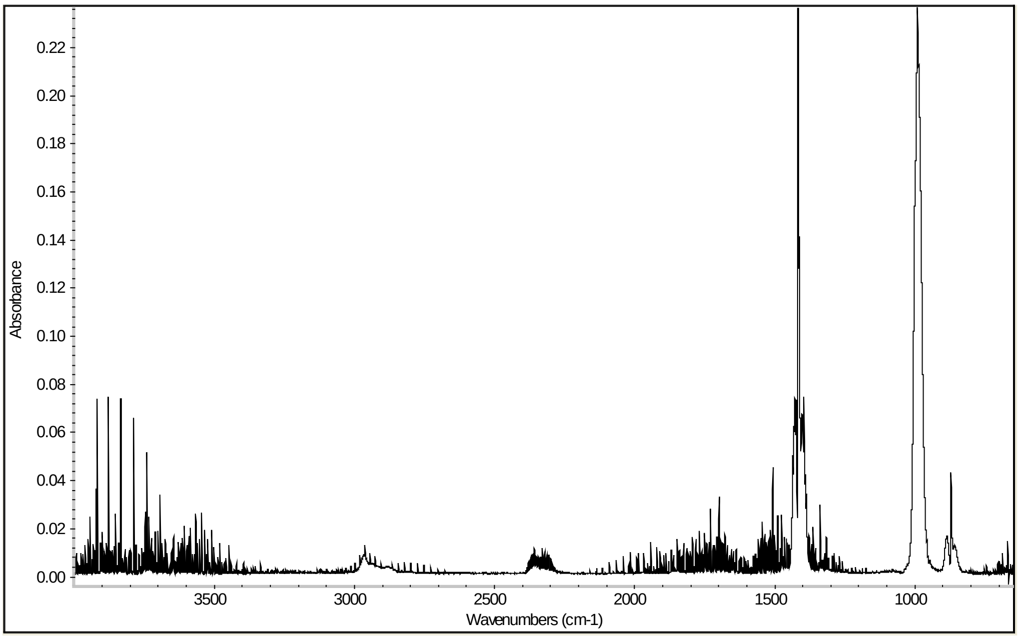


Figure 5 **Spectra of 108 ppm PF5 in argon (bag not flushed – contained water).**

The explanation found was that the PF_5 added to the bag was hydrolysed by the small amounts of water that was present in the bag, to form the decomposition products POF_3 and HF.

The bags were subsequently thoroughly dried before adding PF_5. A spectrum from the content of a gas bag flushed with N_2 is shown in Figure 6. Only very small remains of water can be seen here.

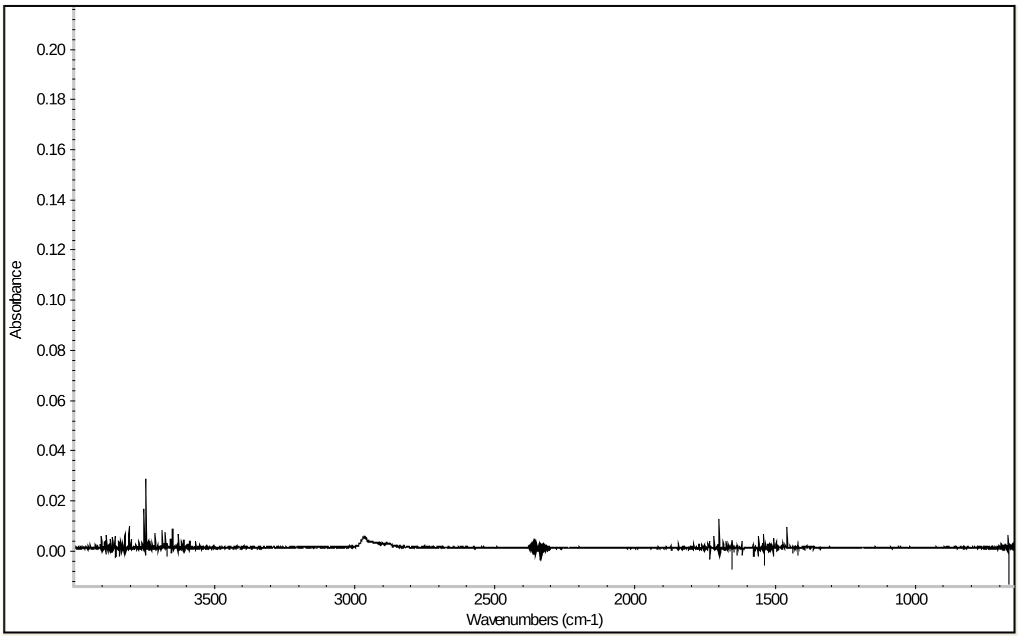


Figure 6 **Spectra of gas content in gas bag flushed with dry N_2.**

By using flushed bags it was possible to locate the spectral bands of PF_5. Figure 7 shows a spectrum of nominally 200 ppm PF_5 in N_2. However, also here the bands of POF_3 and HF can be seen together with the bands of PF_5. It is clear from this that PF_5 is very unstable and decomposes easily. The interesting spectral range for PF_5 is magnified in Figure 8.

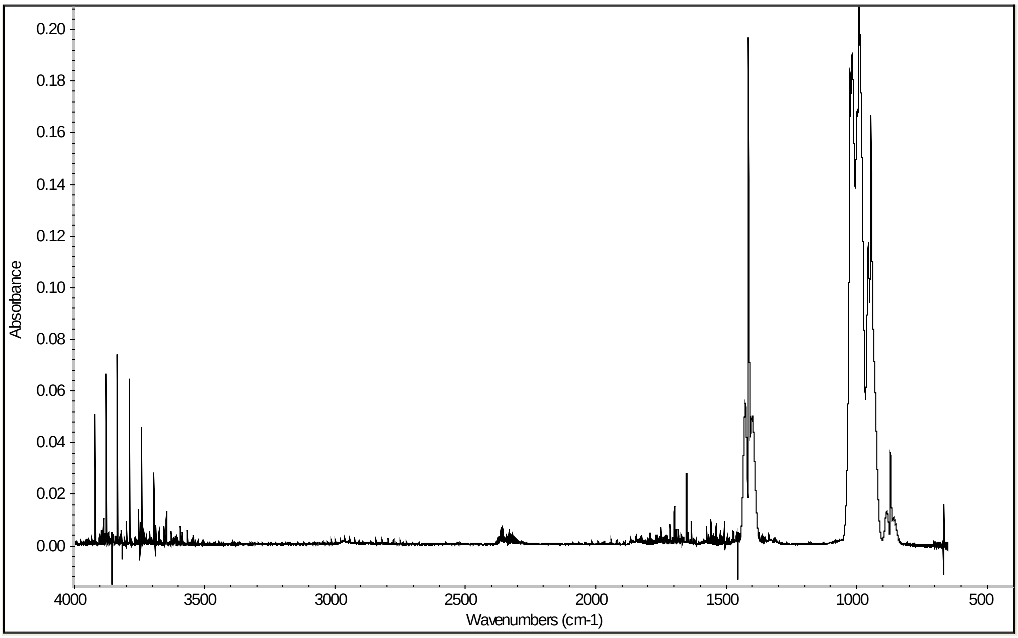


Figure 7 **Spectra of 200 ppm PF_5 in dry N2 (bag flushed).**

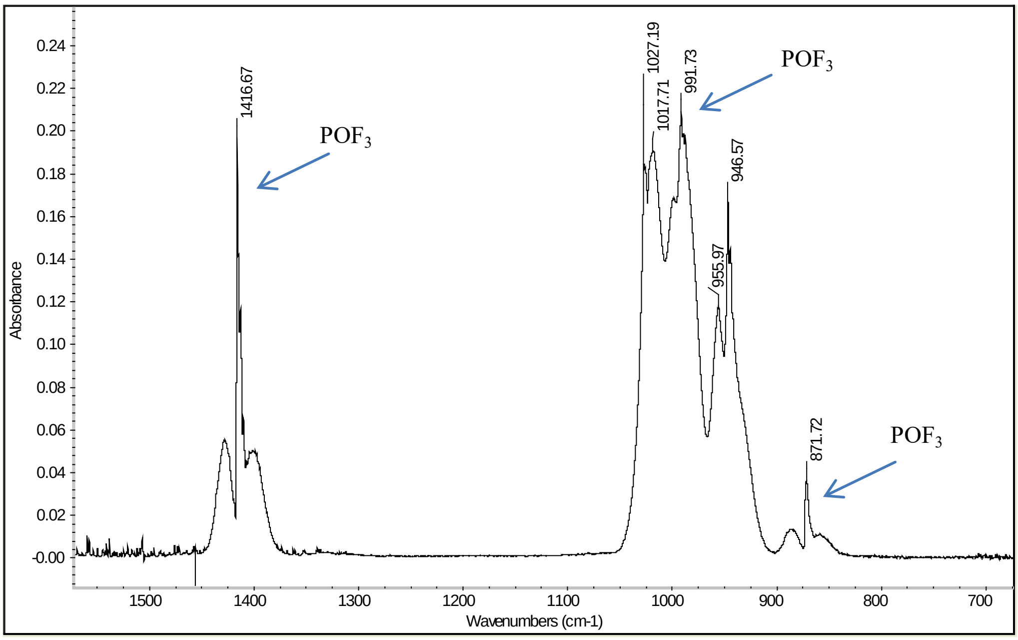


Figure 8 **Spectral bands of PF_5 (from 200 ppm PF_5 in dry N_2).**

The spectral bands of POF_3 are seen in Figure 8 at 871 cm^{-1} (P-F symmetrical stretch), 991 cm^{-1} (P-F asymmetrical stretch) and 1416 cm^{-1} (P-O stretch). Remaining bands are from PF_5 or additional decomposition products of PF_5. PF5 has two stretching modes according to Yang et al. [2]. These are most probably the bands at 1017.71 cm^{-1} and 946.57 cm^{-1}. The remaining two bands found, 1027 cm-1 and 996 cm-1, must thus originate from unidentified decomposition products of PF_5. The bands found that were not from POF_3 are listed in Table 3.

Table 3 **Spectral band positions found from PF_5 and decomposition products.**

Band position (cm^{-1})	Type of band
1017	PF_5: PF stretching [2]
946	PF_5: PF stretching [2]
1027	Band from unknown decomposition product
956	Band from unknown decomposition product
1416	POF_3: P-O stretch
991	POF_3: P-F asymmetric stretch
871	POF_3: P-F symmetric stretch

4.3 Stability of POF_3

The stability of POF_3 at both room temperature and at an elevated temperature was investigated. It was important to have this information to be sure that the calibration mixtures prepared in gas bags were stable and to see if any significant decomposition would take place in the heated sampling and measurement system.

4.3.1 Room temperature

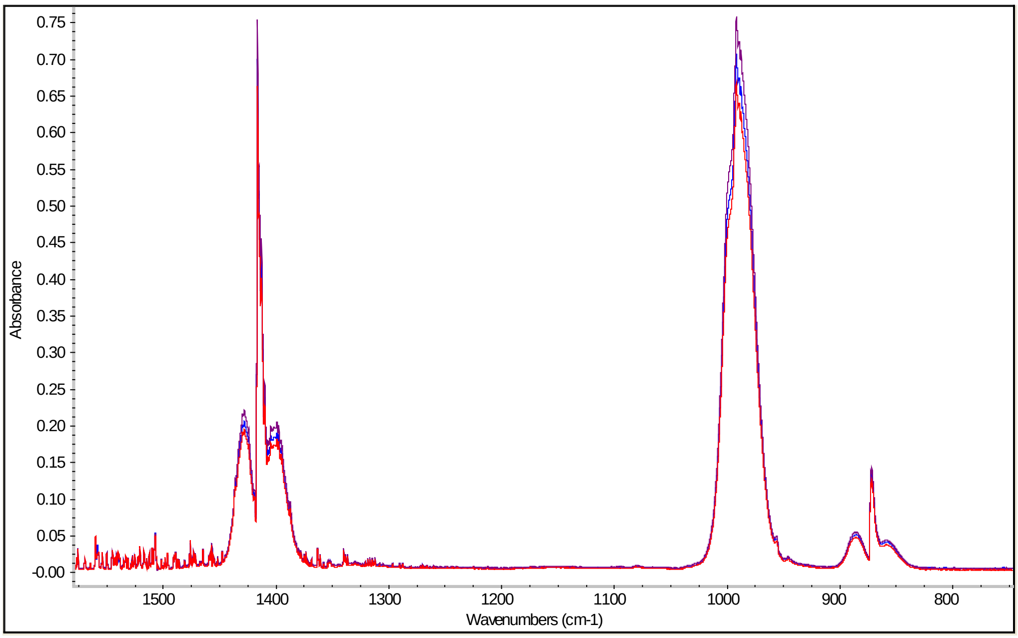


Figure 9 **Spectra of ~200 ppm POF_3 measured in 3 separate Flexfoil bags at 8 min (blue), 16 min (brown) and 33 min (red) after preparation.**

The investigation showed that POF_3 is very stable at room temperature in a gas bag diluted with N_2, which makes it possible to prepare quantitative calibration standards. Figure 9 shows the spectra of ~200 ppm POF_3 from three different gas bags, stored for various length of time before measurement. A very limited decomposition can be seen for the standard stored 33 minutes before measurement.

4.3.2 Elevated temperature

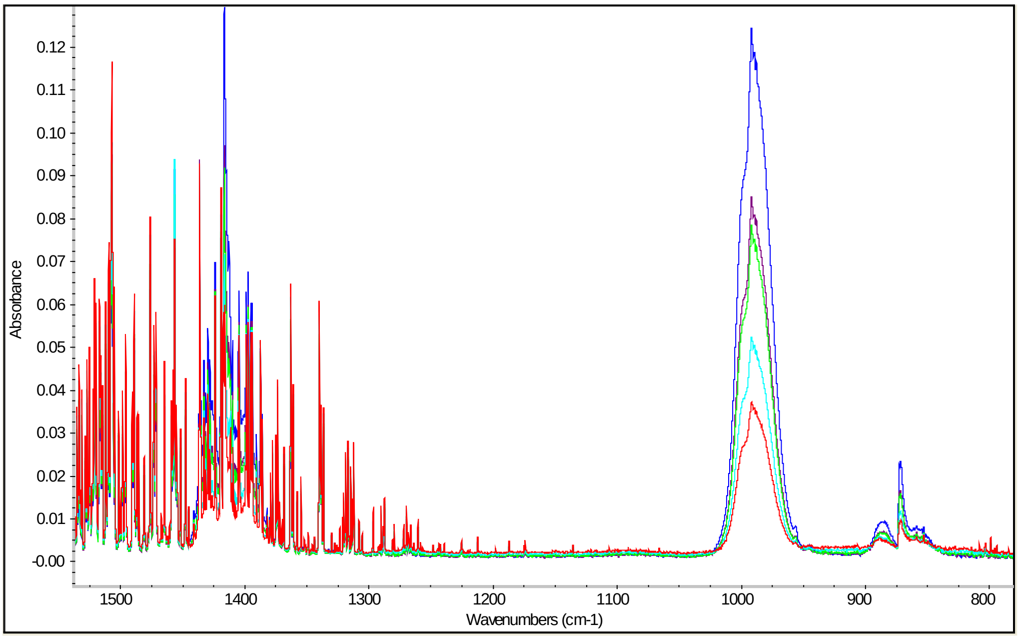


Figure 10 Series of spectra of 41 ppm POF_3 kept at 170°C in the FTIR gas cell for 0 min (blue), 8 min (brown), 10 min (green), 21 min (magenta) and 31 min (red).

The half-life for POF_3 in N_2 at 170 °C is about 15 minutes according to the measurements shown in Figure 10, which means that there is no significant decomposition taking place in the measurement system during the ~10 s response time of the FTIR measurement set-up.

4.4 Heating tests with the Cone Calorimeter

Yang et al [2] have studied the thermal stability of $LiPF_6$ salt and of solutions of LiPF6 in prototypical Li-ion battery solvents by thermogravimetric analysis (TGA) and on-line FTIR. They showed that in the presence of water the decomposition products formed were POF_3 and HF. No new products were observed in 1 molar solutions of $LiPF_6$ in EC, DMC and EMC. In the evaporation tests that are reported below it was investigated whether the same type of decomposition products could be found in tests where the electrolyte was heated in an open container with radiative heating in a Cone calorimeter. Further, combustion tests were conducted where the vapour was ignited to investigate how combustion would change the type of decomposition products.

The sample was placed in a small (~40 mm diameter) steel container under the heating cone of the Cone calorimeter as can be seen in Figure 11. The irradiation of the sample was in the range of 10-15 kW/m^2. The FTIR was connected to the exhaust duct of the Cone calorimeter. Separate tests were conducted with only solvents (DME and PC), the pure $LiPF_6$ salt, and saturated solutions of $LiPF_6$ salt and solvents. Leftovers from the tests can be seen in Figure 12. The FTIR measurement system is described in Section 2.

Figure 11. Open container placed underneath cone heater and ignited

Figure 12. Leftovers in cake-cup after test

4.4.1 Evaporation tests of pure components

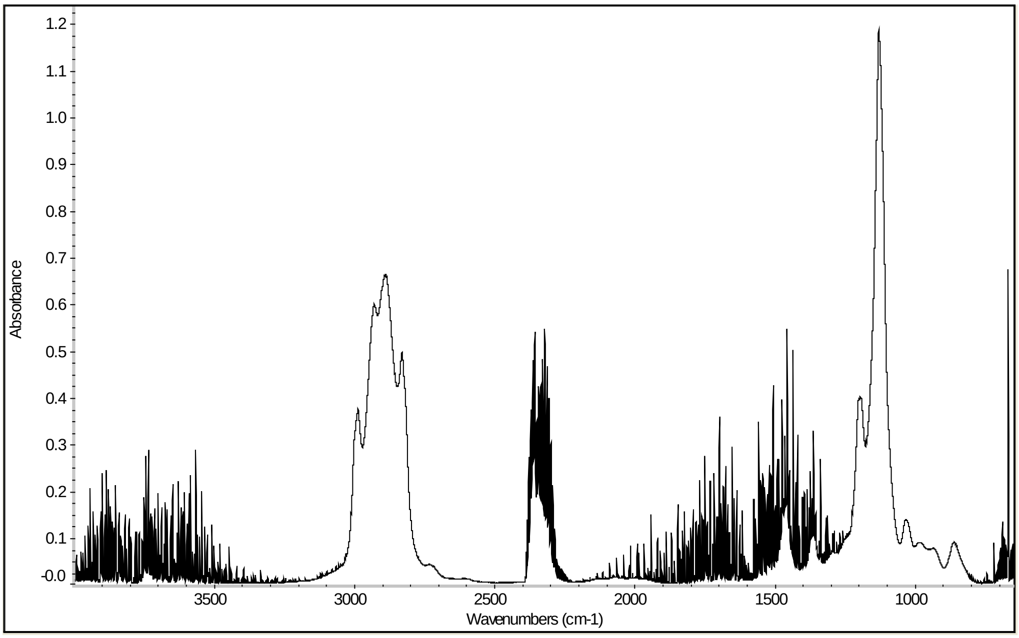


Figure 13 Spectra of Dimethoxyethane (DME) evaporated in the Cone Calorimeter.

Figure 13 shows a spectrum of DME when evaporating from heating in the cone calorimeter with absorption bands around 1100 cm^{-1} and 2900 cm^{-1}. The highest distinctive peak is located at 1129 cm-^{1}.

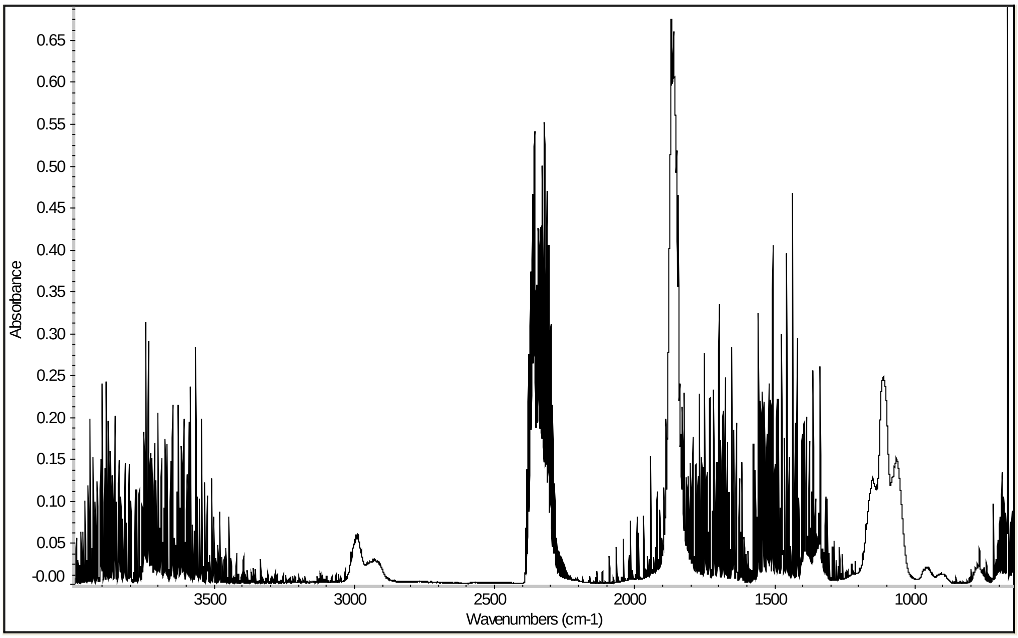


Figure 14 **Spectra of Propylene carbonate (PC) evaporated in the Cone Calorimeter.**

Figure 14 shows a spectrum of PC when evaporating from heating in the cone calorimeter with absorption bands around 1100 cm^{-1}, 1850 cm^{-1} and 2950 cm^{-1}. The two highest distinctive peaks are located at 1114 cm-^{1} and 1867 cm-^{1}.

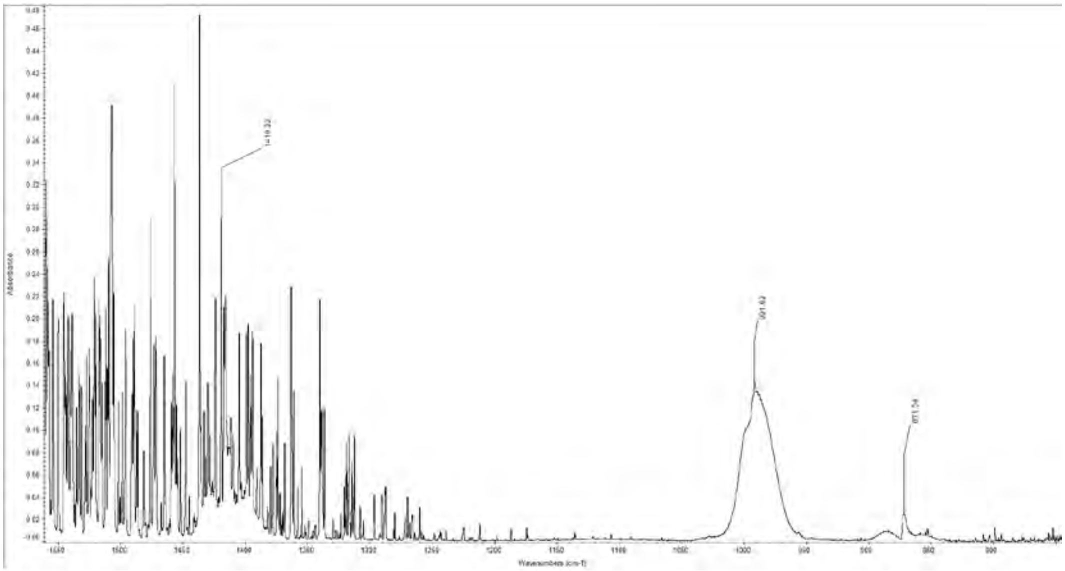


Figure 15 **Spectral bands of evaporation products from Lithium hexafluoride.**

Figure 15 show the spectral bands of POF_3 in a test where pure $LiPF_6$ salt was thermally decomposed in the cone calorimeter. HF could only be qualitatively identified here (not shown) as severe interference of water made quantification impossible in the region up to 4000 cm^{-1} which was the highest wavenumber measured in these early tests.

There are no traces of PF_5 or any decomposition products apart from POF_3 in the spectral range shown in Figure 13.

4.4.2 Evaporation tests with mixtures of components

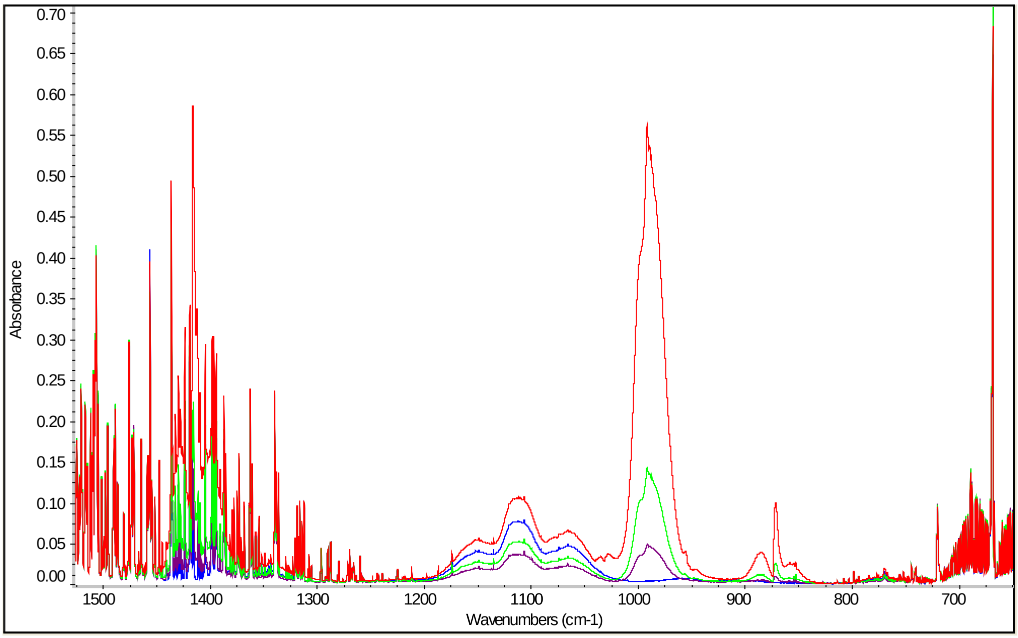


Figure 16 Series of spectra from evaporation test with $LiPF_6$ mixed in Polypropylene carbonate (PC). Spectra measured at 57 s (brown), 82 s (green), 157 s (red) and 257 s (blue) after start of heat exposure.

Spectra from an evaporation test with a saturated solution of $LiPF_6$ salt in PP are shown in Figure 14 above. The spectral band from the solvent is shown around 1100 cm^{-1} together with the three bands of POF_3 at 871 cm^{-1}, 991 cm^{-1} and 1416 cm^{-1}. It can be seen from the overlaid spectra that the emission of POF_3 ends before the solvent is totally evaporated (see blue spectrum from 257 s in Figure 14).

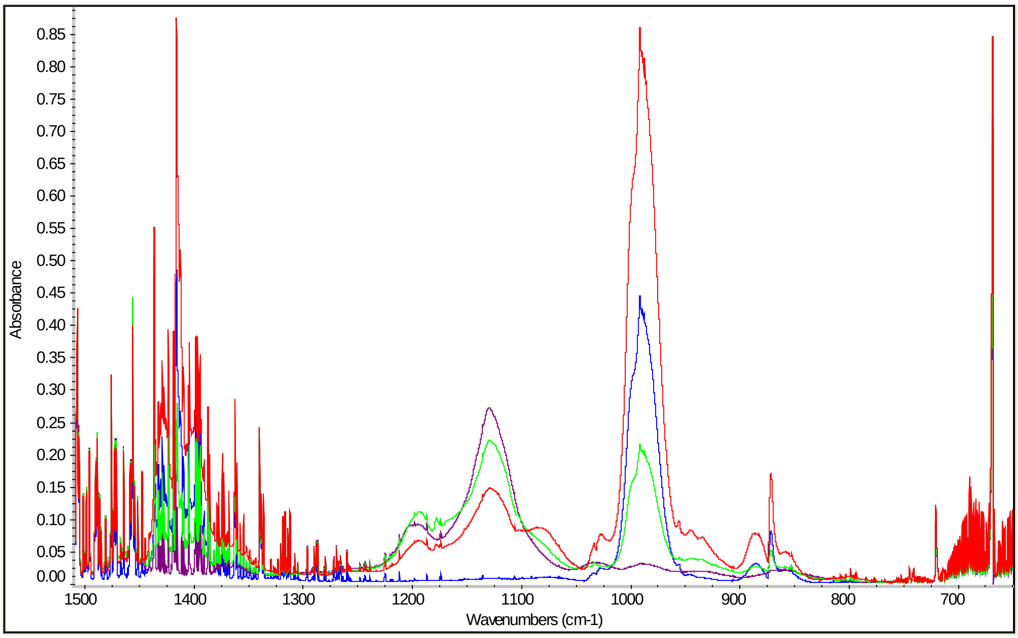


Figure 17 Series of spectra from evaporation test with $LiPF_6$ mixed in Dimethoxyethane (DME). Spectra measured at 30 s (brown), 67 s (green), 117 s (red) and 155 s (blue) after start of heat exposure.

Figure 17 shows a series of spectra from an evaporation test with a saturated solution of $LiPF_6$ salt in DME. Also here the spectral band from the solvent is shown around 1100 cm^{-1} together with the three bands of POF_3 at 871 cm^{-1}, 991 cm^{-1} and 1416 cm^{-1}. Here it can be seen from the overlaid spectra that the emission of POF_3 continues after that the solvent is totally evaporated (see blue spectrum from 155 s in Figure 15). This is the opposite behaviour compared to the solution of $LiPF_6$ salt in PC. One cannot, however, draw any conclusion from this as the emission behaviour of POF_3 here might be an effect of the saturation degree of the two mixtures.

4.4.3 Combustion tests

Test where saturated solutions of $LiPF_6$ salt in DME respective PC, were ignited in the cone calorimeter are reported below. In these tests the same level of external radiative heat flow was used as for the evaporation tests discussed above (10-15 kW/m^2). However, in these tests the electric spark igniter was used to ignite the evaporated fumes over the sample container.

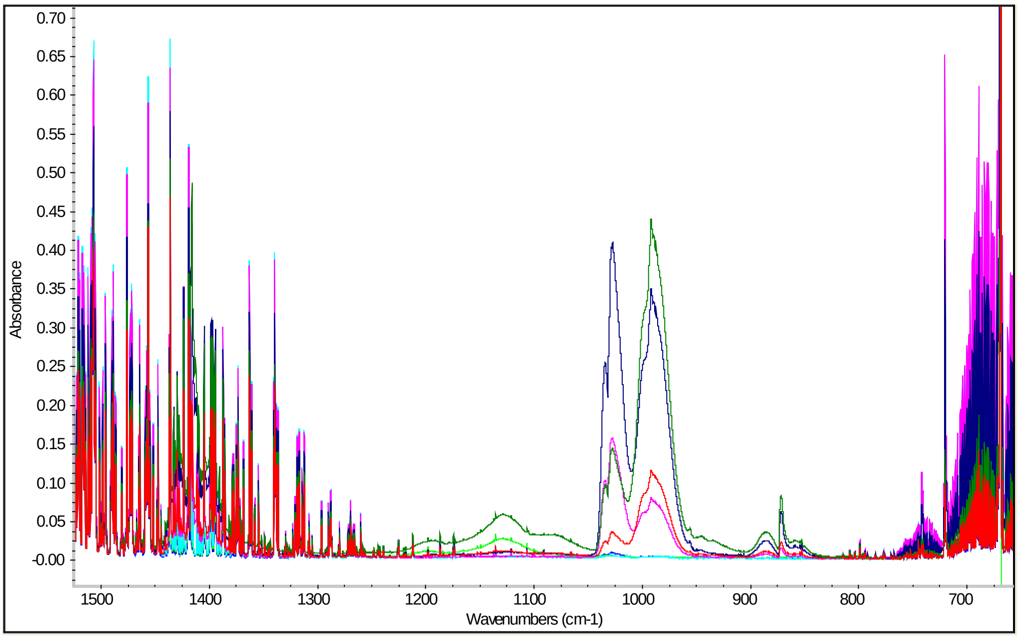


Figure 18 **Series of spectra from fire test with $LiPF_6$ mixed in Dimethoxyethane [DME]. Spectra measured at 5 s (light green), 29 s (aqua), 42 s (pink), 54 s (black), 67 s (dark green), 79 s (red) and 104 s (blue) after start of heat exposure. Ignition at 2 s after start. Flame-out at 95 s.**

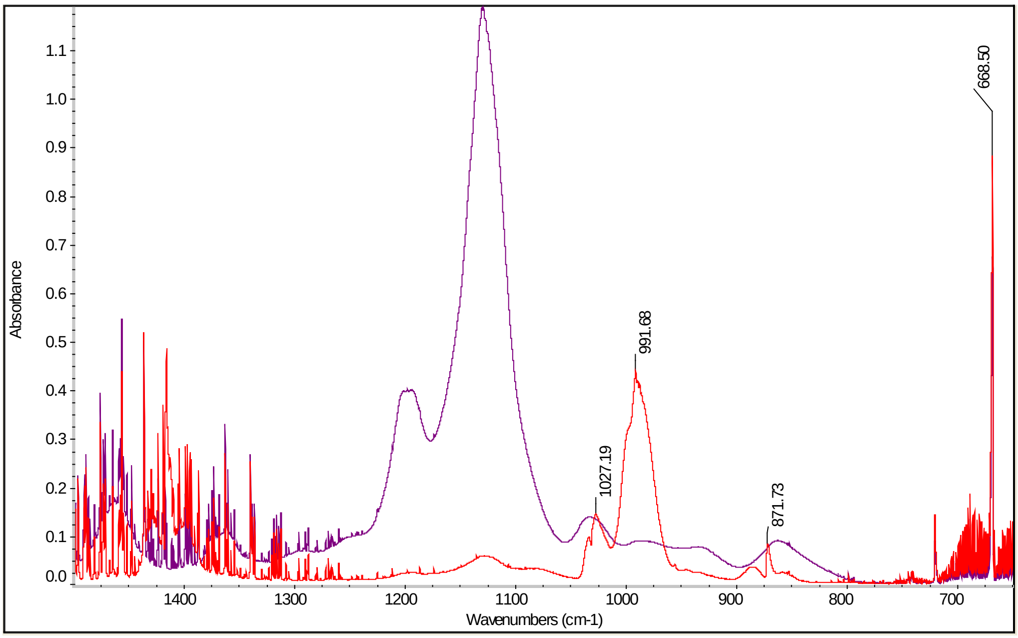


Figure 19 Spectra from the fire test with $LiPF_6$ mixed in DME at 67 s from start of test (red). Overlaid by spectra from evaporation test with DME (purple).

A series of spectra (overlaid) are shown in Figure 18 from the tests with $LiPF_6$ salt in DME. One can clearly see the characteristic spectral features of POF_3 during the period of combustion (2-95 s). Also HF was seen in the spectrum during this period (not shown above). The spectral band from the solvent is shown only in the first few spectra and in the spectrum from 67 s (see Figure 19). The combustion efficiency must have decreased at this time but extinction was not recorded until 95 s.

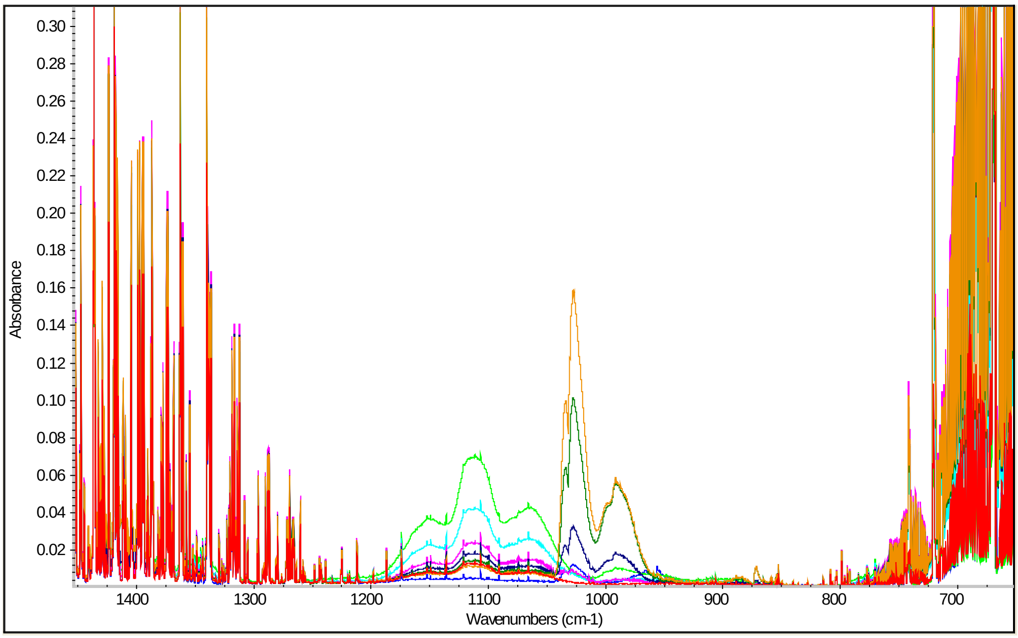


Figure 20 Series of spectra from fire test with $LiPF_6$ mixed in Polypropylene carbonate (PC). Spectra measured at 28 s (red), 53 s (light green), 78s (aqua), 90 s (pink), 103 s (black), 116 s (dark green), 128 s (orange) and 190 s (dark blue) after start of heat exposure. Ignition at 1 min 11 s after start. Flame-out at 170 s.

Figure 20 shows a series of spectra (overlaid) from the tests with $LiPF_6$ salt in PC. The spectral bands of POF_3 (the band at 992 cm^{-1} can be clearly seen in the figure) were seen in the spectra during the period of combustion (71-170 s). Also HF was seen as in the spectra during this period (not shown above). The spectral band from the solvent is clearly shown in the spectra before combustion.

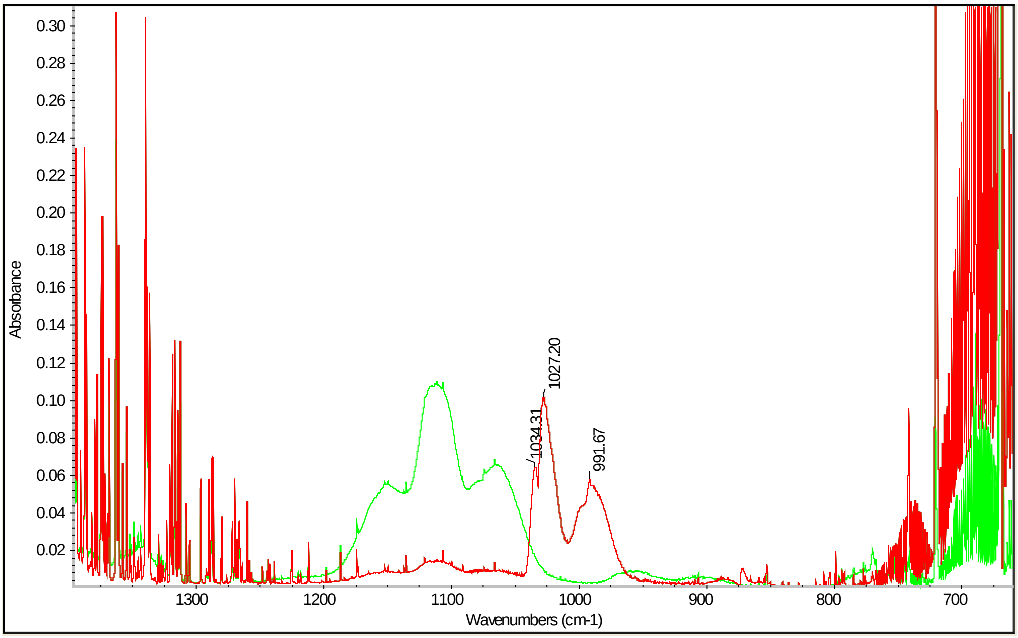


Figure 21 Spectra from the fire test with $LiPF_6$ mixed in Polypropylene carbonate at 116 s from start of test (red). Overlaid by spectra from evaporation test with Polypropylene carbonate (light green).

Figure 21 shows the spectrum collected at 116 s into the combustion test with $LiPF_6$ salt in PC. The spectra of pure PC has been overlaid. Also here one can see two additional peaks which do not originate from POF_3, one at 1027 cm^{-1} and one at 1034 cm^{-1}.

The combustion tests with electrolyte solvents of $LiPF_6$ salt showed that HF and also POF_3 are present in the combustion effluents. This is an important finding. Further, unidentified spectral absorption bands indicate the presence of an additional, possibly fluorine containing, decomposition product.

5 Burner tests with electrolyte

Tests were conducted by using a small propane burner about 2 cm in diameter in which electrolyte salt solutions were introduced through needles or on a spoon as seen in Figure 21. The amount of propane inserted was controlled by a variable area flow-meter. Two different amounts of propane were used, i.e. 7 scale points on the flow meter scale and 5 scale points. The Heat Release Rate (HRR) was measured in all tests. The HRR was found to be 4.8 kW for the 7 scale point case (referred to as the “normal case” below) and 3.2 kW for the 5 scale point case (referred to as the “lower case” below). The amount of electrolyte inserted was controlled by two HPLC pumps.

The Heat Release Rate from the fire was measured by using Oxygen Consumption Calorimetry in the cone calorimeter hood. In some experiments the cone heater and load cell was used. FTIR measurement were made in all tests. The FTIR measurement system is described in Section 2. A schematic of the cone calorimeter is provided in Figure 20.

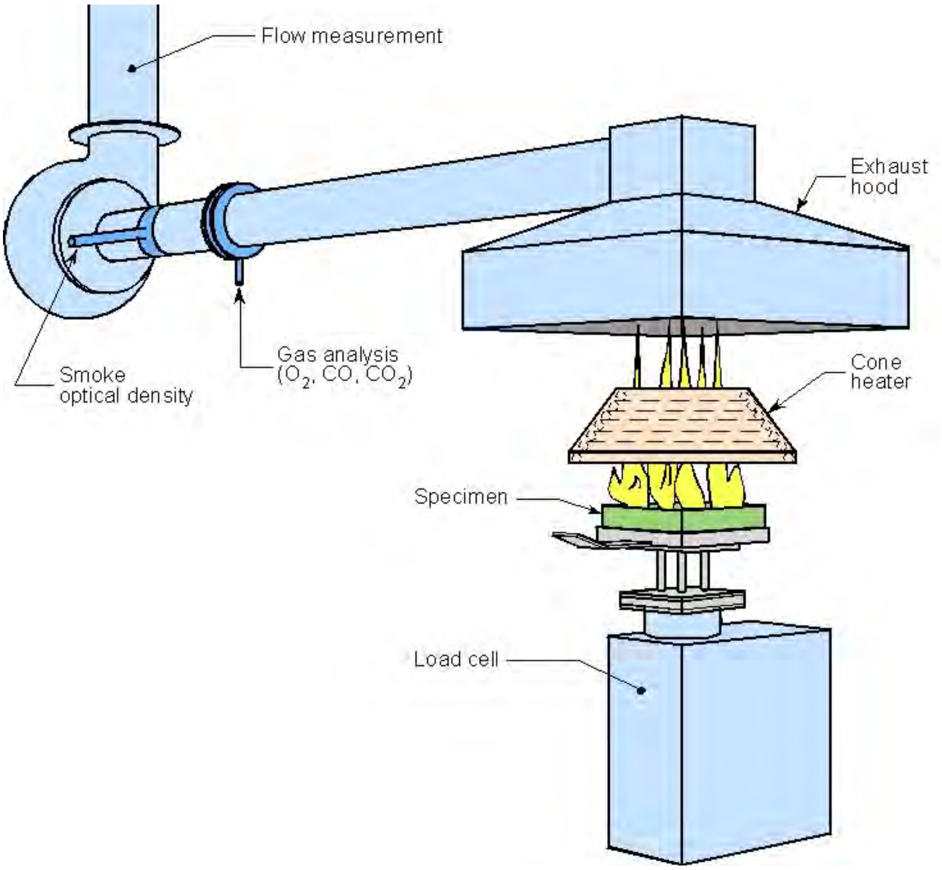


Figure 22 **The cone calorimeter. The heater and load cell was not used in the major part of the tests.**

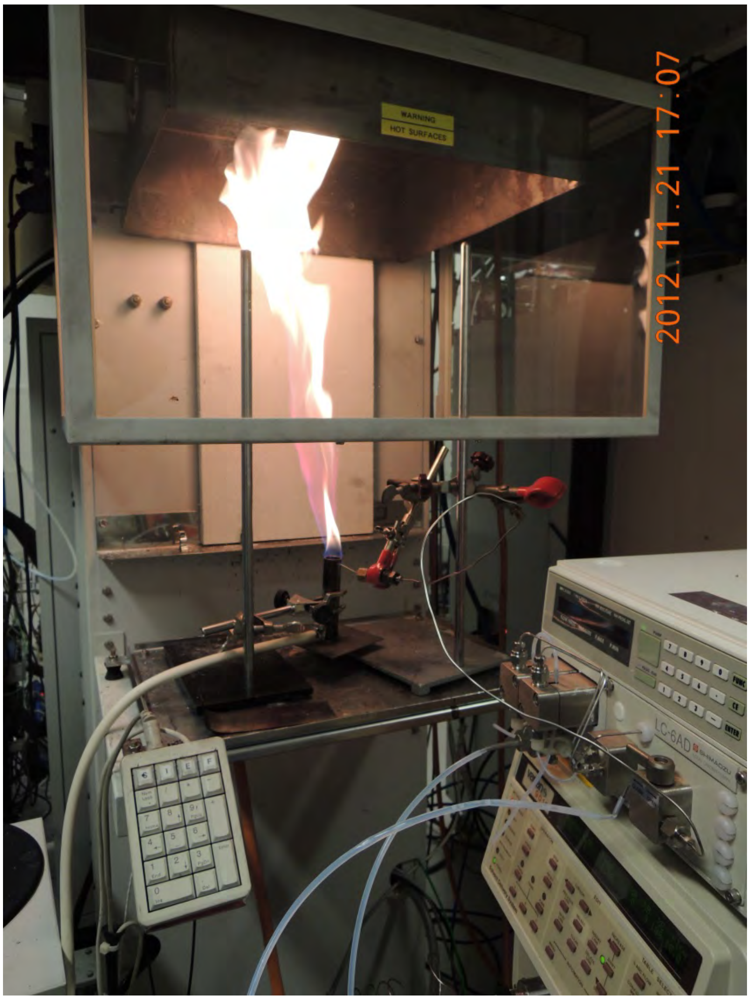


Figure 23 Experimental set-up with the needle inserted in the burner.

5.1 Electrolyte – salt solutions

Solutions of $LiPF_6$ (99 %, Sigma-Aldrich) were prepared by dilution in dimethylcarbonate (DMC, 99% Sigma-Aldrich) and 1,2-dimethoxy ethane (DME, 99% Sigma-Aldrich). The DMC solutions were 1.0 M and 0.4 M respectively and the DME solution was 0.4 M.

5.2 Tests conducted

Tests were conducted in two batches. In the first batch it turned out that the needles became clogged with the salt and it was difficult to produce a spray. Custom made needles were therefore ordered and a new batch of tests was conducted with the new needles.

Tests conducted in the first batch are listed in Table 4. Further description of the test procedures and results is provided in Appendix A. In this batch the propane flow was the same in all tests. The way the solvent and salt were introduced into the flame was varied and the amount was varied. Due to difficulties with achieving a stable spray and clogging of the needles it was not possible to conduct any tests where water was introduced together with salt and solvent.

Table 4 Tests conducted in first batch.

Test nr	Type of test	Fuel	Comment
1	burner	Propane only	Initial test to determine propane HRR
2	Burner + needle	Propane and 5.9 ml/min DME	DME works not as spray but as a beam, possibility that all DME not burnt
3	Burner + Needle	Propane and 5.9 ml/min DME	Needle in bottom of burner instead of top
4	Burner + Needle	Propane and 5.9 ml/min DME	Needle inserted outside of burner
5	Burner + spoon	Propane and 2.4 ml/min DMC	Not a very successful attempt
6	Burner + Needle	Propane and 12 ml/min DMC	and later 5 ml/min
7	Burner + Needle	Propane and 20 ml/min DMC	Interrupted as holder melted
8	Burner + Needle	Propane and 20-18 ml/min DMC	Burner placed a bit lower under the collecting hood
9	Burner + Needle	Propane and DMC 18 ml/min	
10	Burner + Needle	Propane and DMC 18 ml/min with 1 M salt	
11	Burner + needle	Propane and DME 18 ml/min	
12	Burner + needle	Propane and DME 18 ml/min with 0.4 M salt	
13	Burner + Needle	Propane and DMC 18 ml/min 1 M salt	
14	Burner + Spoon	Propane and DMC 1.8 ml/min	
15	Burner + spoon	Propane and DMC 1.8 ml/min + 1M salt	
16	Burner + spoon	Propane and DME 1.8 ml/min + 0.4 M salt	
17	cakecup	DMC + salt 1:1	No external heating, did not burn very well
18	cakecup	DME + salt 1:1	No external heating, did not burn very well

The tests conducted in the second batch are presented in Table 5, additional information about the test procedures can be found in appendix A. The tests were conducted using the same burner as used in the first batch of tests. Two different propane flows were used, 7 and 5 scale points on the flow meter, resulting in a HRR of 4.8 and 3.2 kW respectively. These HRR levels were in the same order of magnitude as the HRR resulting from the electrolyte burning. Most of the tests were conducted on DMC. The salt concentration in the DMC was varied together with the amount of DMC introduced into the flame. In addition some tests were conducted where water was introduced into the flame. The duration of these tests was however, limited because despite careful design of needles that were custom made for this project we encountered problems with creating a stable spray for long periods of time.

Table 5 Tests conducted in second batch.

Test nr	Injection	Other conditions
20	none	Normal propane 7 sp
21	none	Normal propane and water 7 - 8 min and 10 - 11 min
22	15 ml/min 2 min 1 M = 30 ml M	Normal propane 7 sp DMC
23a	15 ml/min 4.5 min 0.4M = 27 ml M	Normal propane during 3 minutes, lower during 1.5 min DMC
23b	15 ml/min 3 min 0.4M = 18 ml M uncertainty for the 15 ml/min, according to HRR only about half	5 skd propane DMC
24	10 ml/min 3 min 1 M (initial 5 minutes injection problematic)	7 sp propane, short while at end with water injection DMC
25	15 ml/min 1 M 2:45 = 41 ml M	7 sp propane DMC
26a	15 ml/min 1 M 1:45	7 sp propane DMC
26b	Cleaning system with water	
26c	15 ml/min 1 M 1:30	7 skd propane, water at end DMC
27	1 M salt in DMC in cakecup	
28	0.4 M salt in DME in cakecup	

5.3 Test Results

Results from tests were $LiPF_6$ salt was injected in the first test batch are presented in Figure 22 - Figure 36. For these tests is HRR presented together with an indication of when different injections were conducted by means of coloured lines in the graphs. In addition are graphs presented with HRR on the left axis and the HF concentration in the exhaust duct on the right hand side axis. Finally one graph is presented for each of these tests where the HF concentration in the exhaust duct is given on the left hand side axis and the POF_3 concentration in the duct on the right had side axis.

When studying the graphs it is important to remember that the concentrations presented are concentrations in the exhaust duct. These depend on the gas flow in the exhaust duct and the amount of salt and electrolyte introduced into the flame. They should not be considered as the concentration in the vicinity of a burning vehicle but are only presented here as concentrations in order to evaluate changes in amount produced due to changes in flame composition etc.

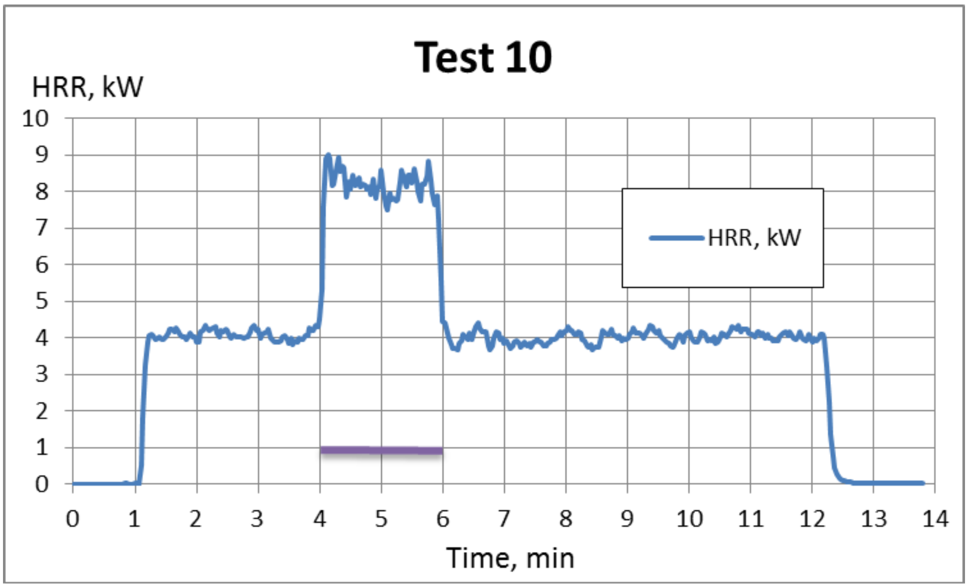


Figure 24 Heat Release Rate (HRR) from test 10. DMC and salt injection (18 ml/min with 1 M salt) indicated as a purple line between time 4 and 6 minutes.

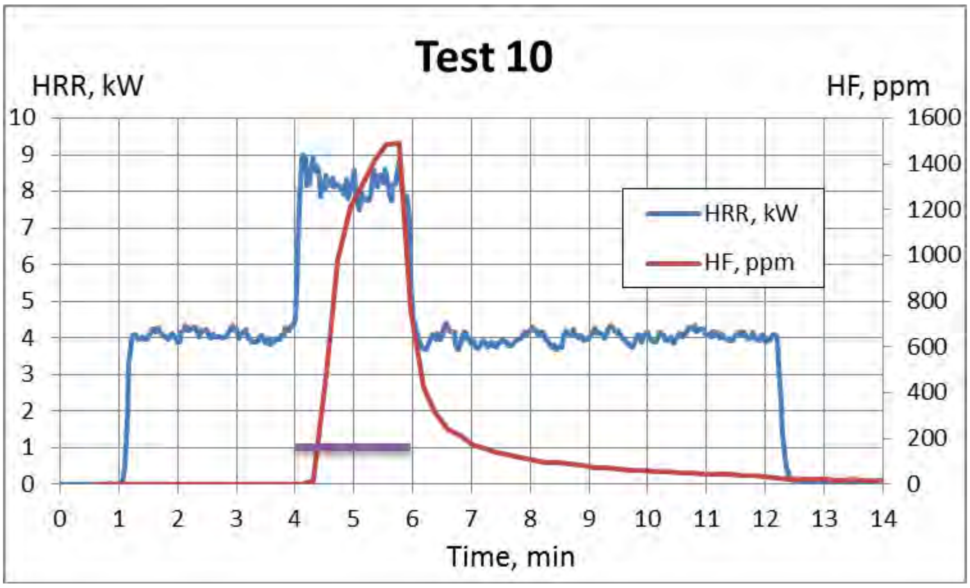


Figure 25 HRR and HF concentration during Test 10. DMC and salt injection (18 ml/min with 1 M salt) indicated as a purple line between time 4 and 6 minutes.

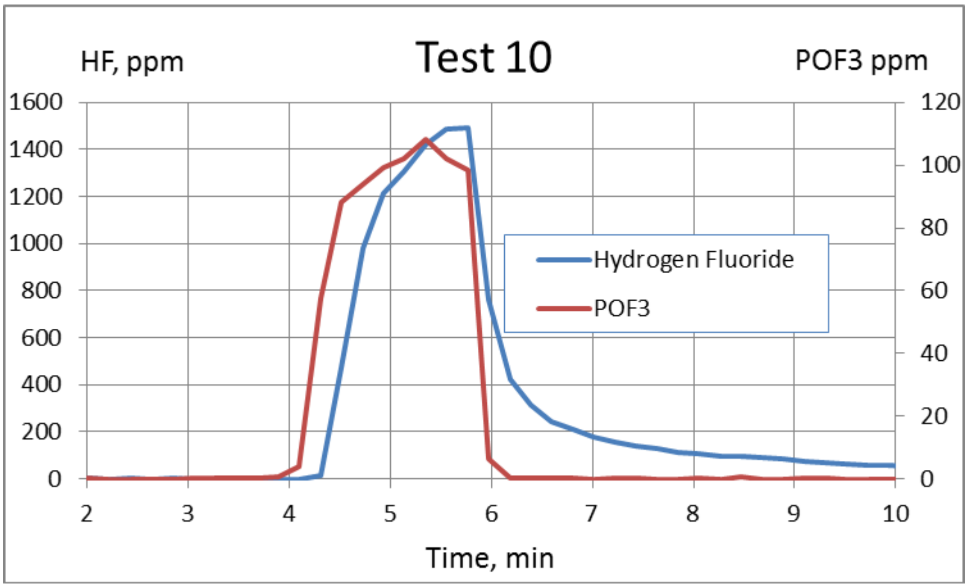


Figure 26 HF and POF_3 concentration as a function of time for test 10. DMC with salt was injected during time 4 to 6 minutes.

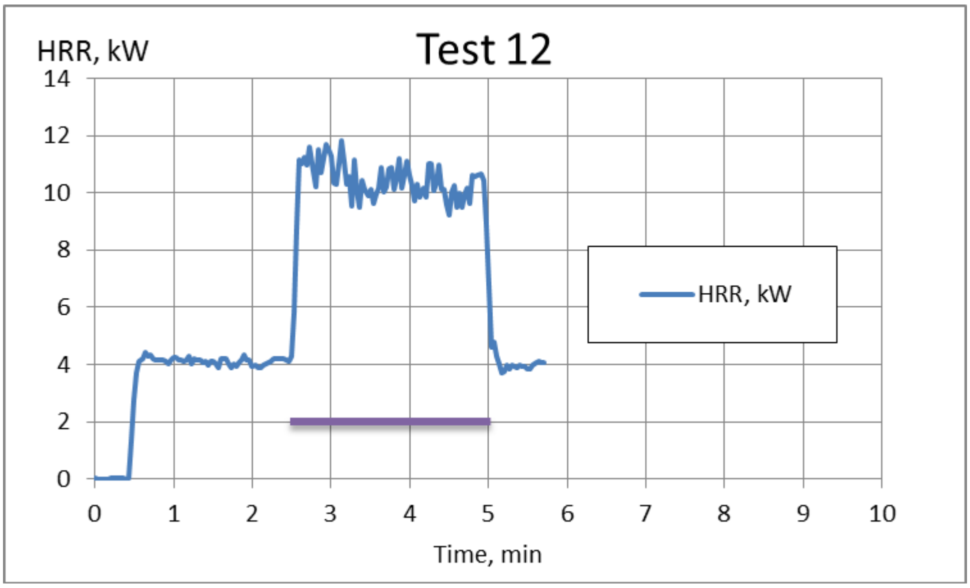


Figure 27 HRR as function of time for test 12. The time period under which DMC with salt was introduced into the flame is indicated with a purple line (2.5 minutes – 5 minutes).

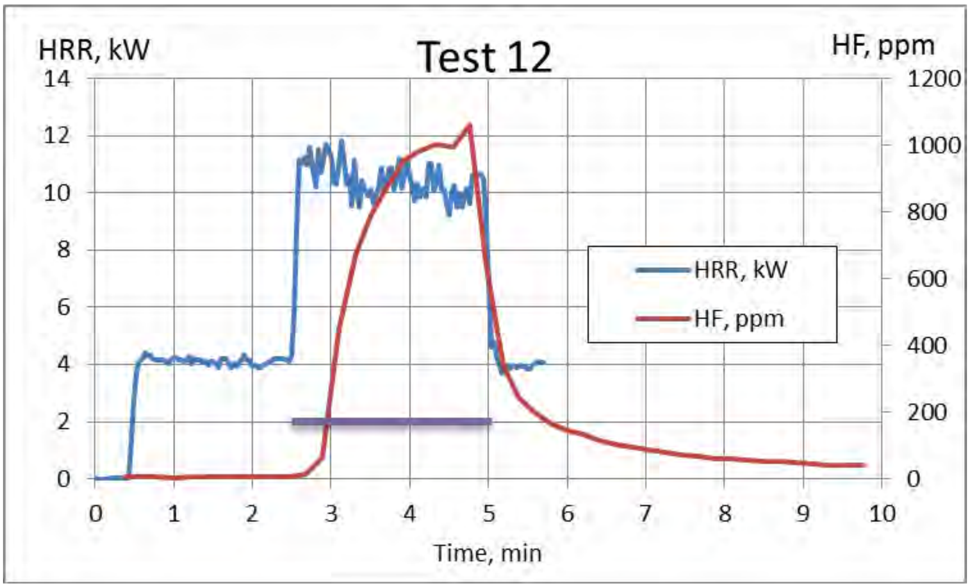


Figure 28 **HRR and HF concentration as function of time for test 12. The time period under which DMC with salt was introduced into the flame is indicated with a purple line (2.5 minutes – 5 minutes).**

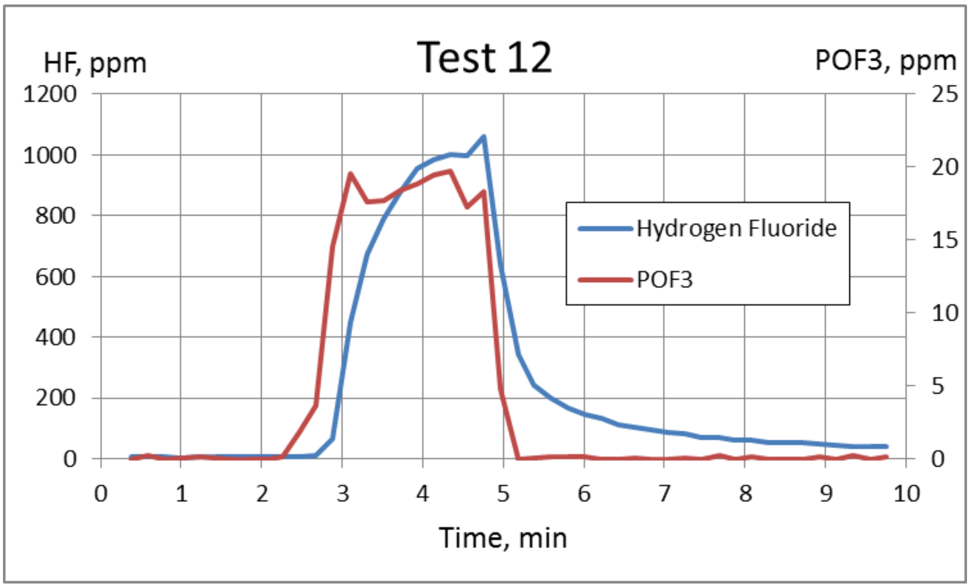


Figure 29 **HF and POF_3 concentration as a function of time for test 12. DME with salt was injected during time 2.5 to 5 minutes.**

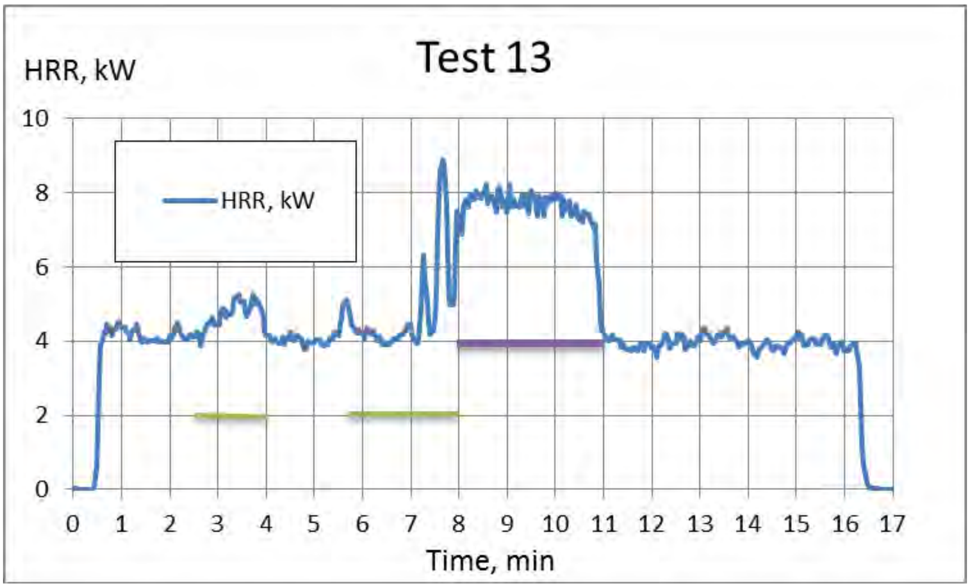


Figure 30 HRR as function of time for test 13. Initial spray attempt with DMC starting at 2:30 had to be interrupted at 4:00 due to difficulties with spray. Second period of pure DMC at time 5:40 until 8:00, both DMC periods indicated with green line in figure. The time period under which DMC with salt was introduced into the flame is indicated with a purple line (8 minutes – 11 minutes).

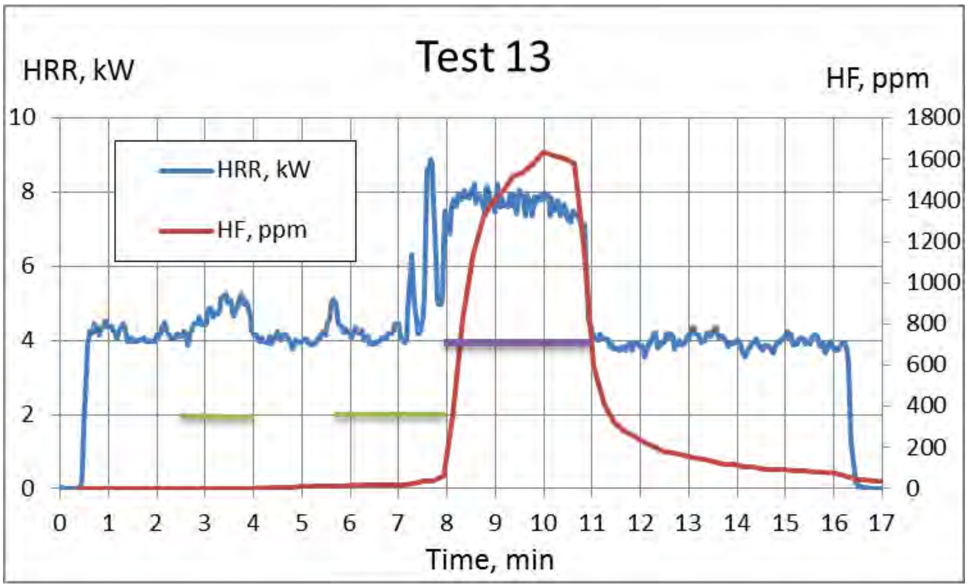


Figure 31 HRR and HF concentration as function of time for test 13. Initial spray attempt with DMC starting at 2:30 had to be interrupted at 4:00 due to difficulties with spray. Second period of pure DMC at time 5:40 until 8:00, both DMC periods indicated with green line in figure. The time period under which DMC with salt was introduced into the flame is indicated with a purple line (8 minutes – 11 minutes).

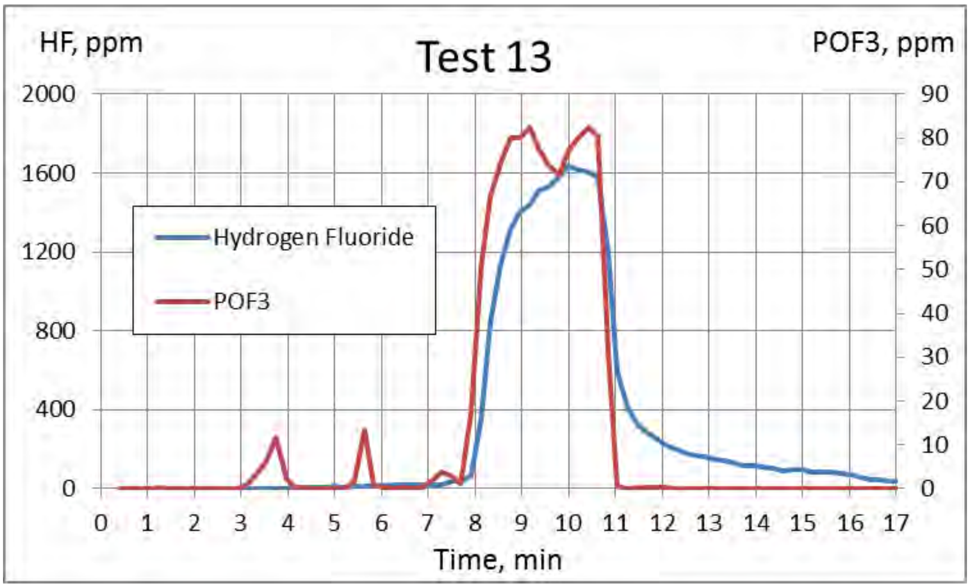


Figure 32 HF and POF_3 concentration as a function of time for test 13. DMC with salt was injected during time 8 to 11 minutes.

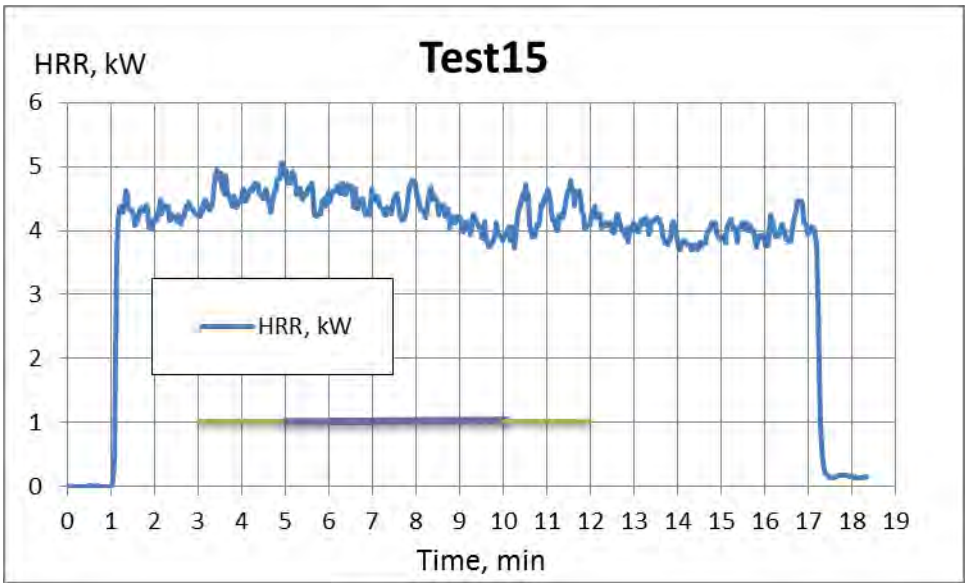


Figure 33 HRR as a function of time for test 15. DMC and salt was inserted through a needle onto a spoon in the flame during time 5 minutes to 10 minutes, DMC only was injected between times 3 and 5 minutes and 10 and 12 minutes.

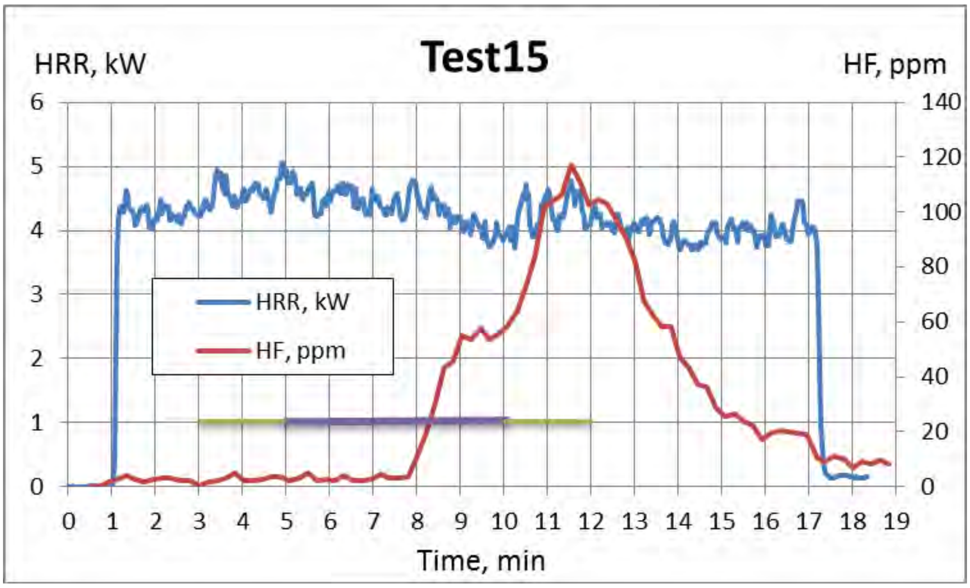


Figure 34 HRR and HF concentration as a function of time for test 15. DMC and salt was inserted through a needle onto a spoon in the flame during time 5 minutes to 10 minutes.

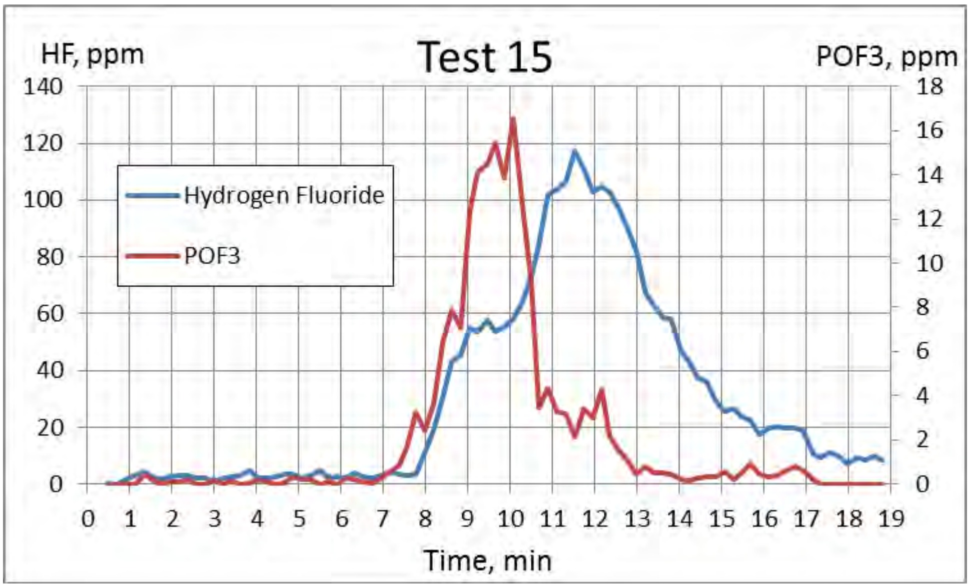


Figure 35 HF and POF_3 concentration as a function of time for Test 15. DMC and salt was inserted through a needle onto a spoon in the flame during time 5 minutes to 10 minutes.

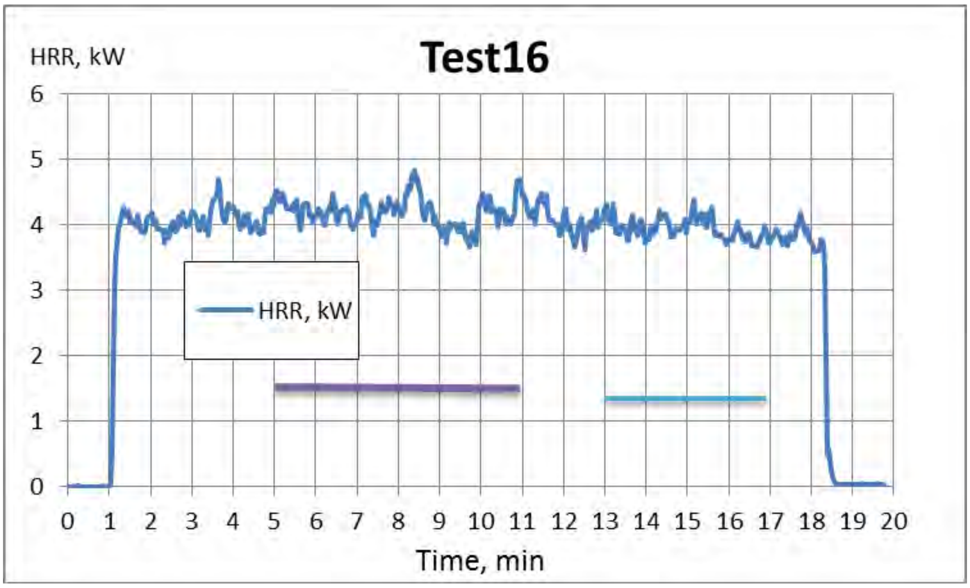


Figure 36 HRR as a function of time for test 16. DME and salt was inserted through a needle onto a spoon in the flame during time 5 minutes to 11 minutes. During time 13 to 17 minutes water was inserted to the spoon instead.

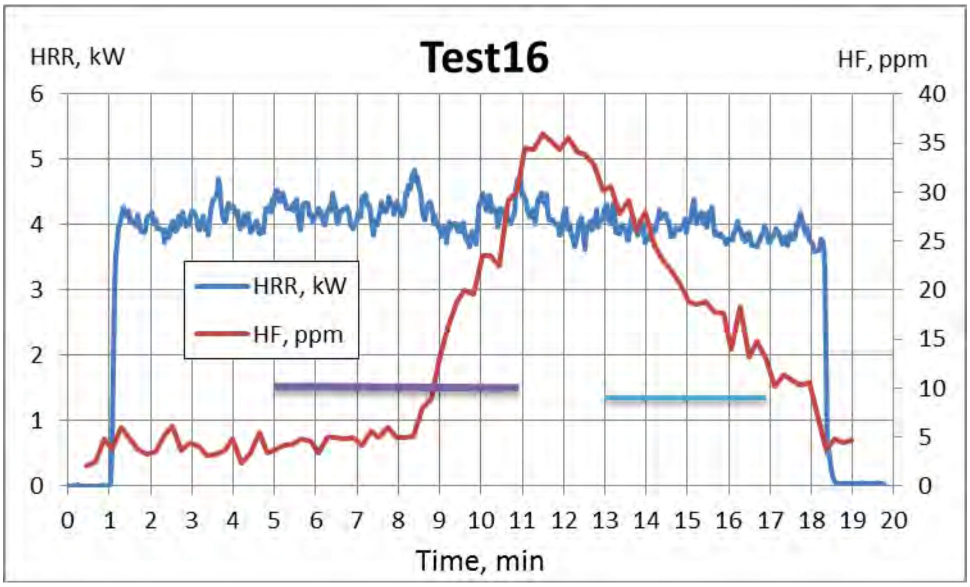


Figure 37 HRR and HF concentration as a function of time for test 16. DME and salt was inserted through a needle onto a spoon in the flame during time 5 minutes to 11 minutes. During time 13 to 17 minutes water was inserted to the spoon instead.

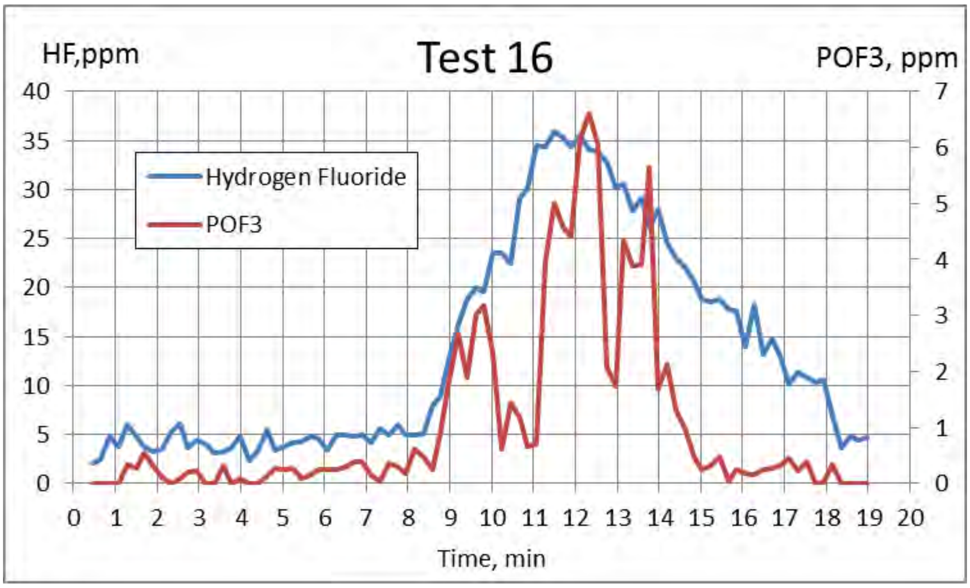


Figure 38 HF and POF_3 concentration as a function of time for Test 16. DME and salt was inserted through a needle onto a spoon in the flame during time 5 minutes to 11 minutes. During time 13 to 17 minutes water was inserted to the spoon instead. Note that the concentration of POF_3 measured here was below the limit of quantification.

The FTIR measurements showed that both HF and POF_3 were always present in the combustion effluents when electrolytes were burning. The measured concentration of HF was always significantly higher than POF_3, often about 20 times higher.

Test 10-16 all shows that the POF_3 seems to appear a bit earlier than HF, this is particular apparent in test 15. It is known that losses of HF occurs in the measurement system and especially in the sampling filter[5]. The effect is most significant at measurements of low concentrations as the proportion captured in the filter in such cases is high compared to the total amount HF sampled through the filter. An effect of HF-losses in the filter is an initial increased response time (until the sampling system is saturated) that can be significant especially in measurements of low concentrations. The filter was exchanged before test 14 but as test 14 was interrupted the filter can be considered as being new for test 15.

Selected filter used in the measurements reported below (test 22-test 27) were analysed for total fluorine content. The analysis results showed that the amounts lost in the filter were low, normally around 5 % on weight basis.

Test results from the second batch of tests are presented in Figure 37 - Figure 53. The result are presented for the tests where solvent and salt was introduced into the flame. For all tests the HRR curve is presented including the HRR from the propane. Different injections are indicated with different colours in the figures, i.e. green for solvent only, purple for salt and solvent, and different blue colours for water and alcohol.

An example of how the flame look liked when salt was injected is given in Figure 39.

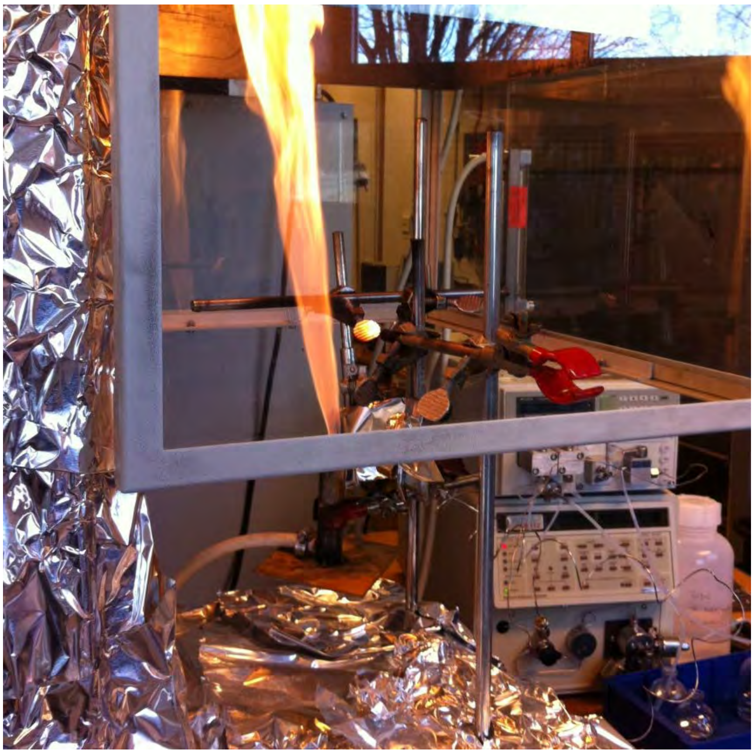


Figure 39 Example of flame when electrolyte and salt is injected, test 25

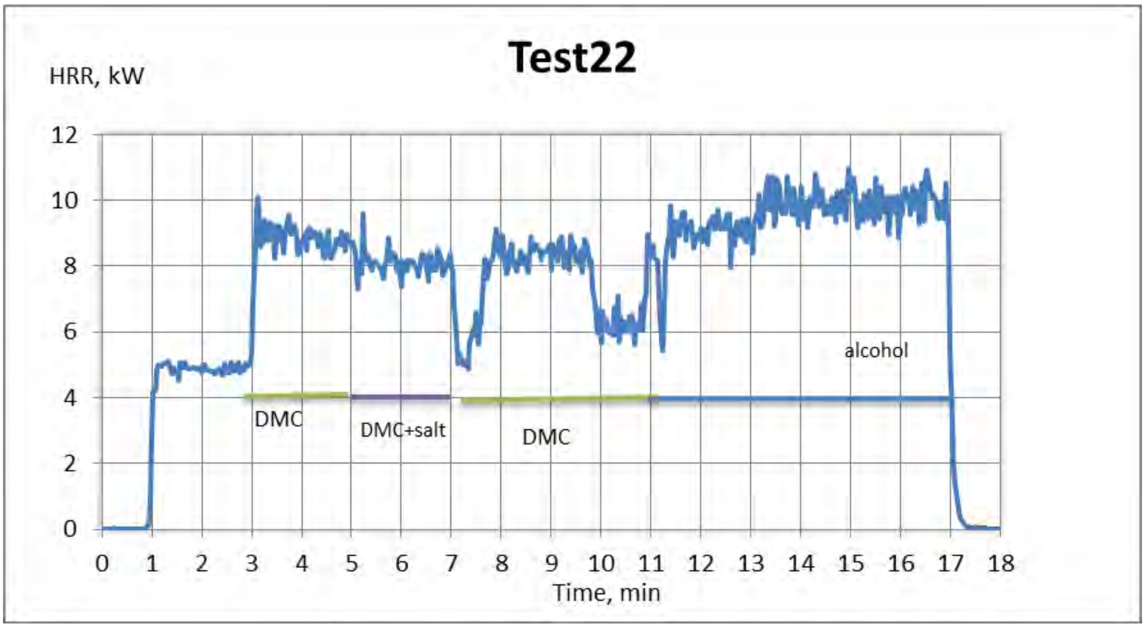


Figure 40 HRR as a function of time for test 22. The different injections period are indicated with a green line for pure DMC, purple line for DMC + salt and a blue line for cleaning with alcohol at the end of the test.

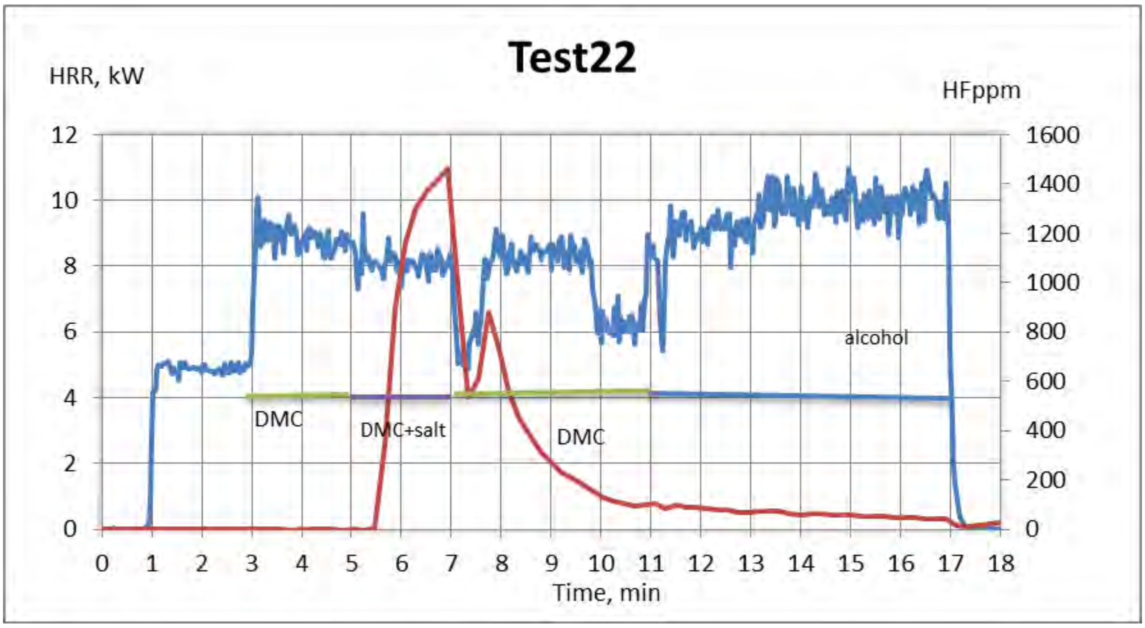


Figure 41 HRR and HF concentration as a function of time for test 22. The different injections period are indicated with a green line for pure DMC, purple line for DMC + salt and a blue line for cleaning with alcohol at the end of the test.

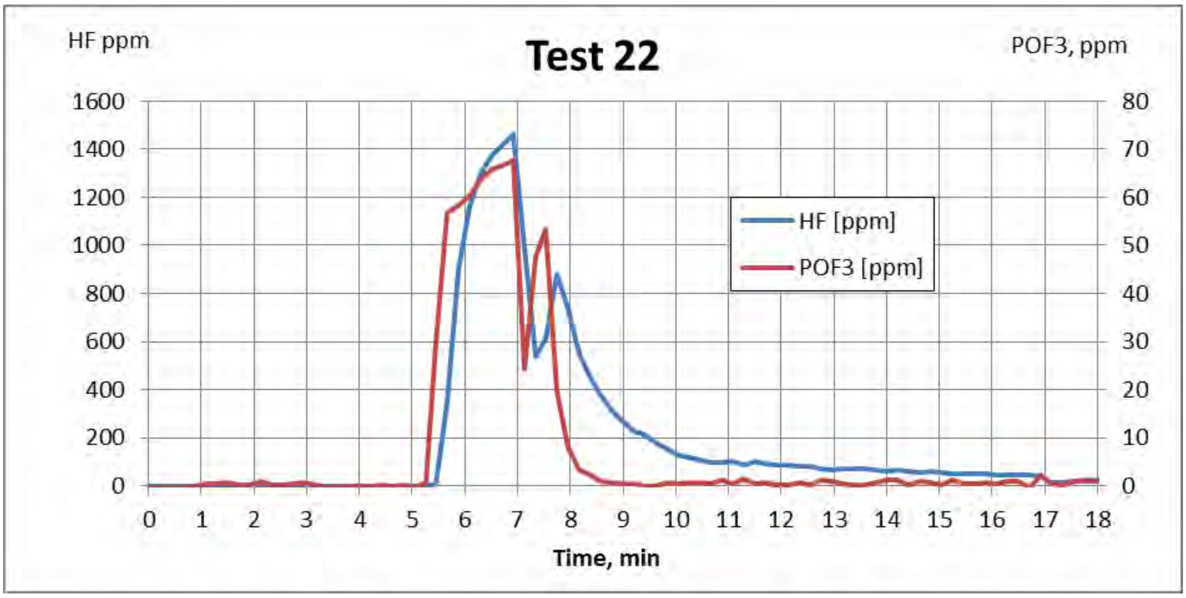


Figure 42 HF and POF_3 concentration as a function of time for test 22. DMC with salt was injected under time 5-7 minutes.

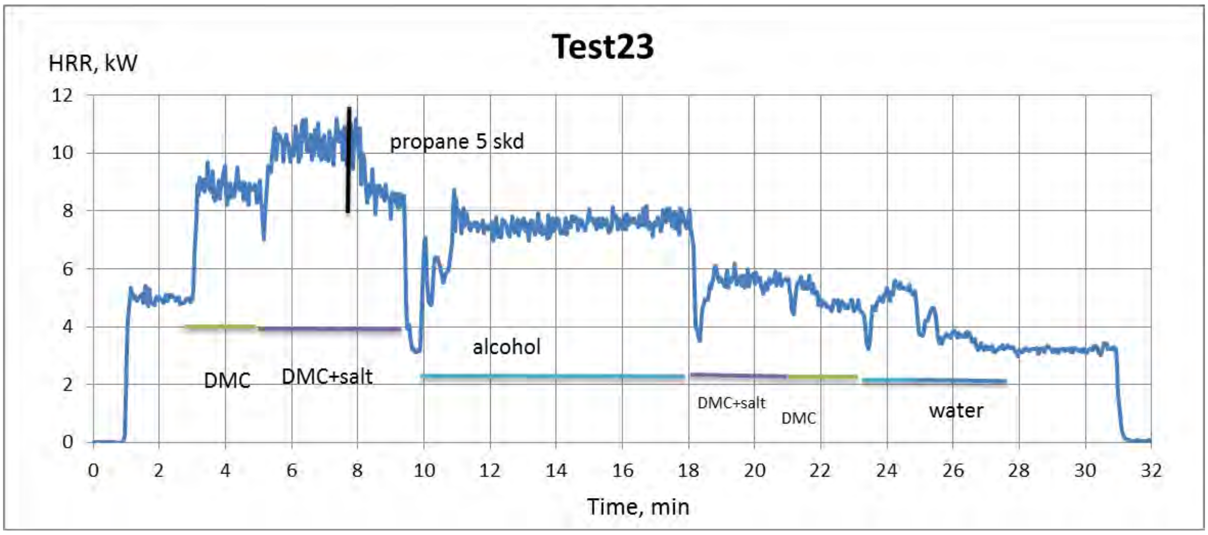


Figure 43 HRR as a function of time for Test 23. The different injections are indicated as green line for DMC only, purple line for DMC with salt (5 minutes until 9:30 and then again 18 until 21 minutes), light blue for alcohol and darker blue for water.

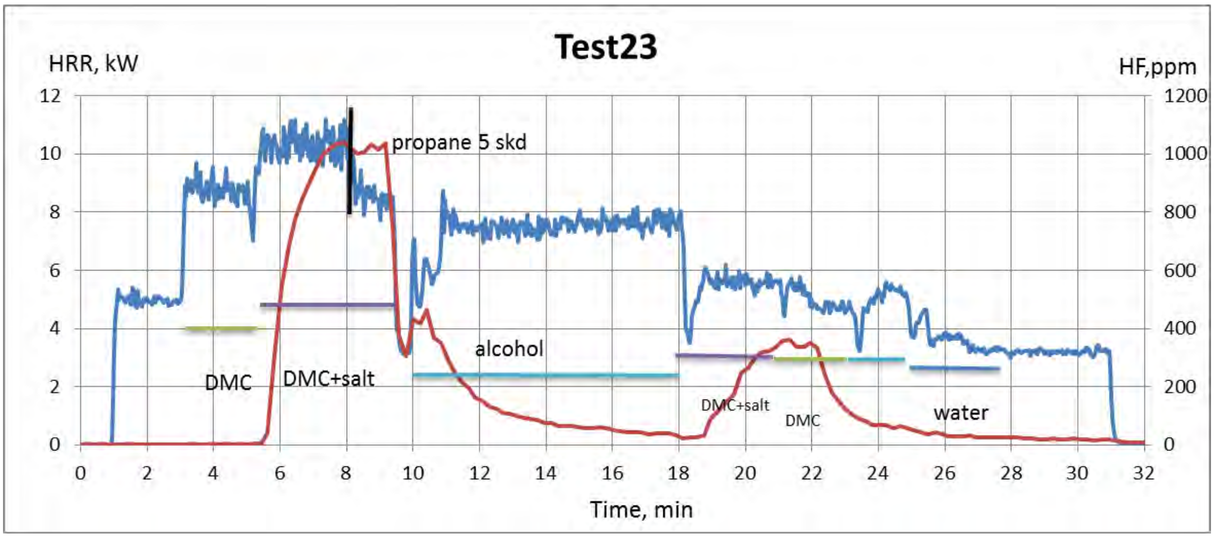


Figure 44 HRR and HF concentration as a function of time for Test 23. The different injections are indicated as green line for DMC only, purple line for DMC with salt, light blue for alcohol and darker blue for water.

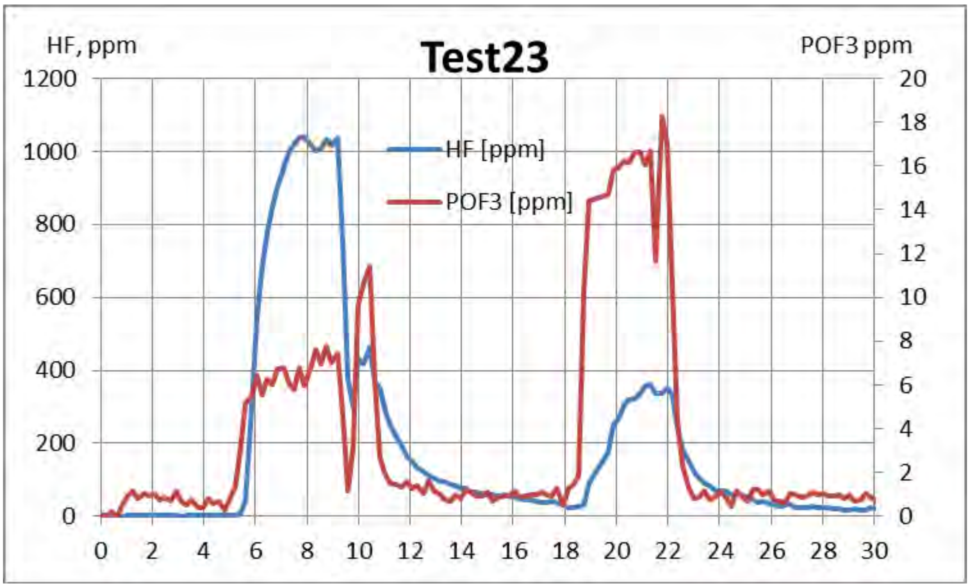


Figure 45 HF and POF_3 concentration in exhaust gases as a function of time for test 23. DMC + salt was injected during time 5 minutes until 9:30 and then again between time 18 and 21 minutes.

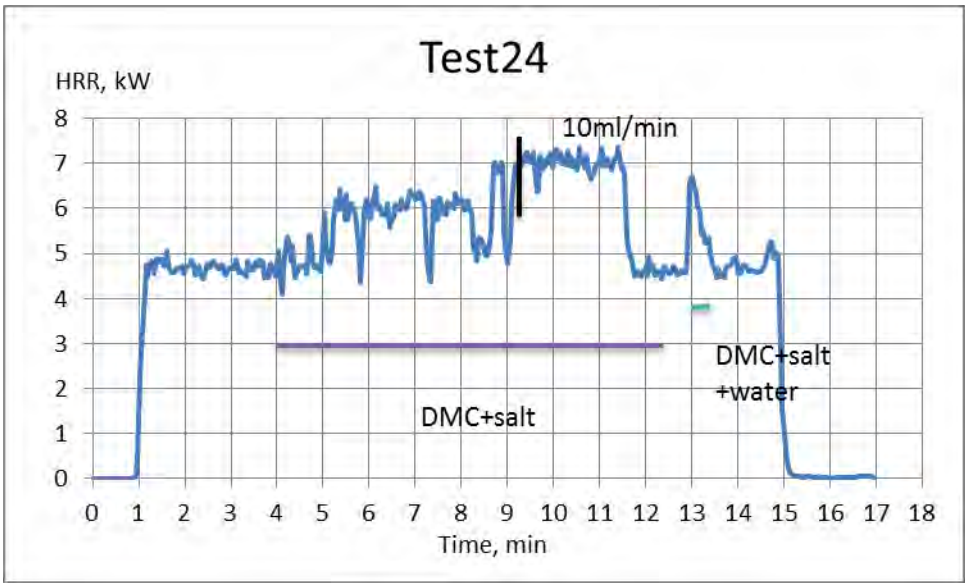


Figure 46 HRR as a function of time for test 24. DMC and salt was injected during time 4 minutes until 12:30, the spray did not work correctly until time 9:15.

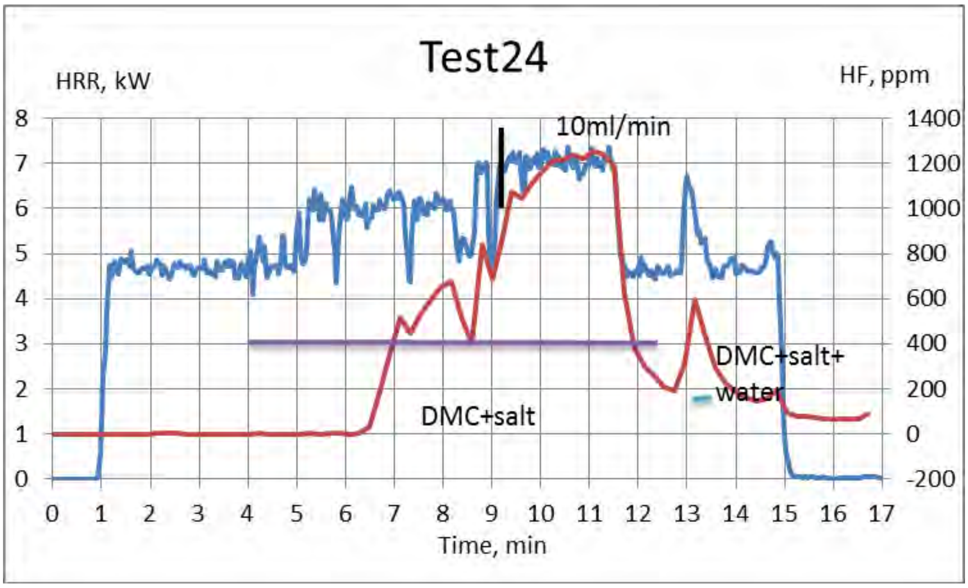


Figure 47 HRR and HF concentration as a function of time for test 24. DMC and salt was injected during time 4 minutes until 12:30, the spray did not work correctly until time 9:15.

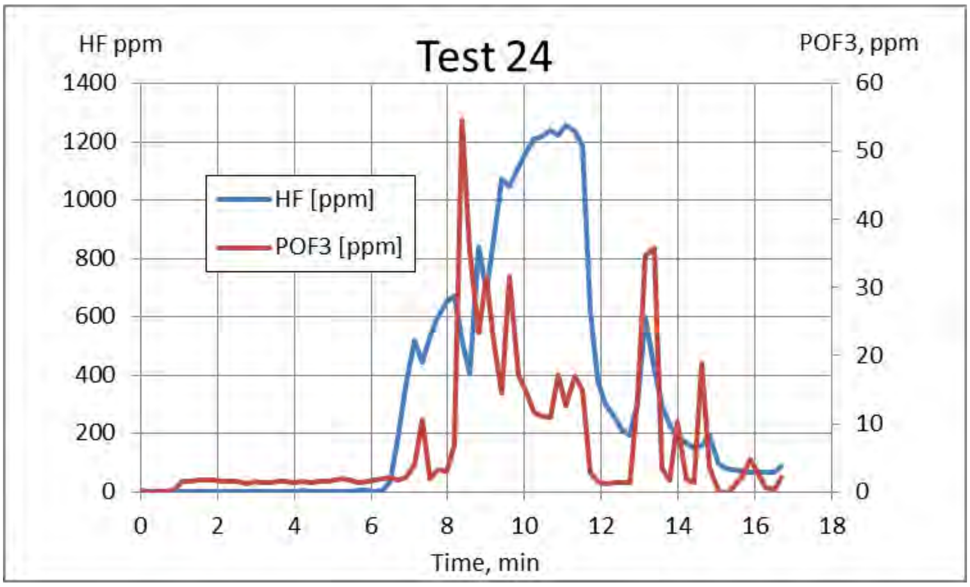


Figure 48 POF_3 and HF concentration as a function of time for test 24. DMC and salt was injected during time 4 minutes until 12:30, the spray did not work correctly until time 9:15.

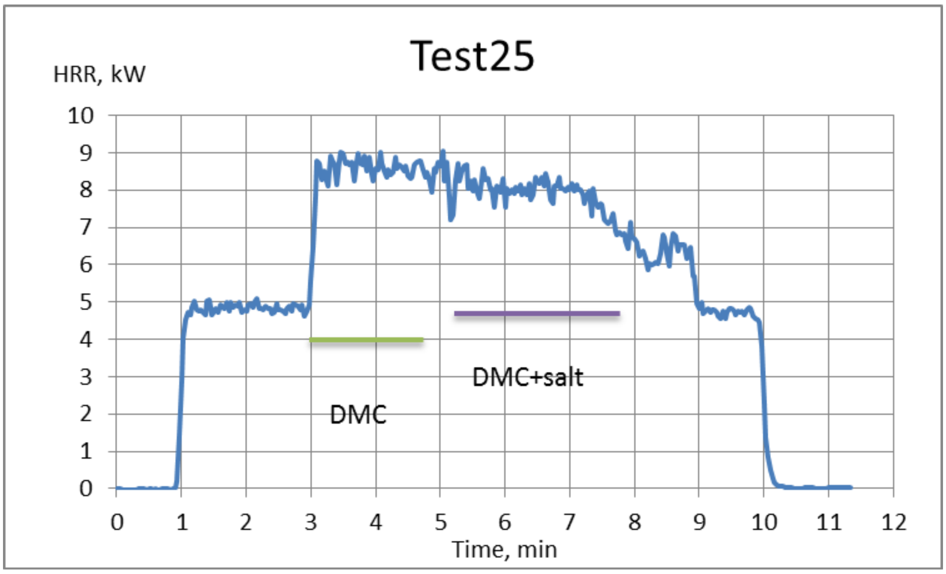


Figure 49 HRR as a function of time for test 25.

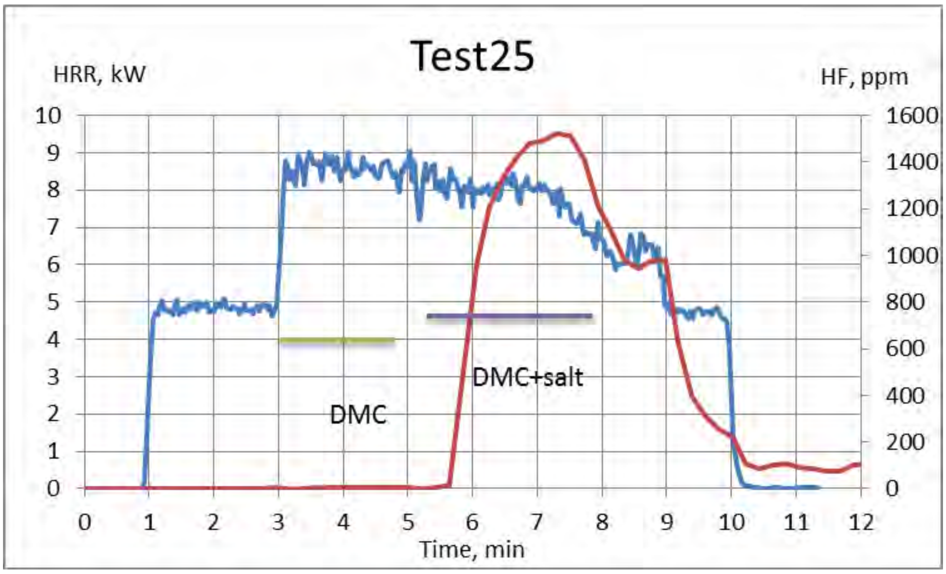


Figure 50 HRR and HF concentration as a function of time for test 25.

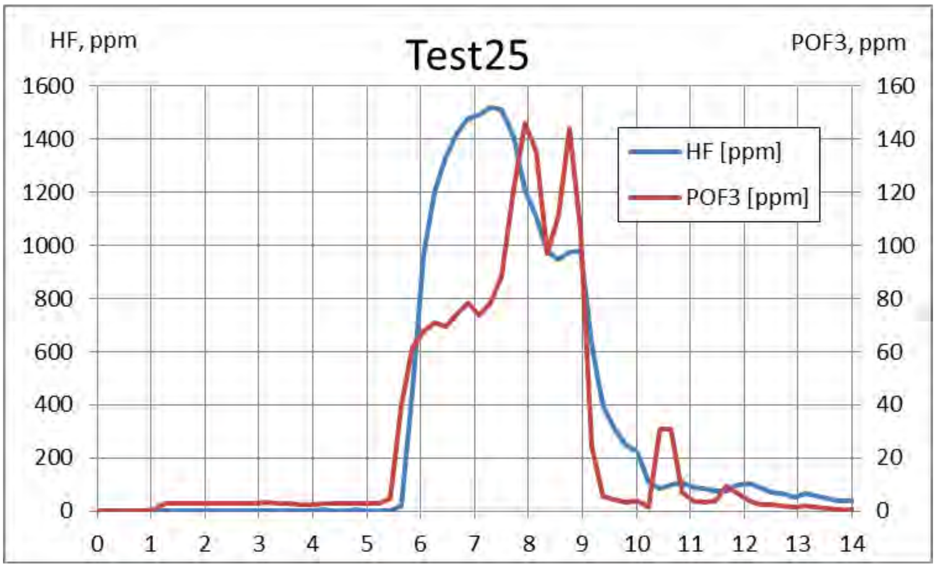


Figure 51 HF and POF_3 concentration as a function of time for test 25.

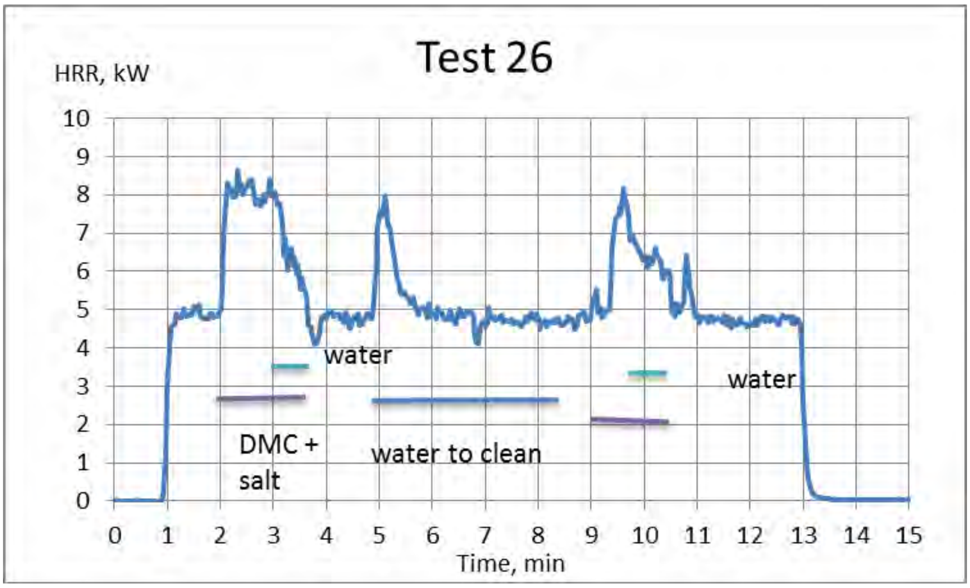


Figure 52 HRR as a function of time for test 26. DMC and salt injection indicated as purple line at time 2 until 3:40 and then at time 9 minutes until 10:30. Water injection into flames by water spray bottle indicated as light blue line from time 3 minutes until 3:40 and then from time 9:50 until time 10:30. Water was injected through the needle between time 5 minutes and 8:30 to clean the system.

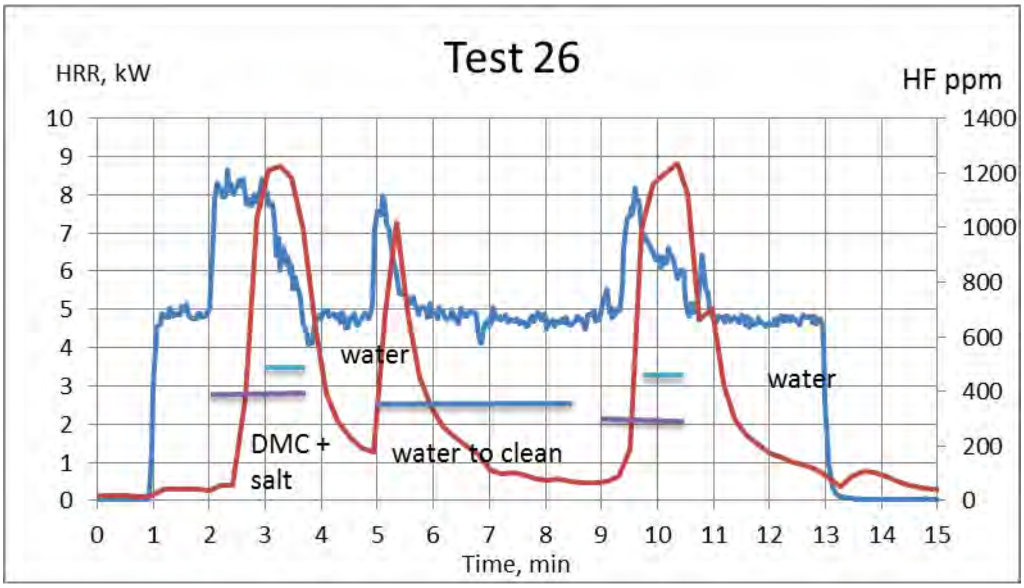


Figure 53 HRR and HF concentration as a function of time for test 26. DMC and salt injection indicated as purple line at time 2 until 3:40 and then at time 9 minutes until 10:30. Water injection into flames by water spray bottle indicated as light blue line from time 3 minutes until 3:40 and then from time 9:50 until time 10:30. Water was injected through the needle between time 5 minutes and 8:30 to clean the system.

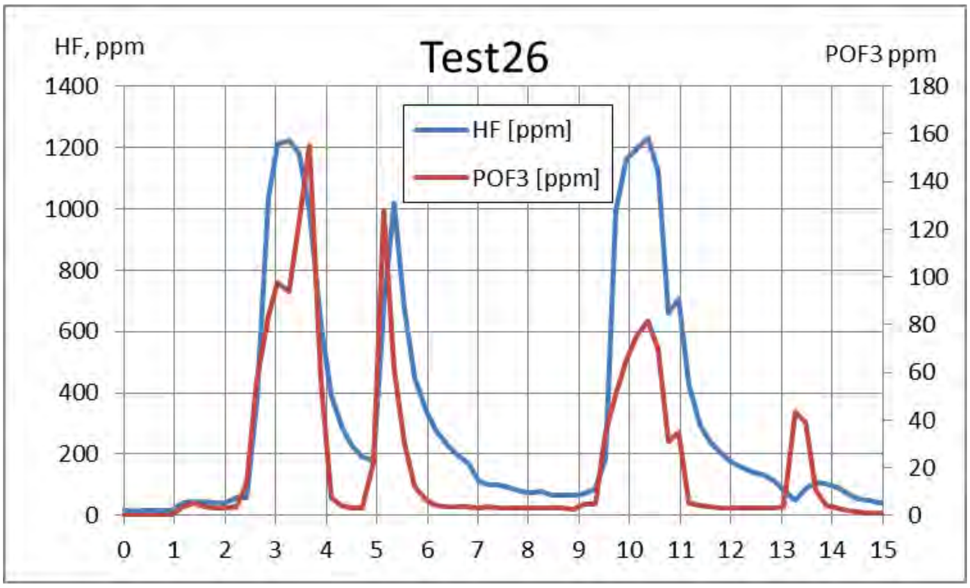


Figure 54 HF and POF$_3$ concentration as a function of time for test 26.

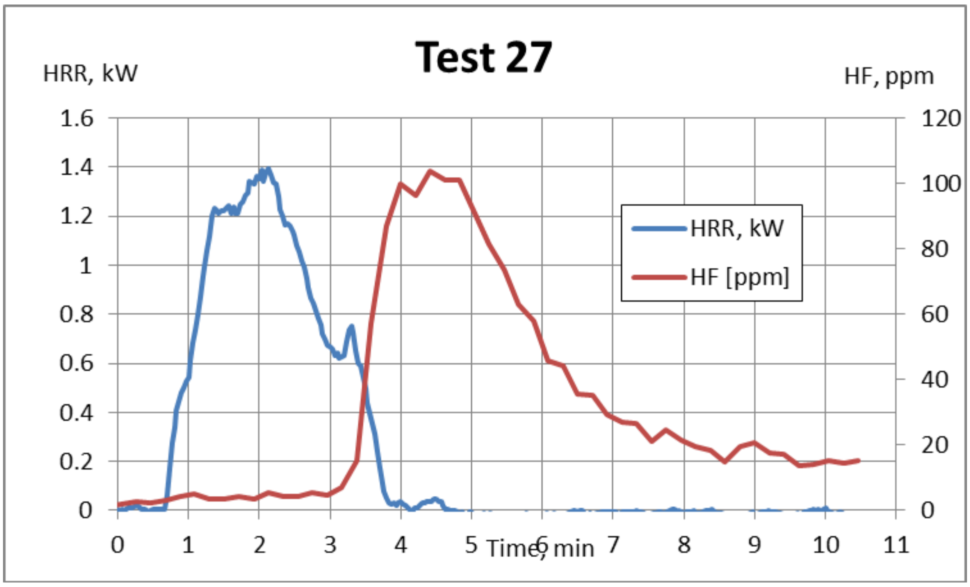


Figure 55 HRR and HF concentration for the cakecup test. Heat radiation applied 10-15 kW/m². Ignited about 15 s after heat application started.

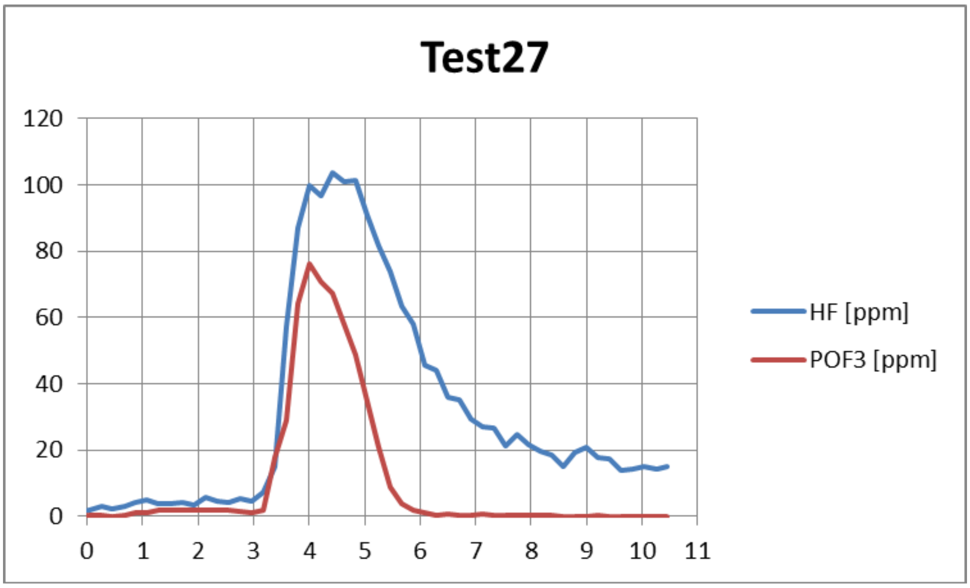


Figure 56 HF and POF3 concentration as a function of time for test 27, test where the electrolyte was heated in a cakecup and ignited by a igniter.

Test 27 shows a different behaviour than the other tests. Unfortunately there was no electrolyte available to explore this further as this was the last test. This could indicate a potential for that toxic gases are produced especially at the end of a fire. This could also reflect that the salt is burnt later that the electrolyte solvent.

The test results from the burner tests in the second batch are summarized in Table 6. The table contains the amount of salt injected expressed as mass of F (grams) based on pump speed, Molar concentration of solution and time sprayed into the flame. This value contains some uncertainty due to uncertainties in conjunction with the pumps and the fact that the spray was not always a spray but more of a beam. The gases produced are expressed as the amount HF and POF_3 in grams, these values are then recalculated into mass of F in grams. The HF values contains also the fluorine content found in the filters analysed after the tests. This value was added to the HF content despite we do not know whether the fluorine is in the form of HF or any other fluorine specie.

Table 6 Results from tests conducted in second batch.

Test nr	Amount salt injected as F (g)	Amount HF (g)	Amount POF$_3$ (g)	Amount HF as F (g)	Amount POF$_3$ as F (g)	Missing F (g)	HF/POF$_3$ by mass
22	3.4	2.5	0.5	2.3	0.3	0.8	5
23a	3.1	2.8	0.1	2.6	0.1	0.4	23
23b	1.7 HRR compensated 0.9	0.8 0.8	0.2 0.2	0.8 0.8	0.1 0.1	0.8 0.0	4 4
24	3.4	4.2	0.5	4.0	0.3	-0.9	8
25	6.3	3.7	1.4	3.5	0.8	2.0	3
26a	4.0	1.4	0.6	1.3	0.3	2.3	2
26b	Cleaning system with water	0.8	0.3	0.7	0.1	-0.8	
26c	1.7	1.6	0.4	1.5	0.2	0.0	4

The results in Table 6 shows that not all F is captured in the measurements. This can be due to that some of the F is not present as HF or POF$_3$ but some other species such as phosphoric acid. We see also that we over-predict the amount of F in two cases, one case where the system was not injected with salt, this was probably due to some remains of salt in the pumps or the filters used to protect the needles from clogging. And one case where time was spent in the beginning of the test to get the spray working with salt. The response time of the FTIR analysis makes it difficult to exclude this initial amount of salt into the system in the calculations unfortunately.

6 Fire tests with batteries

Tests were also conducted on battery cells and batteries used for automotive applications and laptops. Water was added to the flames in one test in order to investigate the influence of water addition to the HF production.

6.1 Batteries tested

The cells in test 1-5 were commercially available pouch cells for automotive applications. The cell is a power optimized cell with a cathode chemistry of $LiFePO_4$, lithium ion phosphate (commonly abbreviated LFP).

The cells in test 6 were commercially available cylindrical cells (of type 26650). The cell is an energy optimized type of LFP, and have been used in e.g. electric vehicles.

The laptop battery pack in test 7 consisted of 2 commercially available battery packs for laptops. Each laptop pack consisted of 6 cells, in which 3 were in series and 2 in parallel, often denoted as 3s2p. The laptop battery pack differs from the other tested cells in several aspects. Firstly, it has a different Li-ion chemistry, which has a higher nominal cell voltage (3.7 V vs 3.2 V for LFP). Secondly, it is a commercially complete battery pack including electronics, plastic housing, electrical connector to laptop, etc. Thirdly, it has a higher pack voltage due to the fact that three cells are connected in series inside the battery pack, increasing the voltage by a factor 3 (to 11.1 V).

All cells were unused. However, the laptop pack was less than 6 months old. The LFP type 1 cells used in tests 1-5 were approximately 1-2 years old and the LFP type 2 cells in test 6 were approximately 2-3 years old.

Table 7 Fire tests with batteries conducted under the hood of the SBI-equipment.

Test no	Cell type	State of Charge, SOC (%)	Nominal capacity (Ah)	No of cells	Total weight (g)
1	LFP type 1, pouch	100 %	35 Ah	5	1 227.9
2	LFP type 1, pouch	100 %	35 Ah	5	1 229.7
3	LFP type 1, pouch	100 %	35 Ah	5	1 229.3
4	LFP type 1, pouch	0 %	35 Ah	5	1 228.6
5	LFP type 1, pouch	50 %	35 Ah	5	1 227.6
6	LFP type 2, cylindrical	100 %	28.8 Ah	9	734.8
7	Laptop battery pack	100 %	33.6 Ah*	2 x (3x2)	639.0

* Corresponding value, rated at each battery pack is 5.6 Ah with 11.1 V.

6.1.1 Cell preparation

All battery cells were charged/discharged to the selected state of charge (SOC) level, using an ordinary power aggregate for labs as well as Digatron battery test equipment. The laptop batteries were fully charged by putting them into a laptop computer.

The five cells, in tests 1-5, were carefully fastened together with steel wire. The poles (tabs) were cut on all cells but one.

The cells in test 6 had originally welded tabs on its poles which after charging were physically removed. The nine cells were placed inside a box, which had steel net at the bottom and top and walls made of a silica board. These specifications were safety precautions in order to avoid possible projectiles.

The laptop pack, which consisted of two identical laptop packs were placed inside a steel net and fastened on the burner grid in order to prevent possible projectiles.

6.2 Experimental apparatus

The tests were conducted in the Single Burning Item apparatus, EN13823, that is normally used for classification of building materials according to the European Classification scheme. This apparatus was chosen as it has a suitable extraction flow for the tests conducted.

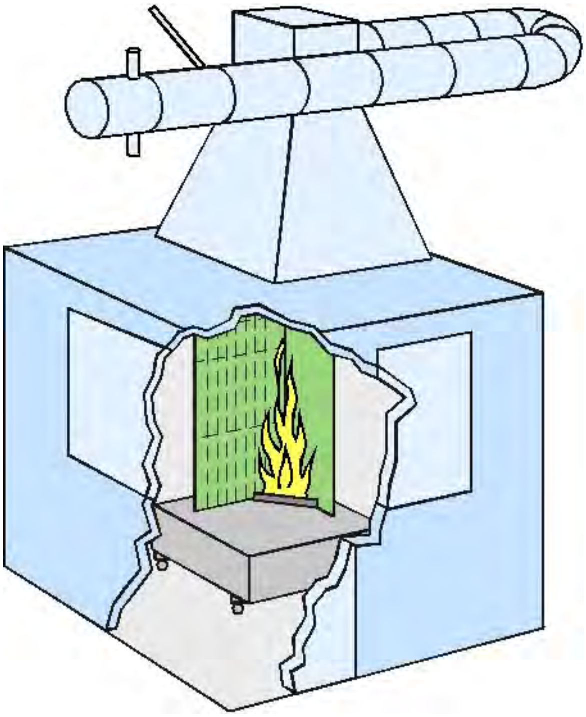


Figure 57 The SBI apparatus.

The cells or batteries were placed on a small table with the table top consisting of wires. A propane burner was placed underneath the batteries/cells.

Figure 58 Experimental set-up test 1-5.

Figure 59 Experimental set-up test 6.

Figure 60 Experimental set-up test 7.

6.3 Experimental procedure

In all tests a premeasuring time of 5 minutes was used for the HRR before the gas supply to the burner was turned on. All tests were video-recorded, video recordings started 1 minute before the burner. FTIR measurements started 2 minutes before the burner. The tests were conducted over two days with tests 1-5 the first day and tests 6-7 the second day. Both days started with a blank test where only the burner was used and HRR and FTIR gases were measured. The HRR from the burner was 14-15 kW. The burner HRR was subtracted from the results.

6.4 Results

In tests 1-3 outbursts of rapid vented gases could be seen. In principle there was one outburst per cell in tests 1-3 with had 100% SOC. In tests 4-5 with lower SOC, no outbursts could be observed. Outbursts could be seen in tests 6-7. The laptop battery pack in test 7 showed rapid venting in several directions and probably had the most energized venting of the seven tests.

In the seven tests, the orientation of the cells were different due to the different battery types (pouch, cylindrical, complete pack). This could potentially have affected the results, since some gases might have been missed by the hood collecting the gases. Also the extent to which gases are mixed in a limited space could have an impact on the results. It was not possible to determine the magnitude of these aspects in these tests. The cells in tests 1-5 were however all oriented which provide for a good comparison between these tests. The other two tests can be considered more as examples of possible scenarios.

All tests were photographed. Phots can be found in appendix C.

6.4.1 Video

All tests were captured on video. Below is the comment to the post-analysis of those videos. Note that the “video time” is 1 minute after the reference time. In other words, the reference time 01:00 corresponds to 00:00 in video time. Video time is used in the tables below.

Table 8 Comment to test 1 from video analyses.

Video time (min:sec)	**Comment**
00:00	Video start
01:20	LPG fire beginnings
02:05	Cell material/vented material is clearly started to burn on the long sides
02:42-57	Outburst 1, 2 angles: ~ 45,100 deg Lighter flame colors (real or due to camera)
05:41-49	Outburst 2
05:53-04	Outburst 3, large flame on the right side from 110-190 deg
06:04-06:49	Venting flame at left side, burning for a relative long time
06:49-59	Outburst 4
07:34-40	Outburst 5
18:25	LPG flames end

Table 9 Comment to test 2 from video analyses.

Video time (min:sec)	**Comment**
00:00	Video start
01:05	LPG fire beginnings
02:13-19	Outburst 1
02:20-03:11	Burning
05:26-35	Outburst 2, 3 angles: ~ 0 (little), 80 (more),120(more) deg
05:56-01	Outburst 3
06:01	Maybe an smaller outburst
06:29-41	Outburst 4 (3 angles as above in No.2)
07:06-17	Outburst 5
18:07	LPG flames end

Table 10 Comment to test 3 from video analyses.

Video time (min:sec)	**Comment**
00:00	Video start
01:10	LPG fire beginnings
02:04-12:06	Outburst 1 (left side 45deg, right side 120 deg (most @ right))
02:31-40	Some smoke from back of cell pack
03:05-09	Outburst 2 (both left and right side)
	More smoke from back of cell pack
05:50-02	Outburst 3 (most on left side, left ~30 deg, right ~ 145 deg) Lighter white-orange color that LPG flame colors
06:24-44	Outburst 4 (most left side, ~40 deg) Incl darker smoke
06:44 – 07:00	Clear cell fire along the long-sides, incl darker smoke
> 07:00	Person with handhold water mist makes entrance
07:13-07:23	Smaller outburst 5 (most left side)
07:41-07:53	Smaller outburst 6 (both sides)
07:40	Water mist on Pulsed by hand (~1 sec per puls) In flames above cell (cell is primarily not touched)
09:02-09:12	No water mist applied during this time, might have been longer time period
~ 09:45	Water mist off
11:15-56	Water mist on, into flames above cell
12:02-30	Water mist on, onto cell
12:43-44	Water mist on, onto cell, one pulse
13:45 – 14:03	Water mist on, into flames above cell
18:10	LPG flames end

Table 11 Comment to test 4 from video analyses.

Video time (min:sec)	**Comment**
00:00	Video start
01:15	LPG fire beginnings
	No outbursts could be seen
33:22	LPG flames end

Table 12 Comment to test 5 from video analyses.

Video time (min:sec)	**Comment**
00:00	Video start
01:12	LPG fire beginnings
	No outbursts could be seen
28:04	LPG flames end

Table 13 Comment to test 6 from video analyses.

Video time (min:sec)	**Comment**
00:00	Video start
01:20	LPG fire beginnings
05:56	Outburst 1 fast (max 0,5 sec), straight upwards
05-57-09	Probably cell venting which is burning
06:13-14	Outburst 2 little longer (0,5-1 sec), straight upwards
06:19-20	Outburst (0,5 sec), straight upwards
06:20-06:40	Probably burning from cell vent
06:46-47	Outburst 3 (1 sec), straight upwards
06:47-55	Burning from cell vent
06:58	Probably burning from cell vent
07:14	Outburst 4, straight upwards
07:14-07:24	Burning from cells
07:24	Outburst 5 very rapidly (~ 100 ms), straight upwards
07:26->	Outburst 6, straight upwards Burning and outburst, ventilation, a lot of activity, hard to
07:26:07:41	Burning over complete battery pack
07:41	Outburst 7 very rapidly, straight upwards
07:41-08:01	Burning from cells
08:01	Outburst 8 very rapidly, straight upwards
08:13	Outburst 9, not straight upwards but upwards to the right
08:15/16	Maybe outburst
08:18	Clear outburst 10 (1 sec), not straight upwards but upwards to the left
08:28	Outburst 11 , straight upwards
08:41-50	Clear outburst 12 (9 sec), not straight upwards but upwards to the left
08:45-53	Maybe outburst 13, long, straight upwards-little right
~07:00 - 10:00	Fire from battery cells (pack) almost finished at 10:00
10:00-12:45	Some flames from time to time, some black smoke
12:45-18:32	Less intense than above, and from time to time: some flames from time to time, some black smoke
18:32	LPG flames end

Table 14 Comment to test 7 from video analyses.

Video time (min:sec)	**Comment**
00:00	Video start
01:20	LPG fire beginnings
02:25	Small fire in left pack, likely in plastics – yellow flames (same as LGP flames)
03:24	One short flame
03:33	One short flame
03:34-39	Outburst 1 (4-5 sec)
03:43	One short flame
03:46-48	Outburst 2 (2-3 sec)
03:54	One short flame
03:58-01	Outburst 3 (2-3 sec)
04:04-08	Outburst 4 (3-4 sec)
04:12-14	Outburst 5 (2-3 sec)
04:15-19	Outburst 6 (4 sec), maybe several
04:22-23	Outburst 7 (2 sec), can have been multiple, last 20 sec
04:35-38	Outburst 8 (2-3 sec)
04:56-57	Outburst 9 (1 sec)
05:02-03	Outburst 10 (1 sec)
> 06:00	Light smoke
06:50-07:00	10 sec white smoke
> 07:00	Light smoke
18:14	LPG flames end

6.4.2 HRR and gas measurements

The results from the HRR measurements are summarized in Table 15. The HRR curves are presented in Figure 58 for test 1, 2 and 3, Figure 61 for test 4 and 5 and Figure 62 for test 6 and 7 respectively. Figure 59 indicates when outbursts of gases could be observed from the video while Figure 60 shows the HRR results from test 3 together with indications of when water mist was sprayed into the flames. Even if the maximum HRR was about the same for test 1, 2, 3 and 7, the test performance was quite different with large flames and material sprouting out from the laptop cells.

Table 15 Summary of results from the fire tests.

Test no	Weight loss (g)	Max heat release (kW)	Total heat release (kJ)
1	346	48	6826
2	342	44	6645
3	341	42	7130
4	353	9.5	7356
5	354	14	7460
6	145	26	2409
7	258	50	3036

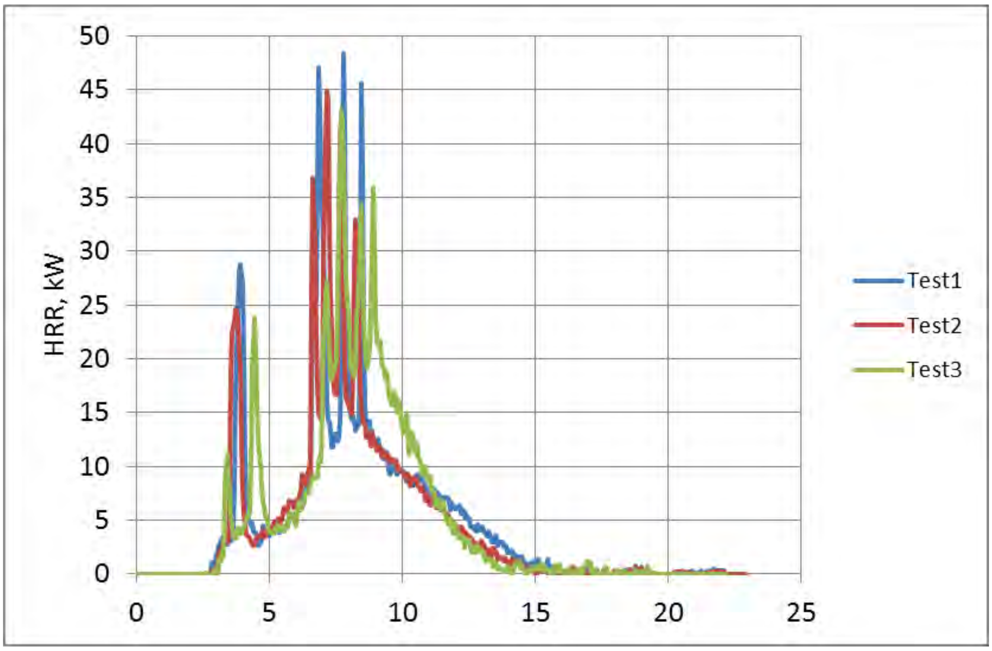


Figure 61 HRR measurements from test 1-3.

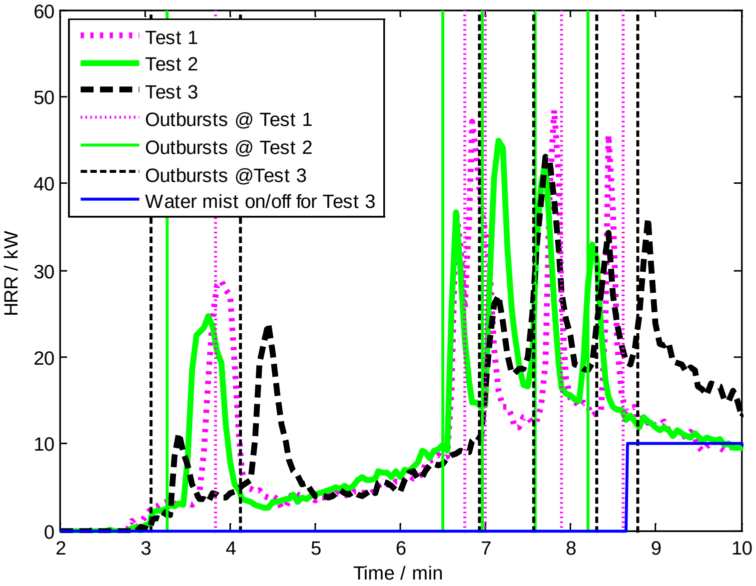


Figure 62 HRR measurements with outbursts as noted in the videos marked together with water mist injection for test 3.

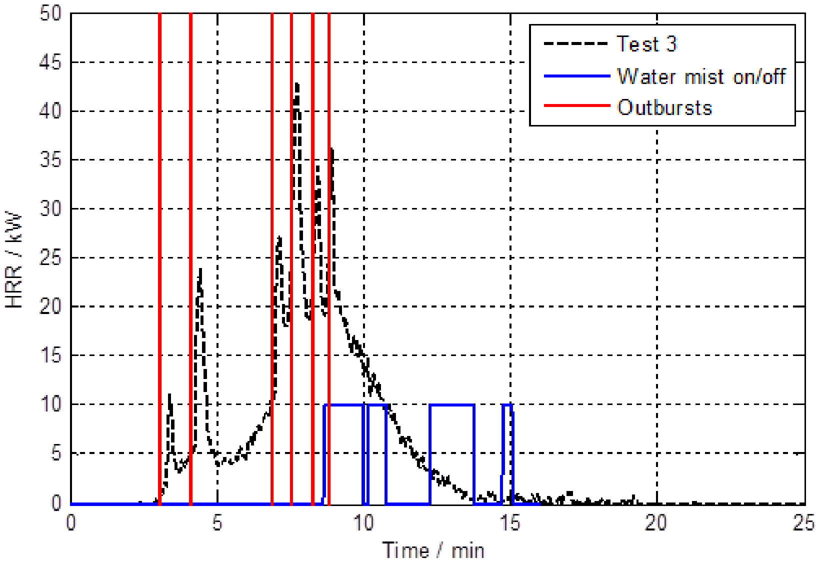


Figure 63 Water mist injection for test 3.

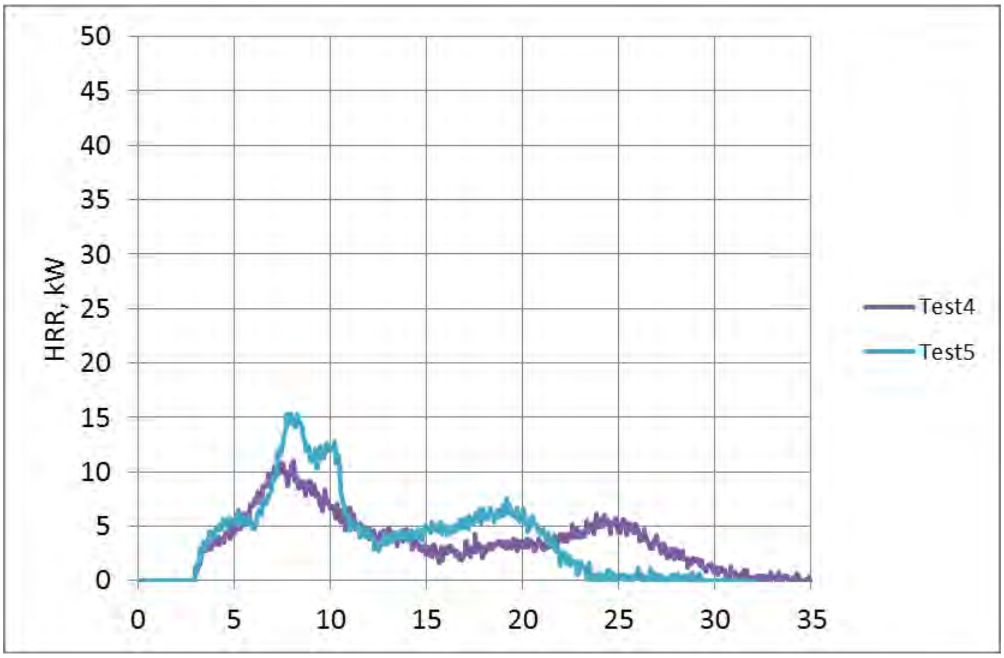


Figure 64 HRR measurements from test 4-5.

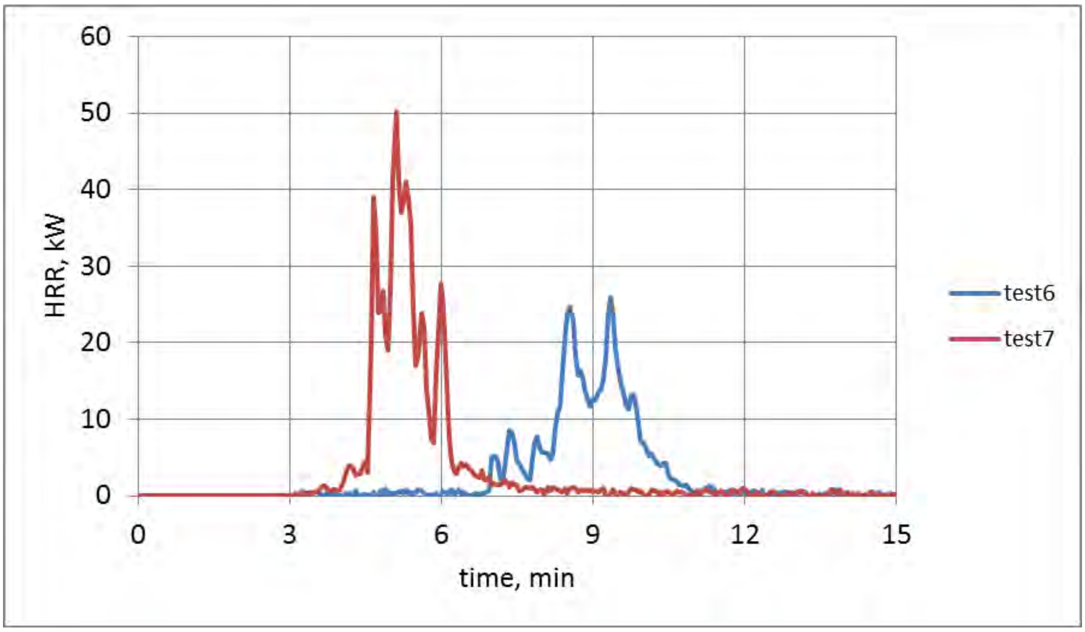


Figure 65 HRR measurements from test 6 and 7.

The FTIR measurements show production of HF in all tests, but POF_3 could not be detected. The measured concentrations of HF were generally quite low but well above the detection limits. Maximum concentrations in tests 1-2 were about 15 ppm and the duct flow was decreased before remaining tests to increase the HF concentration in the duct. The maximum concentration in the remaining tests were in the range 30 - 50 ppm.

The high dilution in the exhaust duct means that POF_3 might have been produced but not detected by the FTIR. Assuming that the ratio between HF and POF_3 concentration was 20 as seen in the spray-tests with the cone calorimeter, that would correspond with maximum POF_3-concentrations below 1 ppm in tests 1-2 and 2.5 ppm in tests 3-5 which is below the quantification limit (6 ppm) for the FTIR.

The amount of HF produced during tests 1-5 is presented in Table 16. It is clear that the low concentration of HF resulted in a very large relative loss of HF in the sampling filters. In addition is the HF production presented together with the HRR in Figure 65-Figure 69 for test 1-5. The delay of HF compared to HRR seen in the production curves below is most probably influenced by retention in the filter. More results can be found in Appendix B.

From Table 15 it is evident that the total amount of HF produced is lower for the fully charged cells than those cells with a lower SOC. This could be due to the rapid outbursts of gases during these tests so that parts of the gases might not have been collected, but as the Total Heat Release (THR) from the tests are in the same order of magnitude then it seems that most of the gases were captured. Alternatively, the prolonged fire duration allowed more HF to be produced as it might give a chance for a more complete burning, or else it has something to do with how the Fluorine is available in the battery at different SOCs. It has not been possible to explore this further at this stage.

Table 15 also show that despite the larger peak in production rate of HF in test 3 where water was introduced into the flame, the total amount of HF was still the same.

Table 16 **Results of HF analysis with FTIR from test 1-5.**

Test no	Max production rate (g/s)	Total amounts from FTIR (g)	Total amounts from filter (g)	Total amounts (g)	Total yields (mg/g)
1	0.0088	3.2	1.7	4.9	14
2	0.0077	3.9	2.4	6.3	18
3	0.0154	4.2	1.5	5.7	17
4	0.0102	9.7	1.6	11.3	32
5	0.0164	12.0	1.9	13.9	39

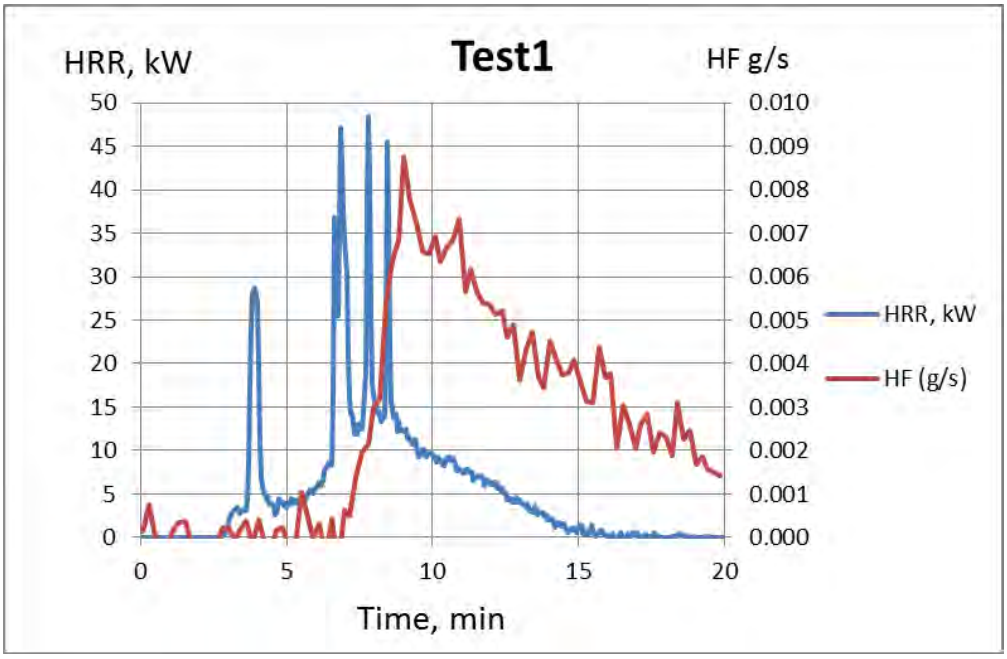


Figure 66 **HRR and HF production as a function of time for test 1. The HF production only includes the readout from the FTIR so HF that is captured in the filter is not included.**

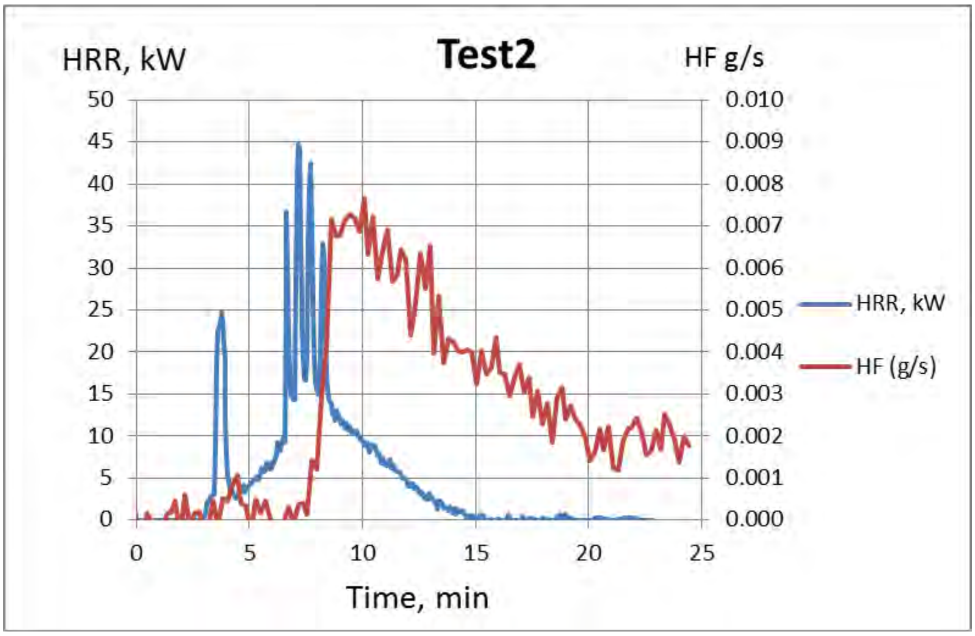


Figure 67 **HRR and HF production as a function of time for test 2. The HF production only includes the readout from the FTIR so HF that is captured in the filter is not included.**

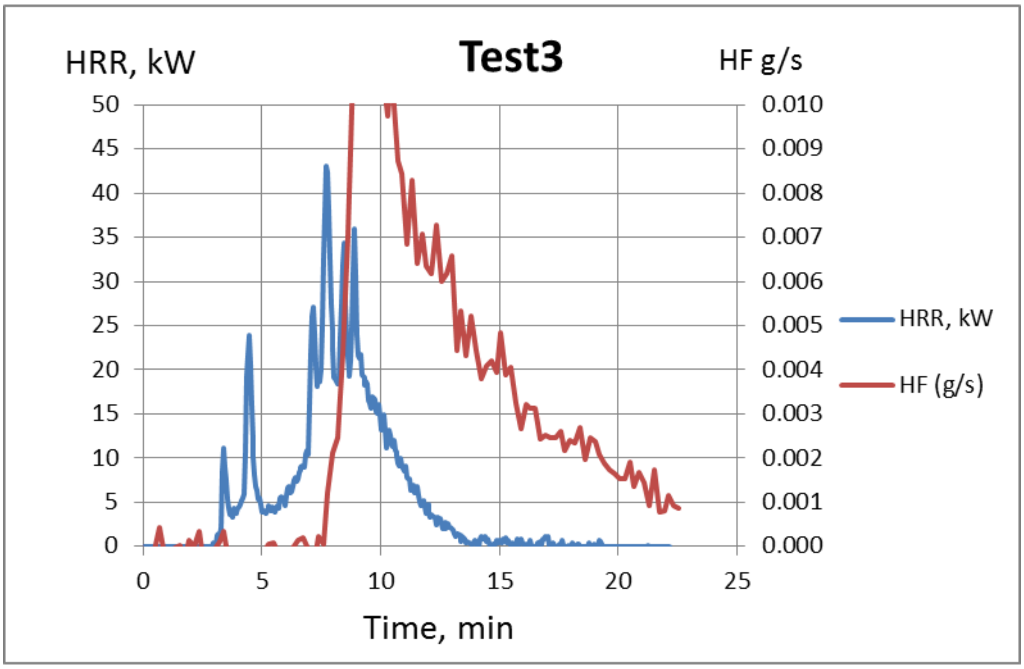


Figure 68 HRR and HF production as a function of time for test 3. The HF production only includes the readout from the FTIR so HF that is captured in the filter is not included.

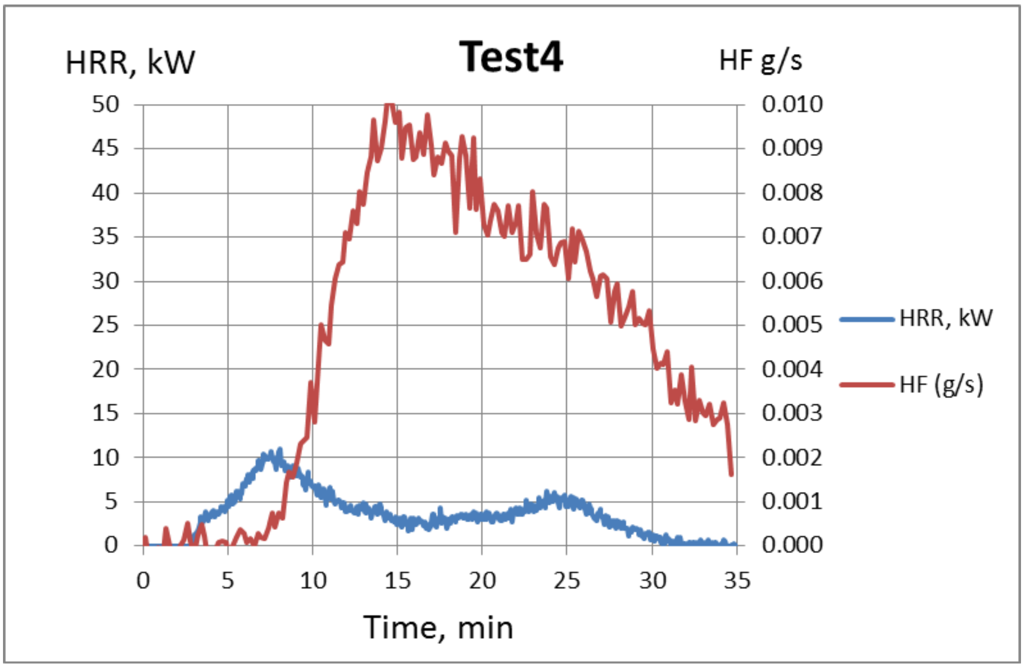


Figure 69 HRR and HF production as a function of time for test 4. The HF production only includes the readout from the FTIR so HF that is captured in the filter is not included.

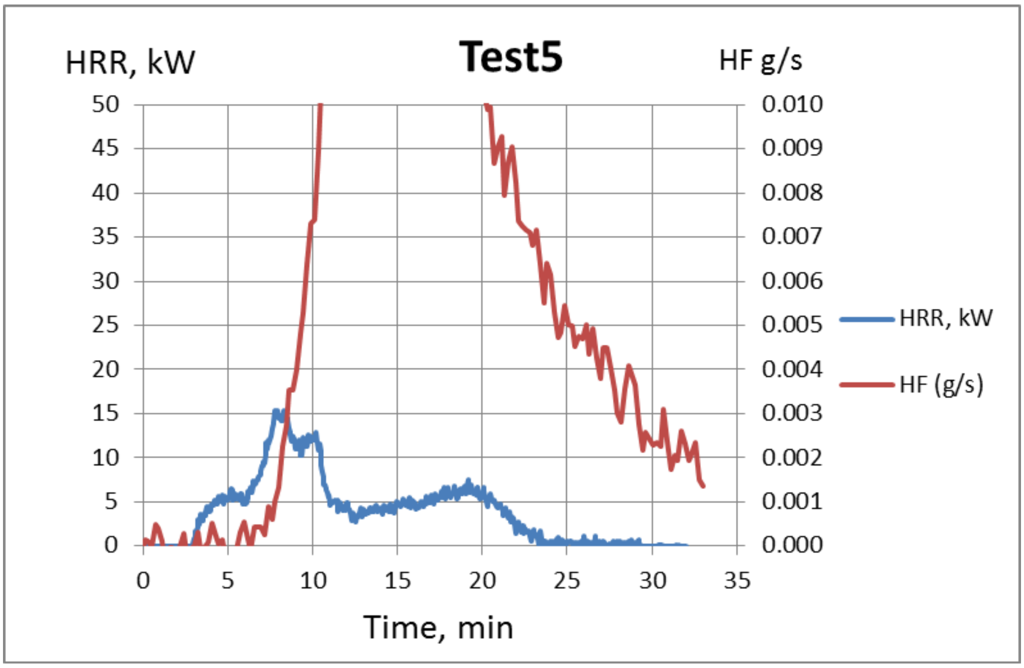


Figure 70 HRR and HF production as a function of time for test 5. The HF production only includes the readout from the FTIR so HF that is captured in the filter is not included.

The results from test 6 and 7 are available in Table 17 and Figure 70. As seen the yields of HF is much lower for the lap top cells, in fact the HF detected online was below the determined detection limit. Partly this is because the burnable mass in the laptop cells is also the plastic around the battery. But this does not explain all the difference. One plausible explanation is that the laptop cells exploded with liquid splashed on the walls in the equipment and some slat might have been missed there.

Table 17 Results of HF analysis with FTIR from test 6-7.

Test no	Max production rate (g/s)	Total amounts from FTIR (g)	Total amounts from filter (g)	Total amounts (g)	Total yields (mg/g)
6	0.0029	1.2	1.0	2.2	15
7	0.0011	Not detected	1.9	1.9	7.3

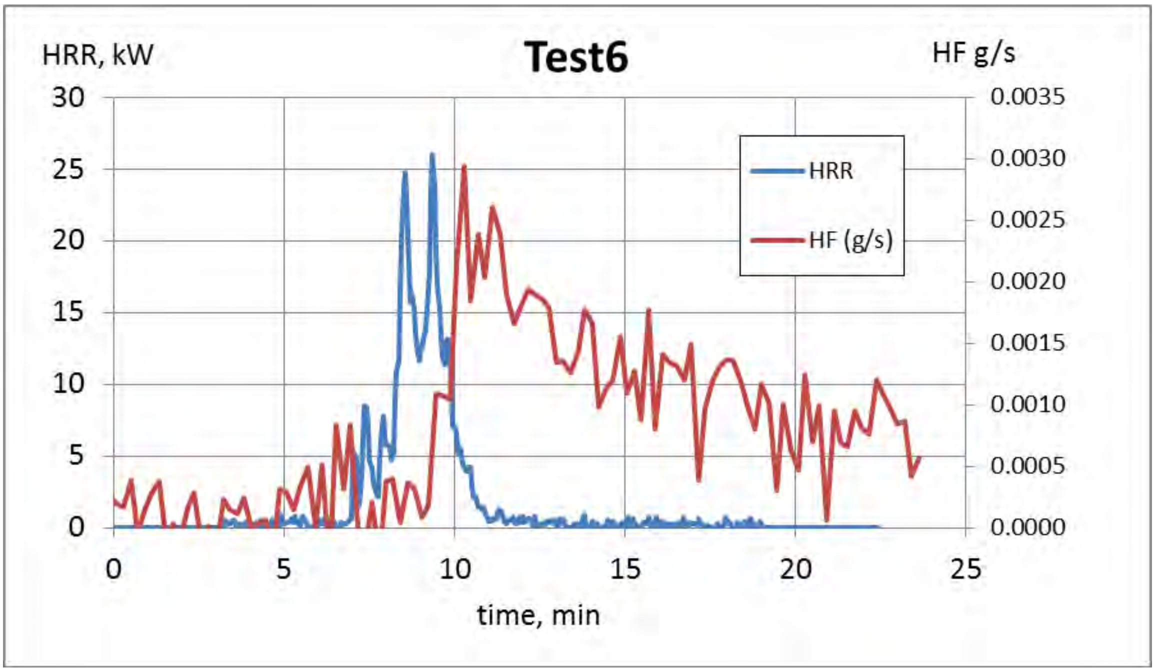


Figure 71 HRR and HF production as a function of time.

6.5 Discussion

Looking at the results from these reduced scale tests alone the emission data can be difficult to interpret. An important aspect in this context is a comparison with emission data from a traditional car fire. Emission data from a complete vehicle fire is scarce. Lönnermark and Blomqvist[6] have made measurements both on a full scale fire and parts of a vehicle like door panels, dashboard etc. The vehicle tested in the full scale fire was a medium class model from 1998. No HF could be detected in these tests either in the small-scale tests or in the full scale test but significant amounts of HCN (NGV 1.8 ppm, TGV 3.6 ppm), HCl (TGV 5 ppm) and SO_2 (NGV 2 ppm, TGV 5ppm).

Recently Lecocq, Bertana, Truchot and Mairlair reported emission data from both a full-scale fire of a fully charged Electric Vehicle (EV) and a full-scale fire of a similar Diesel vehicle fully gassed[7]. This showed an initial peak of HF produced for both vehicles. This peak was higher than the amount of HF produced later in the fire stage when the battery started to burn in the EV but the amount of HF produced by EVs were at least twice the amount from the Diesel vehicles. The amounts reported are presented in Table 18. The initial HF peak might have been caused by the AC liquid.

The battery cells tested in this study were power optimized cells that one could find in a plug-in hybrid electric vehicle (PHEV). A typical PHEV could have 432 cells (9.7 kWh, 345.6 VDC nom, 108s4p, cell: 7Ah, 3.2 V nominal). This means that the emissions reported in the battery cell tests should be multiplied with a factor of 432/5 = 86.4 to reflect a case where the complete battery is consumed in a fire. This results in a value of 400-1200 g HF depending on SOC with a low value for a high SOC. This is in the same order of magnitude as the valued reported by Leqoqc et. al. (657 and 919 respectively) as presented in Table 18.

Similar, if the result from the burner tests are extrapolated to the amount of HF one would get if the entire amount of electrolyte in a vehicle is consumed in a fire, one ends up in a large variation of values, 1200 – 2800 g of HF. These values are on the high end and higher than the value measured in the cell tests and larger than the values reported by Leqocq et. al. However, considering the large extrapolation done here going from a small number of completely different fire scenario the differences are not that big. In the burner test the electrolyte was introduced in a pure state and it had to go into the flame. In the vehicle test one cannot be 100% sure that all electrolyte is consumed, in addition, we do not known what kind of vehicle it was in the full vehicle test, this might differ from the assumptions on power etc. that was made in the extrapolation.

Table 18 Comparison with complete vehicle fire emissions.

Study/vehicle	HF (g)	HCN (g)	HCl (g)	SO2 (g)
Lönnermark/Blomqvist	No HF detected	170	1400	540
Leqocq et al. Diesel1	621	167	1990	
Leqocq et al. EV1	1540	113	2060	
Leqocq et al. Diesel2	813	178	2140	
Leqocq et al. EV2	1470	148	1930	
This study, cell tests	400-1200 depending on SOC, high SOC gives low amount of HF			
This study, burner tests	1200-2800			
This study, cakecup test	950			

The experimental results in this study could not show any significant change in the constitution of gases emitted if water is used as an extinguishing media. The battery cell experiment showed a higher concentration of HF produced during the actual spraying with water but the total amount HF was still the same. No change could be observed in the burner tests due to introduction of water.

7 Conclusions

The work presented here shows that it is possible to use FTIR to measure HF and POF_3 online in fire tests including Li-ion batteries at different scales.

POF_3 was detected in all the small scale tests using pure electrolyte. However, no POF_3 was detected in the tests on cells. The detection limit for POF_3 was 6 ppm. Extrapolating from the small scale tests to the cells tests one ends up at concentrations below 6 ppm, which probably explains why no POF_3 was detected in these tests.

It is an important finding that POF_3 is emitted from a battery fire as this will increase the toxicity of the fire effluents. The amount of POF_3 is shown to be significant, 5-40 % of the HF emissions on a weight basis.

No PF_5 could be detected in any of the tests. The reason for this is probably the high reactivity of this specie. This was also demonstrated by the difficulty to produce a calibration gas mixture for PF_5.

There was no apparent experimental evidence that using water had a significant impact on the amount of HF produced if water is used as an extinguishing media. The use of water to extinguish a battery fire has the potential to shift the chemistry to favour the production of HF over POF_3. The toxicity of POF_3 is not known but substances similar to POF_3 are highly toxic, more toxic than HF. Therefore shifting the chemistry to favour the production of HF over POF_3 may be toxicologically favourable. More information is needed to resolve this issue especially as POF_3 can be emitted under other cell venting situations and not only fires.

Extrapolating the results from these experiments one ends up in the same order of magnitude in amount of HF as reported in the few available complete EV vehicle burns. This is an indication that the small scale experiments conducted in this project provide useful information to analysing the risks associated with emissions from Li-ion batteries in fires and the impact of water application during the fire.

8 References

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Appendix A Tests conducted in burner

Tests conducted are listed in Table 1. Each of the tests are then presented in tables (test procedure) and figures.

Table 1 Tests conducted

Test nr	Type of test	Fuel	Comment
1	burner	Propane only	Initial test to determine propane HRR
2	Burner + needle	Propane and 5.9 ml/min DME	DME works not as spray but as a beam, possibility that all DME not burnt
3	Burner + Needle	Propane and 5.9 ml/min DME	Needle in bottom of burner instead of top
4	Burner + Needle	Propane and 5.9 ml/min DME	Needle inserted outside of burner
5	Burner + spoon	Propane and 2.4 ml/min DMC	Not a very successful attempt
6	Burner + Needle	Propane and 12 ml/min DMC	and later 5 ml/min
7	Burner + Needle	Propane and 20 ml/min DMC	Interrupted as holder melted
8	Burner + Needle	Propane and 20-18 ml/min DMC	Burner placed a bit lower under the collecting hood
9	Burner + Needle	Propane and DMC 18 ml/min	
10	Burner + Needle	Propane and DMC 18 ml/min with 1 M salt	
11	Burner + needle	Propane and DME 18 ml/min	
12	Burner + needle	Propane and DME 18 ml/min with 0.4 M salt	
13	Burner + Needle	Propane and DMC 18 ml/min 1 M salt	
14	Burner + Spoon	Propane and DMC 1.8 ml/min	
15	Burner + spoon	Propane and DMC 1.8 ml/min + 1M salt	
16	Burner + spoon	Propane and DME 1.8 ml/min + 0.4 M salt	
17	cakecup	DMC + salt 1:1	No external heating, did not burn very well
18	cakecup	DME + salt 1:1	No external heating, did not burn very well

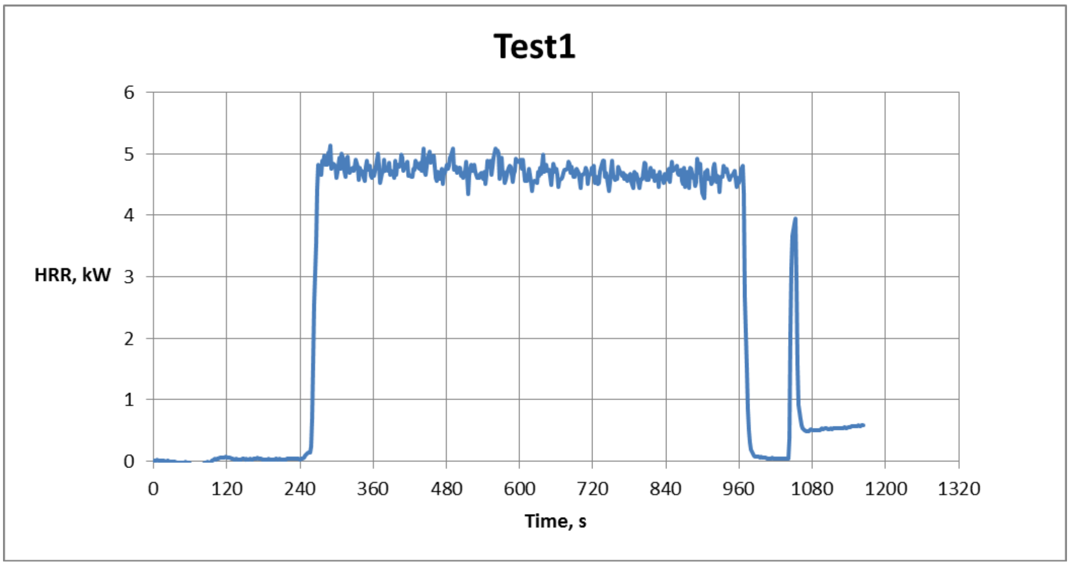

Figure 1 HRR from test 1, propane burner at 7 sp.

Table 2 Test procedure test 2

Time Min:sec	Comment
0	FTIR and HRR measuremtn started
1:00	Burner with 7 sp propane started
1:34	First numbers from FTIR available
6:00	Start DME injection 5.9 ml/min, DME works not as spray but as a beam, possibility that all DME not burnt

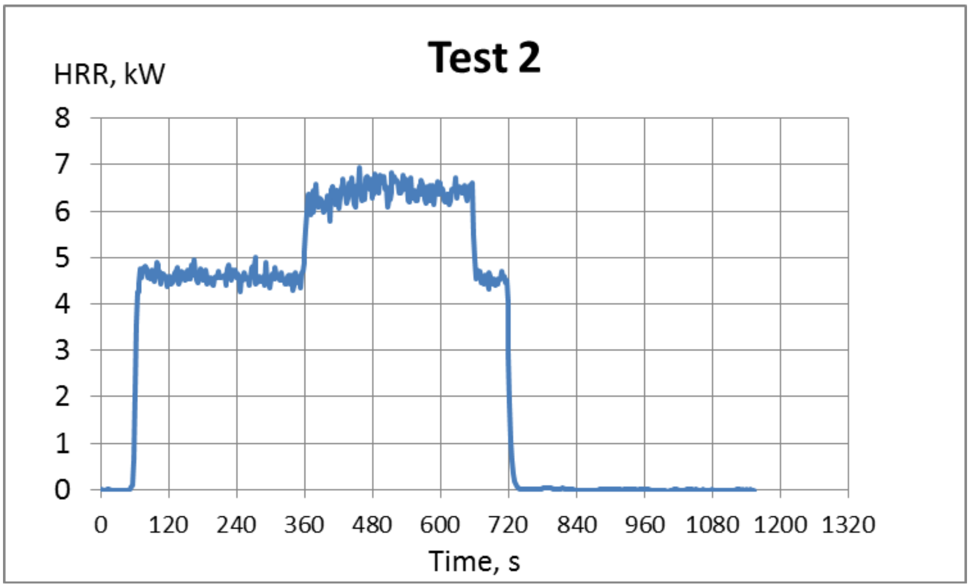

Figure 2 HRR from test 2

Table 3 Test procedure test 3

Time Min:sec	Comment
0	FTIR and HRR measurements started
1:00	Burner with 7 sp propane started
1:30	First numbers from FTIR available
6:00	Start DME injection 5.9 ml/min, Needle inserted in bottom of burner instead
8:00	test was interrupted as the spray hit the burner

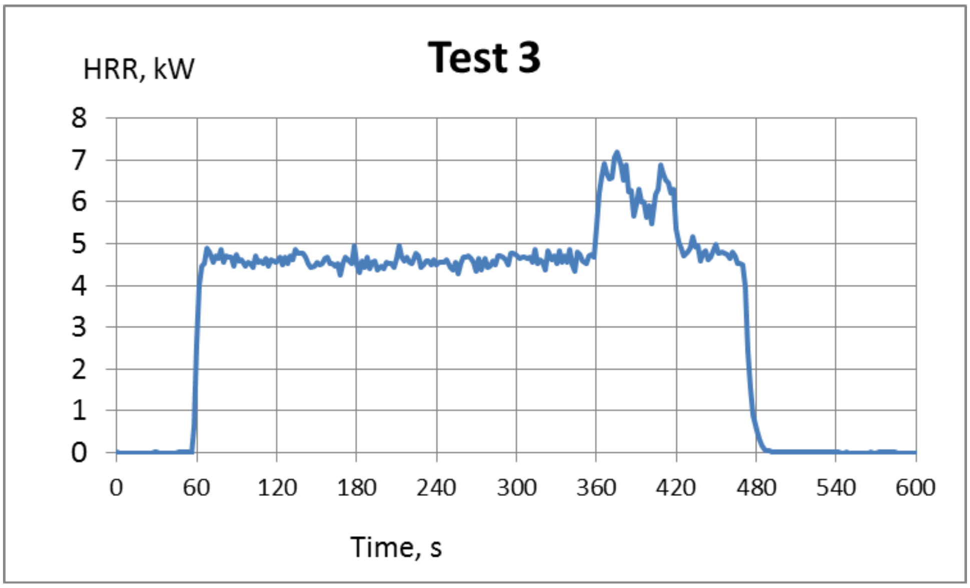

Figure 3 HRR from test 3

Table 4 Test procedure test 4

Time Min:sec	Comment
0	FTIR and HRR measurement started
1:00	Burner with 7 sp propane started
1:33	First numbers from FTIR available
4:00	Start DME injection 5.9 ml/min, Needle placed outside of burner

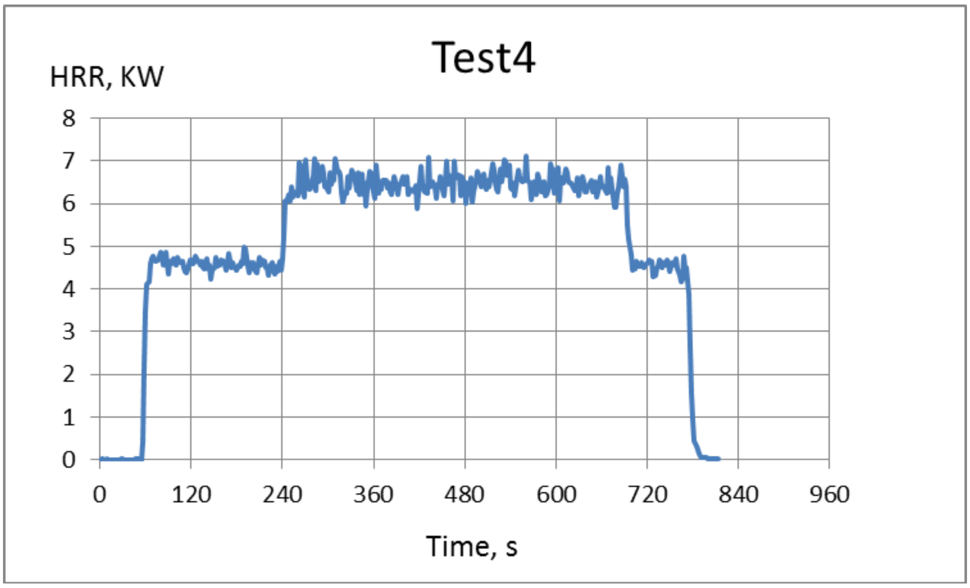

Figure 4 HRR from test 4

Table 5 Test procedure test 5

Time Min:sec	Comment
0	FTIR and HRR measurement started
1:03	First numbers from FTIR available
2:00	Burner start
10:30	Start DMC injection 2.4 ml/min onto spoon placed in flame
	Not a successful attempt

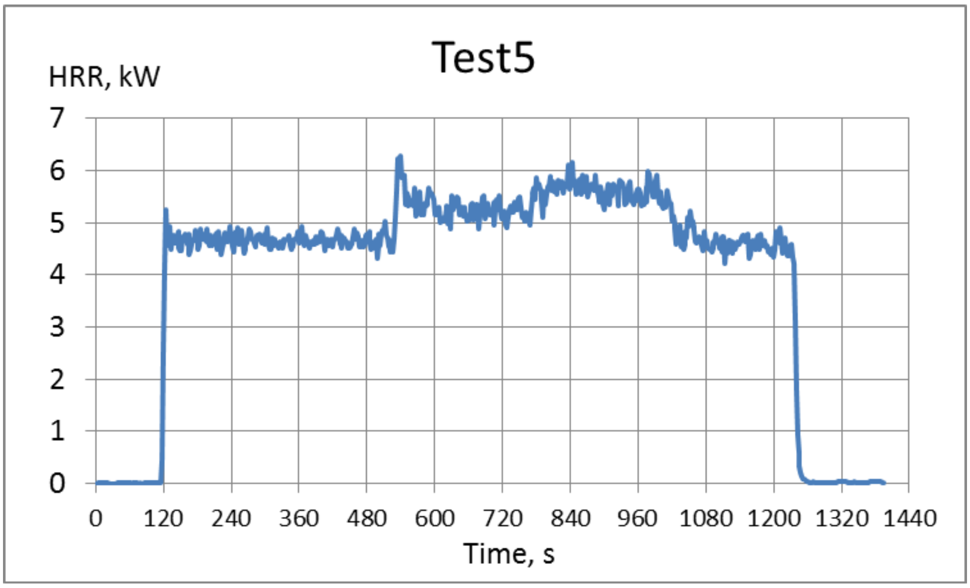

Figure 5 HRR from test 5

Table 6 Test procedure test 6

Time Min:sec	Comment
0	FTIR and HRR measurement started
1:00	Burner (propane) start
1:23	First numbers from FTIR available
6:00	Start injecting DMC 12 ml/min onto spoon
6:45	Injection interrupted
7:30	Injection started again flow 5 ml/min
8:00	Injection interrupted
8:57	Flame extinguished
10:09	Flame lit again
10:30	Injection 5 ml/min
12:00	Injection ended and flame turned off

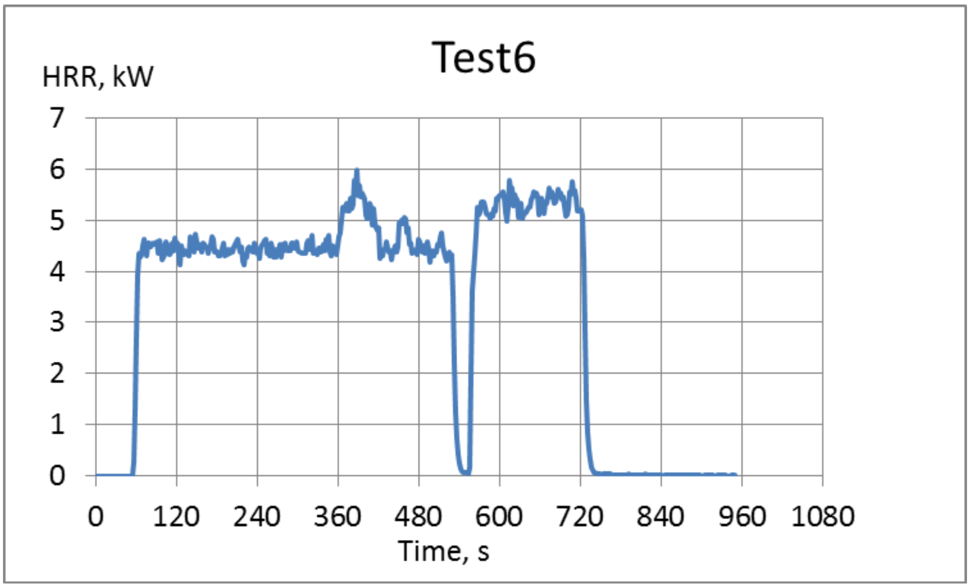

Figure 6 **HRR from test 6**

Table 7 **Test procedure test 7**

Time Min:sec	Comment
0	FTIR and HRR measurement started
0:41	First numbers from FTIR available
1:10	Burner start
6:00	Start injecting DMC 20 ml/min spray
7:45	Injection interrupted as holder melted
10:00	Burner off

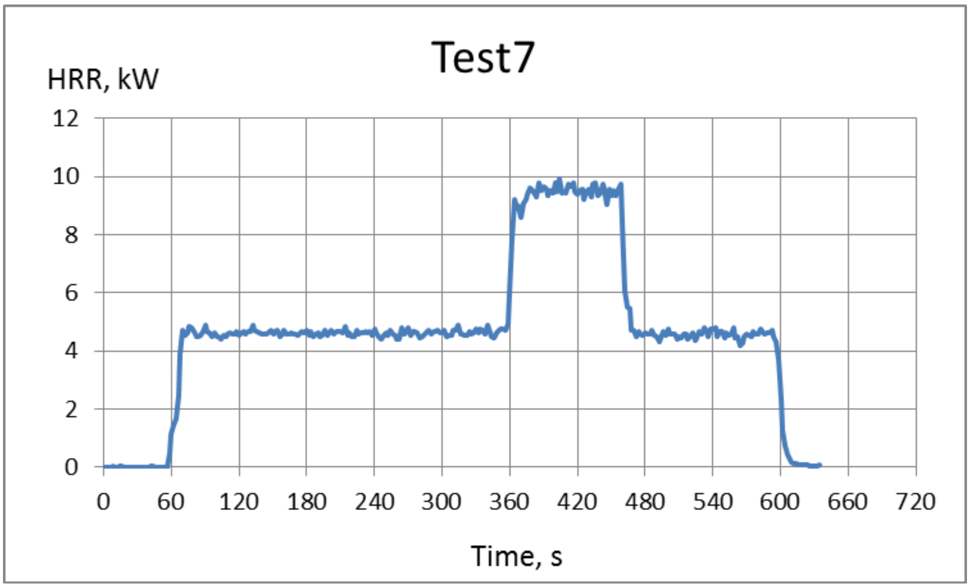

Figure 7 **HRR from test 7**

Table 8 Test procedure test 8

Time Min:sec	Comment
0	FTIR and HRR measurement started
0:44	First numbers from FTIR available
1:00	Burner start, burner placed lower in relation to collecting hood
6:00	Start injecting DMC 20 ml/min spray
8:30	Start decreasing injection until 18 ml/min
9:30	Injection off

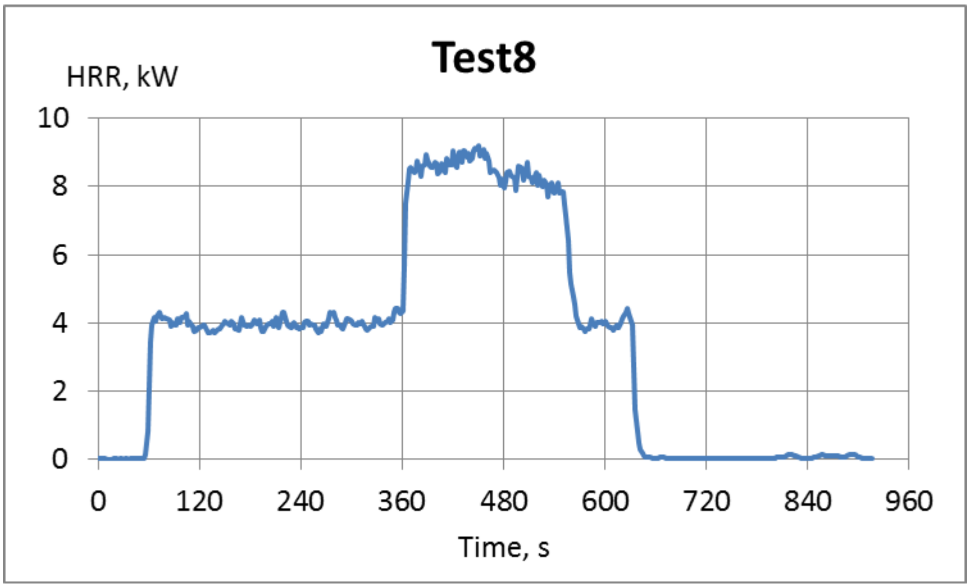

Figure 8 HRR from test 8

Table 9 Test procedure test 9

Time Min:sec	Comment
0	FTIR and HRR measurement started
0:33	First numbers from FTIR available
1:00	Burner start
4:00	Start injecting DMC 18 ml/min spray
7:00	DMC off
10:30	Burner off

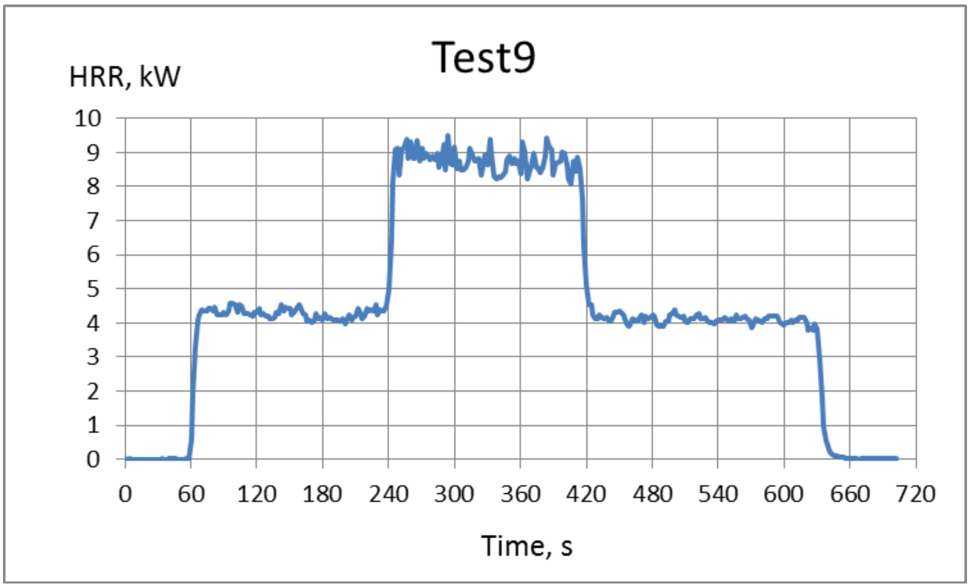

Figure 9 HRR from test 9

Table 10 **Test procedure test 10**

Time Min:sec	Comment
0	FTIR and HRR measurement started
0:54	First numbers from FTIR available
1:09	Burner start
4:00	Start injecting DMC + salt 18 ml/min spray
6:00	DMC off
12:20	Burner off

Table 11 **Test Procedure test 11**

Time Min:sec	Comment
0	FTIR and HRR measurement started
0:59	First numbers from FTIR available
1:00	Flame start
4:00	Start injecting DME 18 ml/min, flame turns purple, salt still available in system!
8:40	Stop spray
13:55	Start injecting DME again after cleaning of hoses
15:30	Stop injection
16:43	Burner off

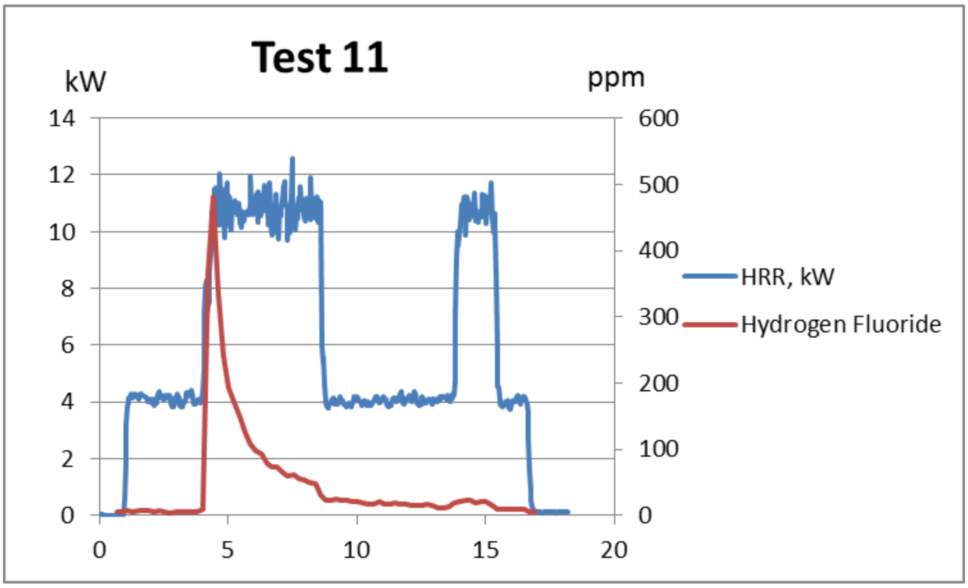

Figure 10 **HRR and HF concentration test 11**

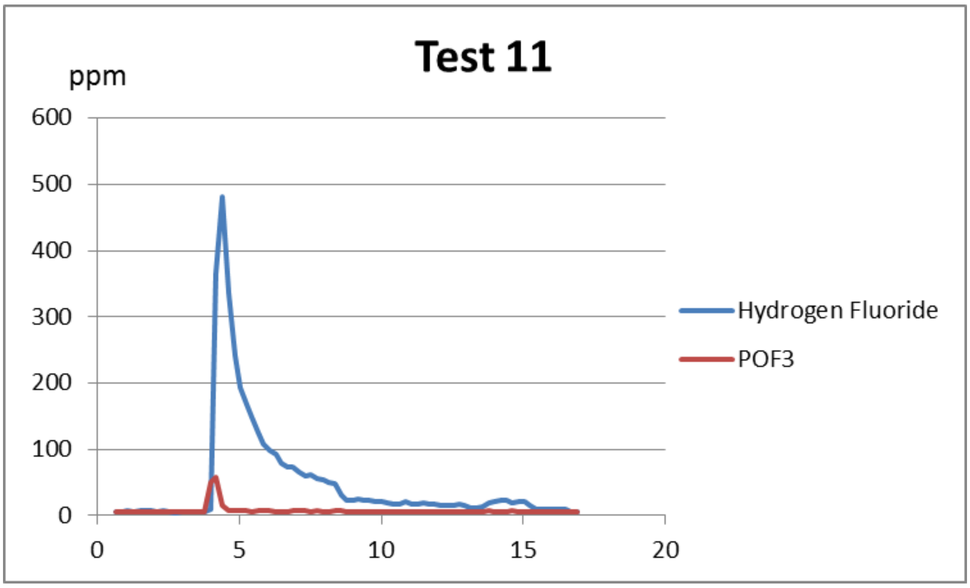

Figure 11 **HF and POF_3 concentration test 11**

Table 12 **Test procedure test 12**

Time Min:sec	Comment
0	FTIR and HRR measurement started
0:30	Flame start
0:43	First numbers from FTIR available
2:30	Start injecting DME 18 ml/min + 0.4 M salt
5:00	Stop spray
10:00	Burner off

Table 13 Test procedure test 13

Time Min:sec	Comment
0	FTIR and HRR measurement started
0:30	Flame start
0:45	First numbers from FTIR available
2:30	Start injecting DMC + 1 M salt 18 ml/min
3:20	Flow increased to 20 ml/min
4:00	Stop spray due to no spray
5:40	Injection clean DMC
7:00	Gets spray
8:00	Start salt + DMC injection
11:00	Injection end
16:22	Burner off

Table 14 Test procedure test 14

Time Min:sec	Comment
0	FTIR including numbers on screen
3:00	HRR measurement started
3:30	Flame start
5:30	Start injecting DMC + 1 M salt 1.8 ml/min in spoon
7:15	Interrupted due to stop in needle

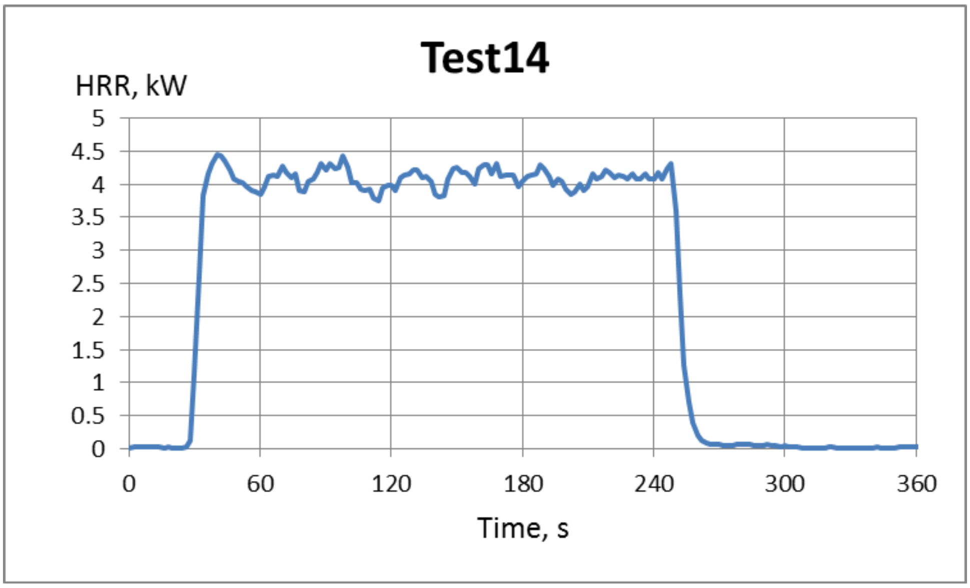

Figure 12 HRR test 14

Table 15 Test procedure test 15

Time Min:sec	Comment
0	FTIR and HRR measurement started
0:48	First numbers from FTIR available
1:05	Flame start
3:00	Start injecting DMC 1.8 ml/min onto spoon
5:00	Start injecting DMC + salt 1.8 ml/min onto spoon
10:00	Start injecting DMC 1.8 ml/min onto spoon
11:00	Injecting water instead, come through white plug in opening
15:15	Stop injection
17:15	Burner off

Table 16 **Test procedure test 16**

Time Min:sec	Comment
0	FTIR and HRR measurement started
0:45	First numbers from FTIR available
1:07	Flame start
3:00	Start injecting DMC 1.8 ml/min onto spoon
5:05	Start injecting DMC + salt 1.8 ml/min onto spoon
11:15	Start injecting DMC 1.8 ml/min onto spoon
13:00	Injecting water instead
16:50	Stop injection
	Burner off

Table 17 **Test procedure test 17**

Time Min:sec	Comment
0	FTIR and HRR measurement started
0:47	First numbers from FTIR available
2:30	Light the 2g DMC + 2 g salt in open cup
3:40	Fire extinguishes itself
5:27	Light the 2g DMC + 2 g salt in open cup
6:40	Fire extinguishes itself
10:00	end

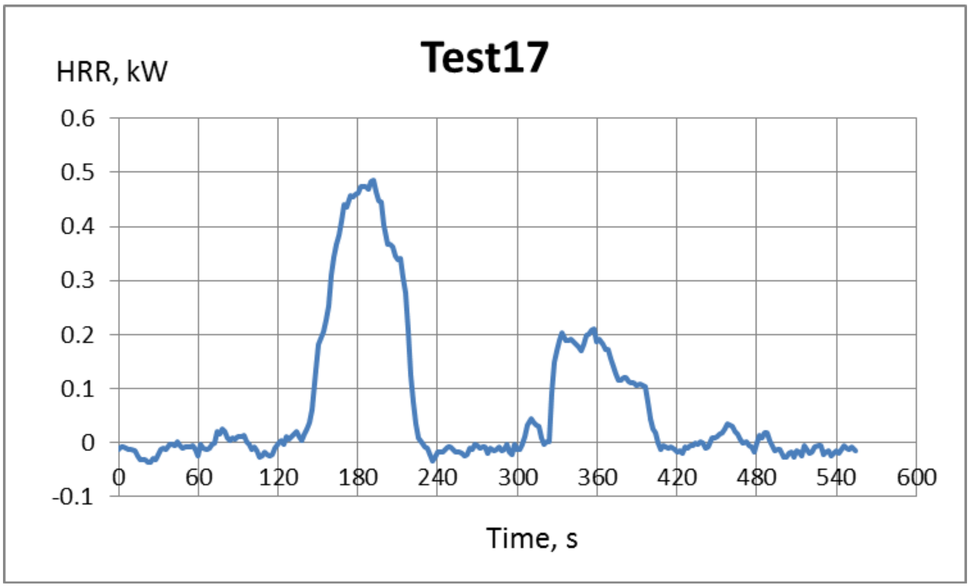

Figure 13 **HRR test 17**

Table 18 **Test procedure test 18**

Time Min:sec	Comment
0	FTIR and HRR measurement started
0:62	First numbers from FTIR available
6:50	Light the 2g DMC + 2 g salt in open cup
7:30	Fire extinguishes itself
10:48	Light the 2g DMC + 2 g salt in open cup
11:50	Fire extinguishes itself
10:00	end

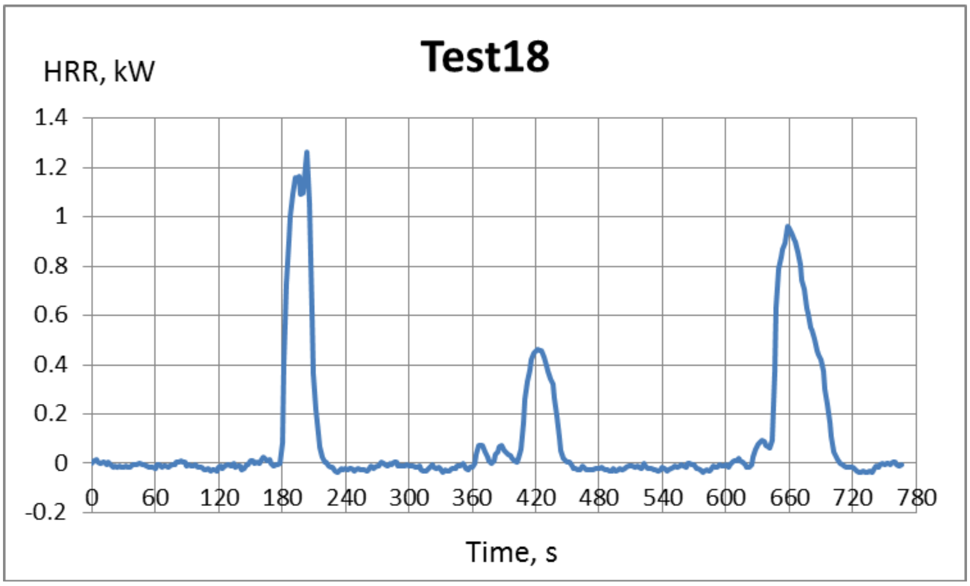

Figure 14 HRR from test 18

No test 19 was conducted

Table 19 Test procedure test 20

Time Min:sec	Comment
0	HRR measurement started
1:30	FTIR measurements start
1:59	FTIR values available
2:30	Start propane 7 skd
7:30	Stop propane

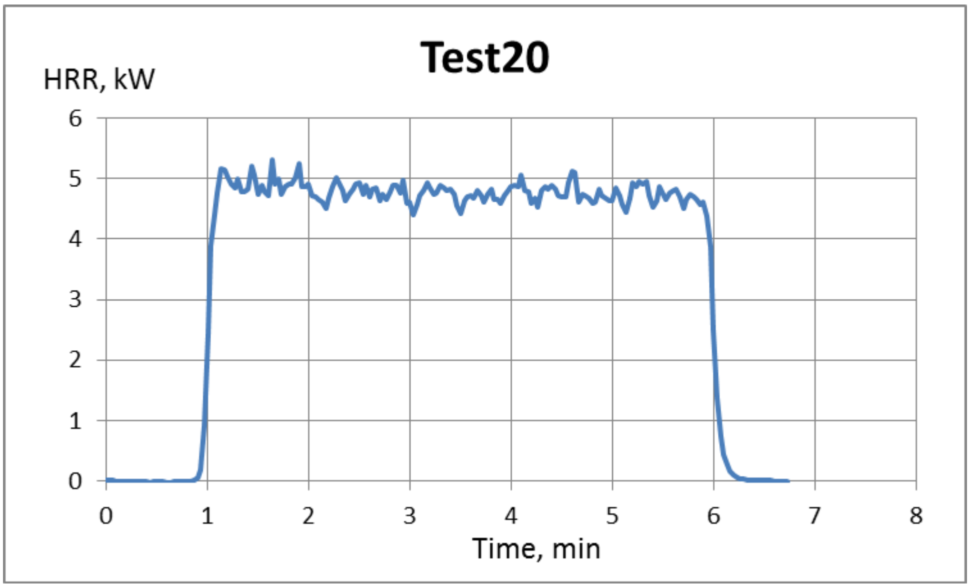

Figure 15 HRR from test 20 Propane only gave a mean HRR of 4.78 kW

Table 20 **Test procedure test 21**

Time Min:sec	Comment
0	FTIR measurement started
0:28	FTIR values available
4:00	Start HRR measurements
5:00	Flame start
7:00-8:00	Spray water into flame
10:00-11:00	Spray water into flame
13:00	Stop flame

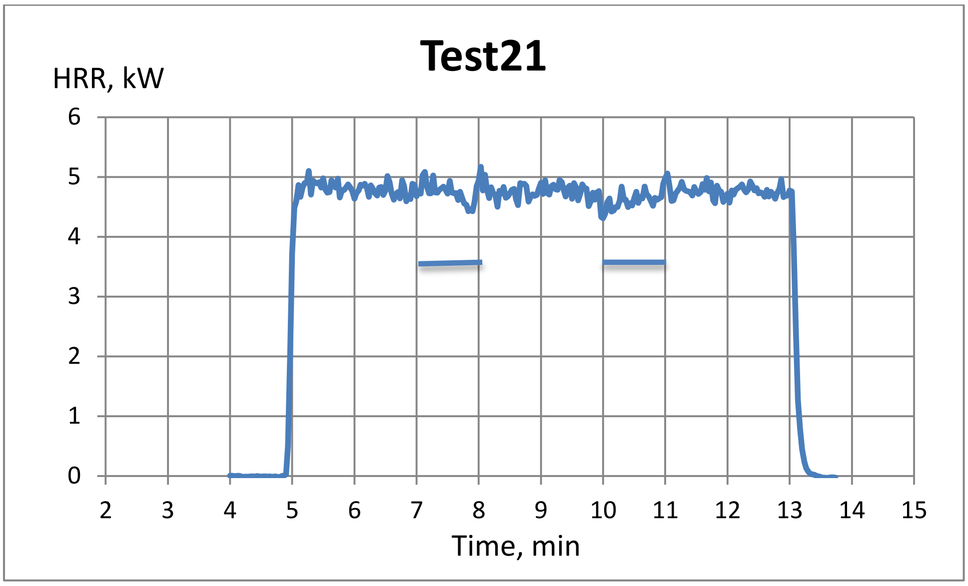

Figure 16 **HRR from test 21. Propane + water injection by spraybottle. Sprayinjection of water marked in figure with horisontal lines**

Table 21 **Test procedure test 22**

Time Min:sec	Comment
0	FTIR measurement started
0:25	First numbers from FTIR available
2:00	Start HRR measurements
3:00	Start propane flame
5:00	Start injecting DMC 15 ml/min
7:00	Start injecting DMC with salt 1 M
9:00	DMC only, spray not OK until 9:40
13:00	Injecting ethanol
19:00	Stop flame, inject water through needle

Table 22 Test procedure test 23

Time Min:sec	Comment
0	FTIR measurement started
0:40	First numbers from FTIR available
2:00	Start HRR measurements
3:00	Start propane flame
5:00	Start injecting DMC 15 ml/min
7:00	Start injecting DMC with salt 0.4 M
10:00	Propane decreased to 5 skd
11:30	Pump stopped
12:00	Injecting ethanol
20:00	Injecting DMC and salt 0.4 M
23:00	Injecting DMC only
25:00	Injecting ethanol only
27:00	Injecting water only
30:00	Propane only
33:00	Stop flame

Table 23 Test procedure test 24

Time Min:sec	Comment
0	FTIR measurement started
0:27	First numbers from FTIR available
2:00	Start HRR measurements
3:00	Start propane flame
6:00	Start injecting DMC 15 ml/min with salt problematic
11:15	Decreased to 10 ml/min
14:25	DMC finished
15:00	Start again
15:05	Started injecting weater also, stop in system directly
17:00	Stop flame

Table 24 Test procedure test 25

Time Min:sec	Comment
0	FTIR measurement started
0:37	First numbers from FTIR available
2:00	Start HRR measurements
3:00	Start propane flame 7 skd
5:00	Start injecting DMC 15 ml/min
7:00	Start injecting DMC with salt 1 M
10:00	Spary became beam, turned injection off
12:00	Stop flame

Table 25 **Test procedure test 26**

Time Min:sec	Comment
0	FTIR measurement started
0:38	First numbers from FTIR available
2:00	Start HRR measurements
3:00	Start propane flame 7 skd
4:00	Start injecting DMC 15 ml/min with salt 1 M
5:00	Water spray into flame
5:40	Spray became beam
7:00	Injecting water through needle for cleaning
11:00	Start injecting DMC 15 ml/min with salt 1 M
11:50	Water spray into flame
12:30	Spray became beam
15:00	Stop flame

Table 26 **Test procedure test 27**

Time Min:sec	Comment
0	FTIR measurement started
0:30	First numbers from FTIR available
2:00	Start HRR measurements
2:30	Cakecup with 1 M DMC placed into Cone calorimeter
2:47	Radiation starts, immediate ignition
5:45	Flames extinguish themself
11:45	End heat exposure

Test28
0.4M salt in DME in cakecup, 15 kW/m² radiation applied as heating, spark placed above surface
Ignition about 13 s after heat radiation started.
The electrolyte burned up and then new was added at 7 minutes 35 s.

Unfortunately the FTIR program ceased to work during this test.

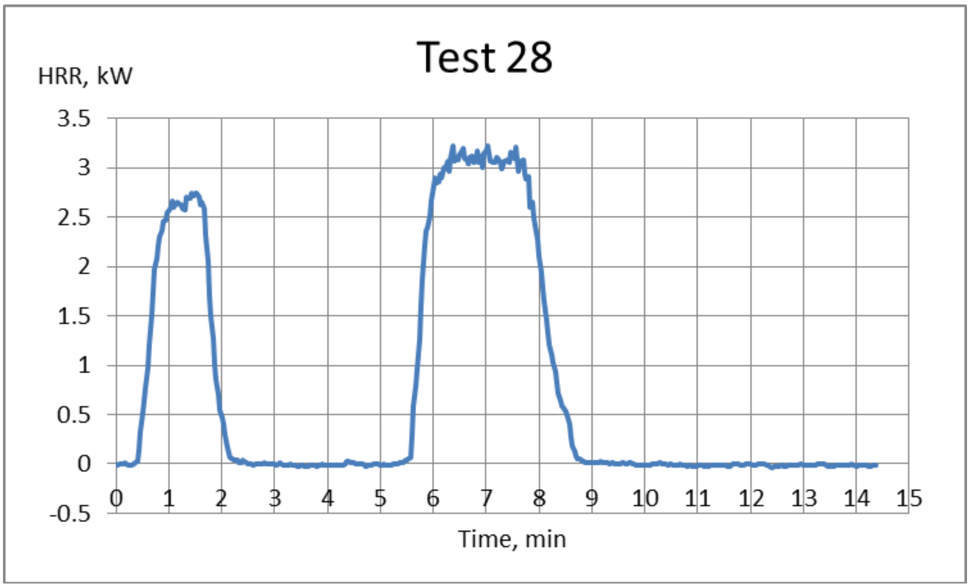

Figure 17 **HRR test 28**

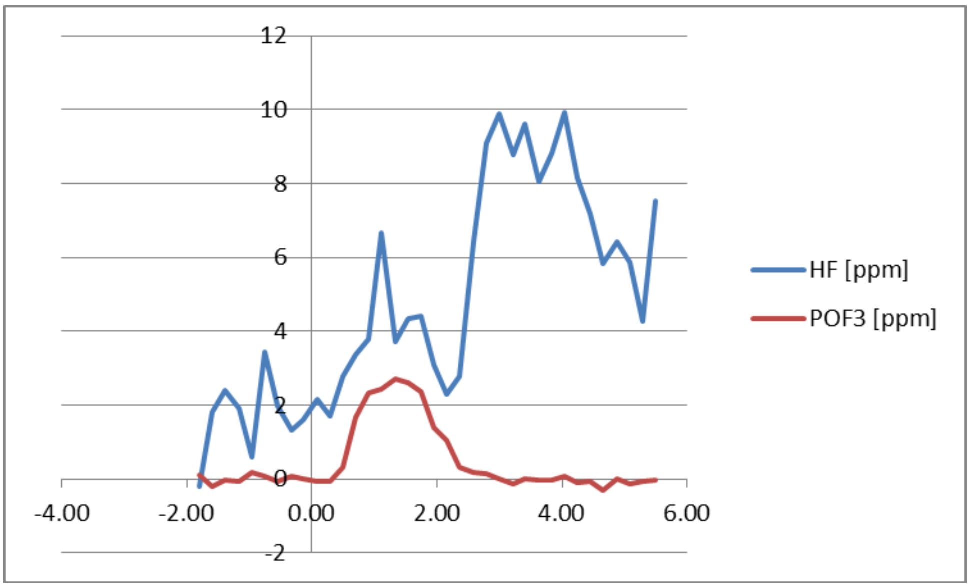

Figure 18 HF and POF$_3$ test 28

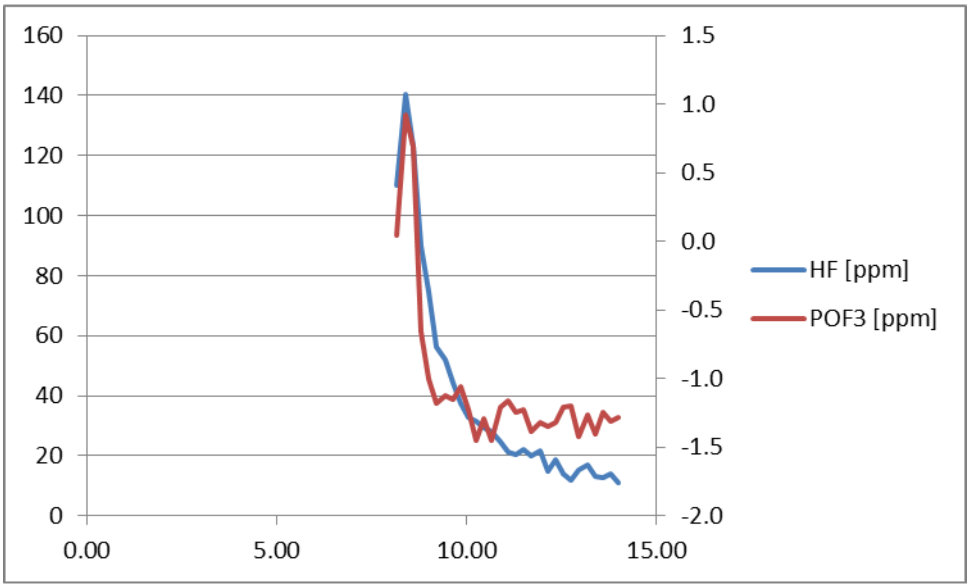

Figure 19 HF and POF$_3$ test 28

Appendix B Results from batterycell tests

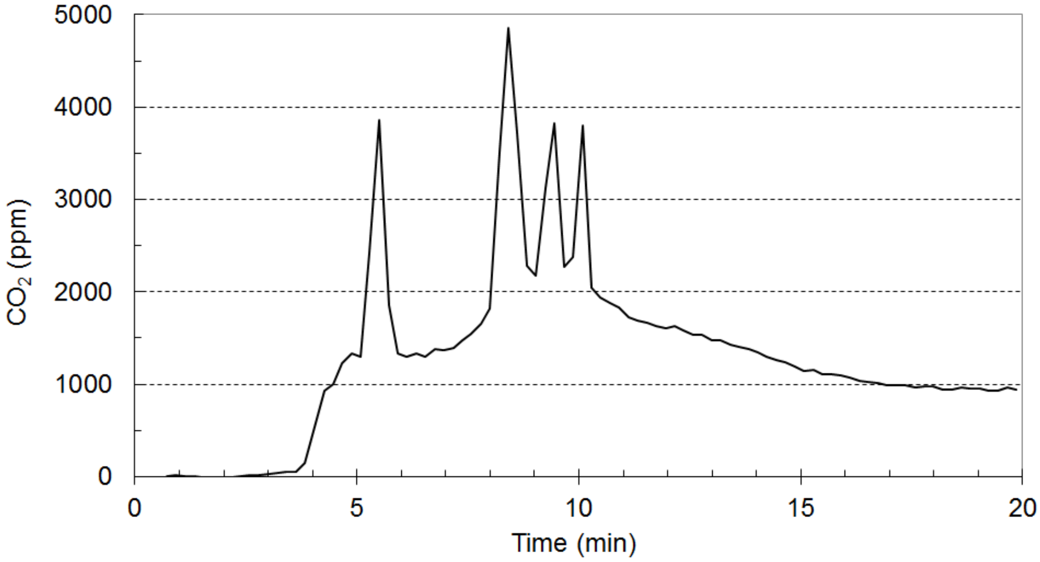

Figure 1 Concentration of CO_2 measured by FTIR in Test 1.

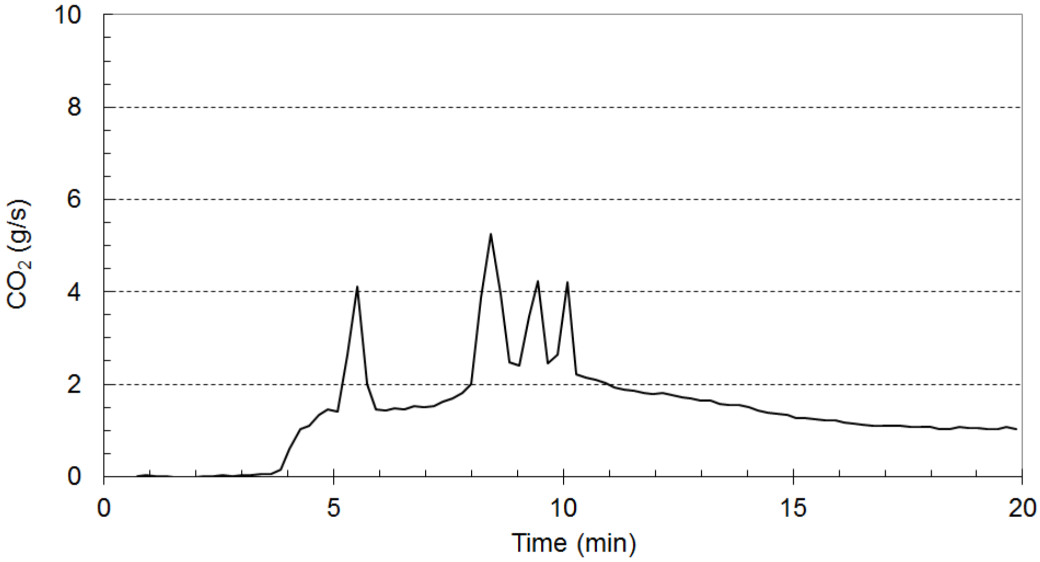

Figure 2 Production rate of CO_2 measured by FTIR in Test 1.

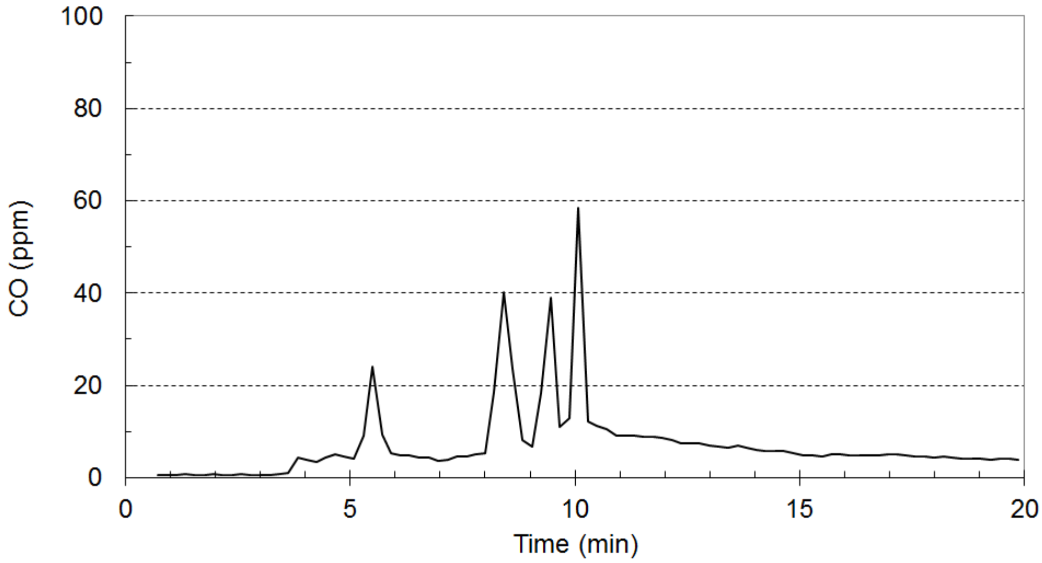

Figure 3 **Concentration of CO measured by FTIR in Test 1.**

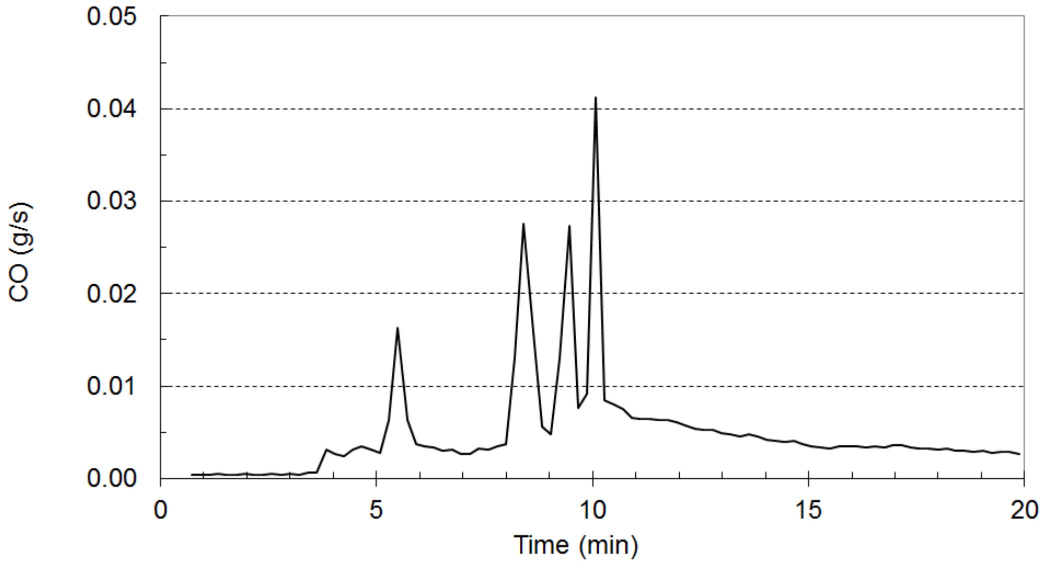

Figure 4 **Production rate of CO measured by FTIR in Test 1.**

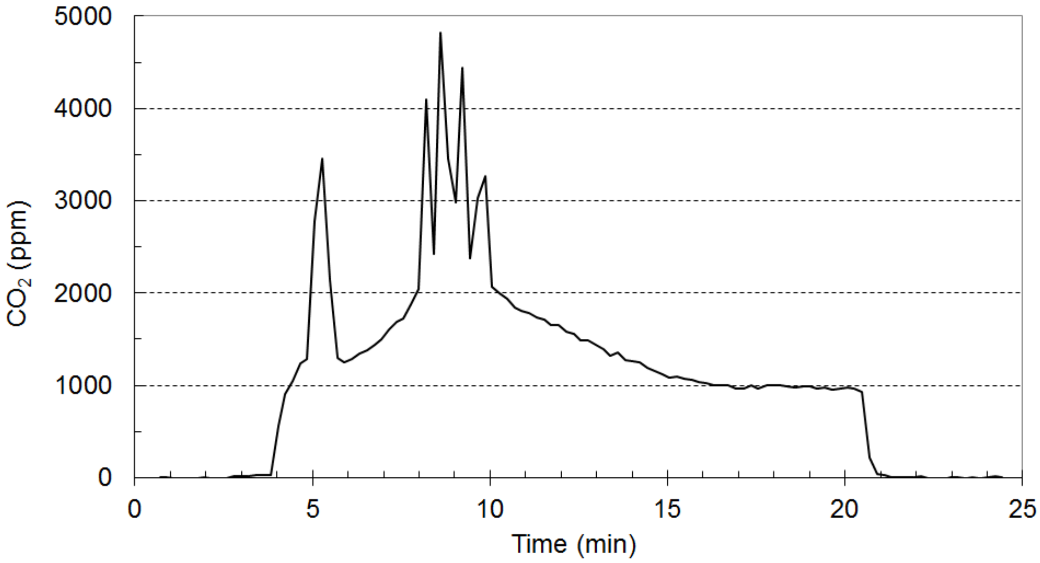

Figure 5 Concentration of CO_2 measured by FTIR in Test 2.

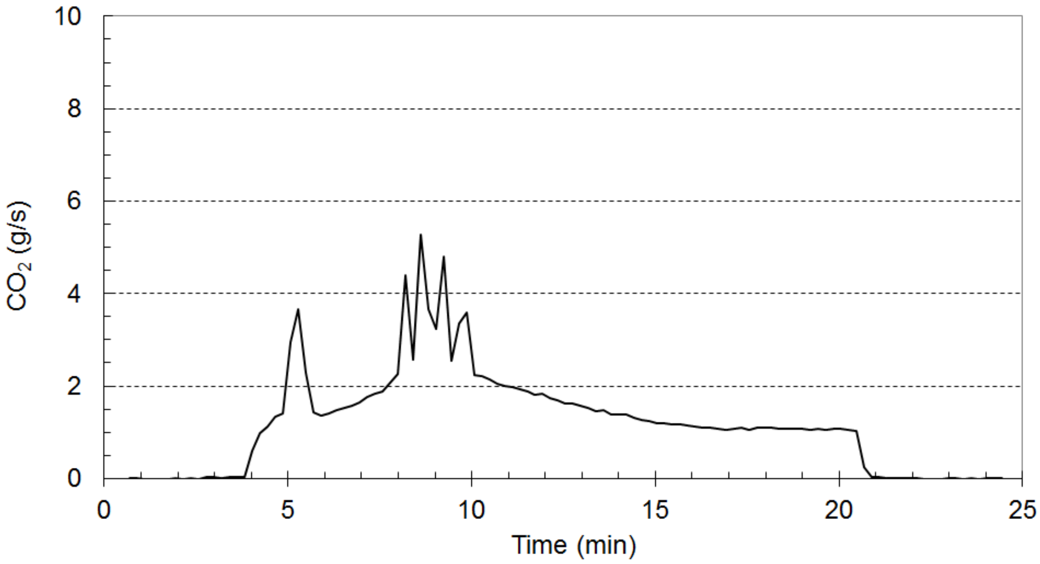

Figure 6 Production rate of CO_2 measured by FTIR in Test 2.

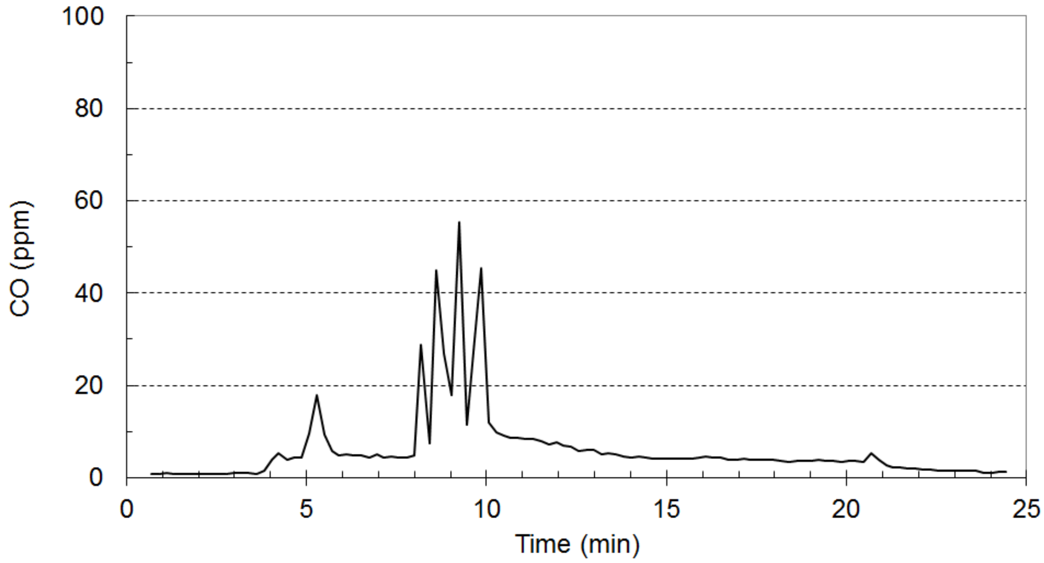

Figure 7 Concentration of CO measured by FTIR in Test 2.

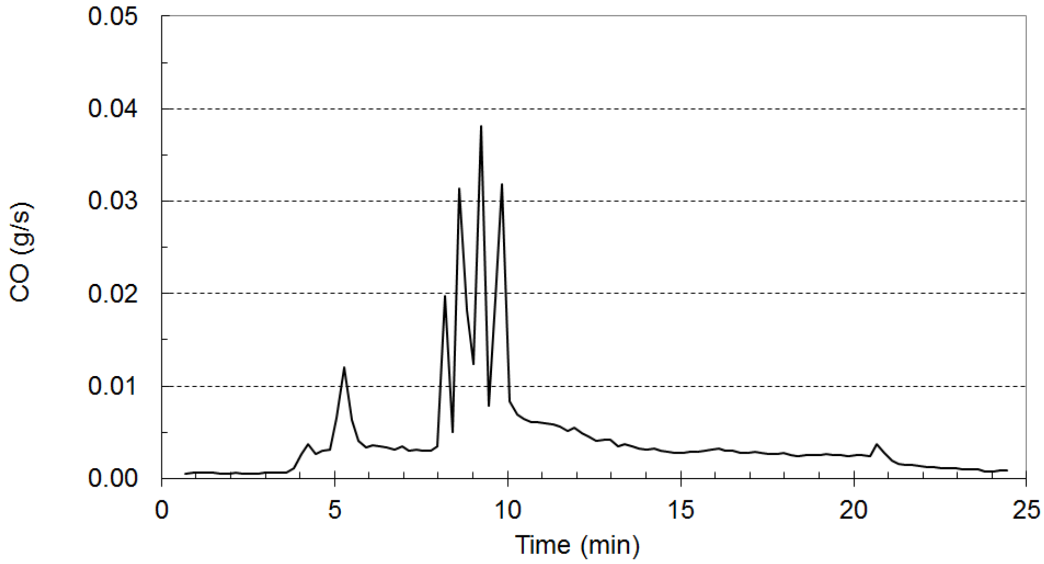

Figure 8 Production rate of CO measured by FTIR in Test 2.

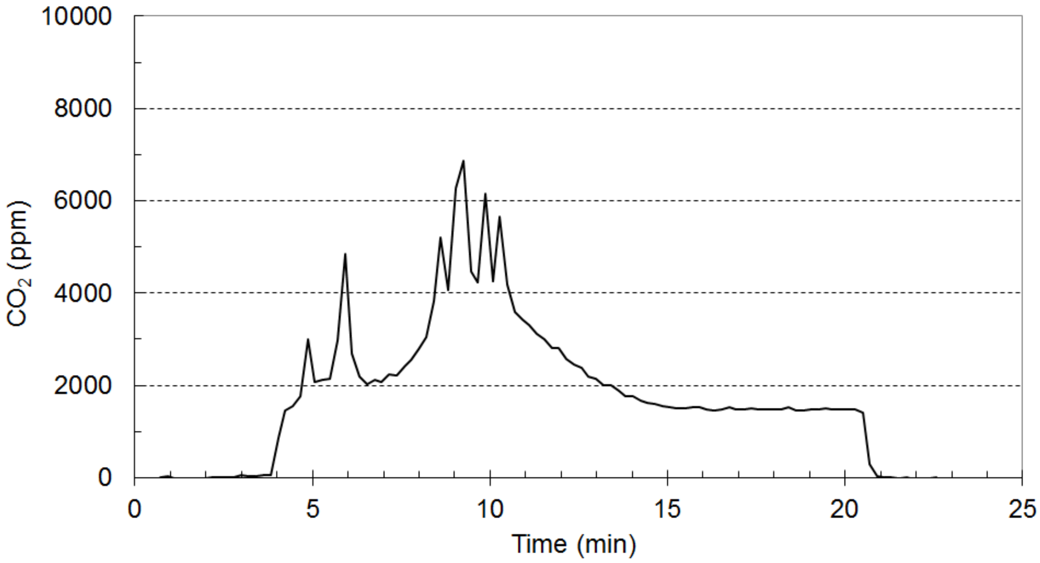

Figure 9 Concentration of CO_2 measured by FTIR in Test 3.

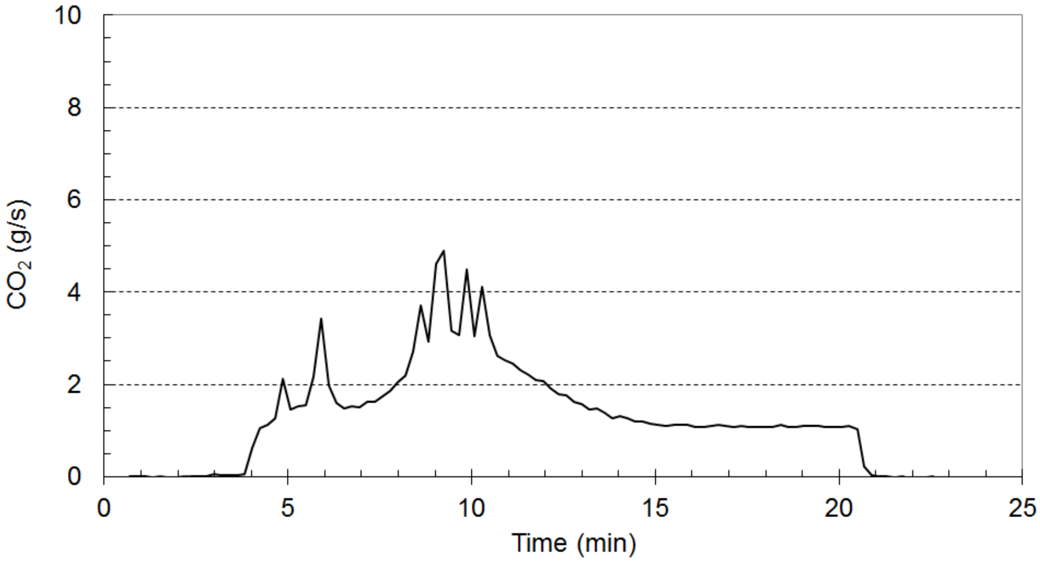

Figure 10 Production rate of CO_2 measured by FTIR in Test 3.

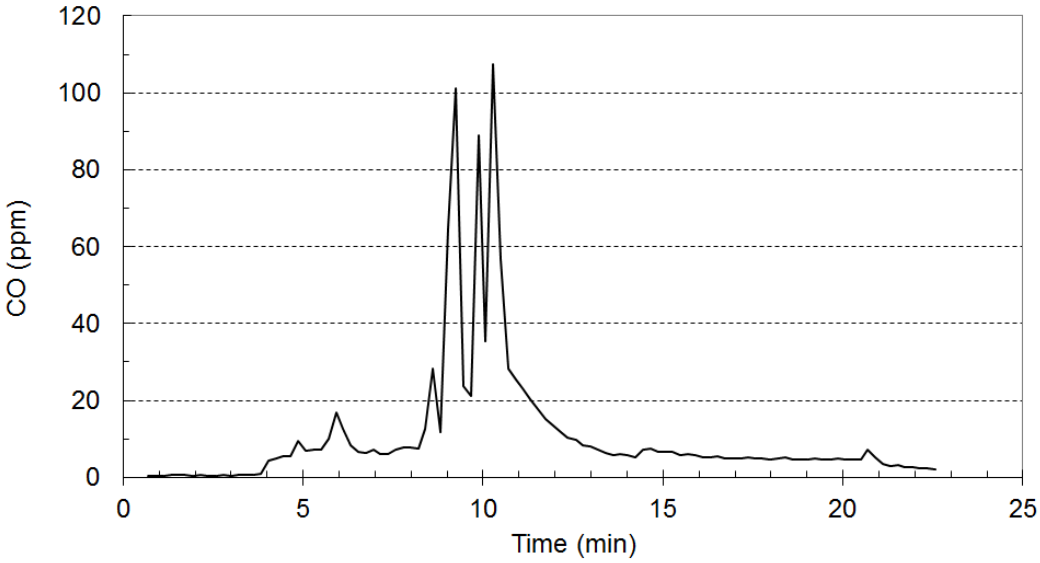

Figure 11 **Concentration of CO measured by FTIR in Test 3.**

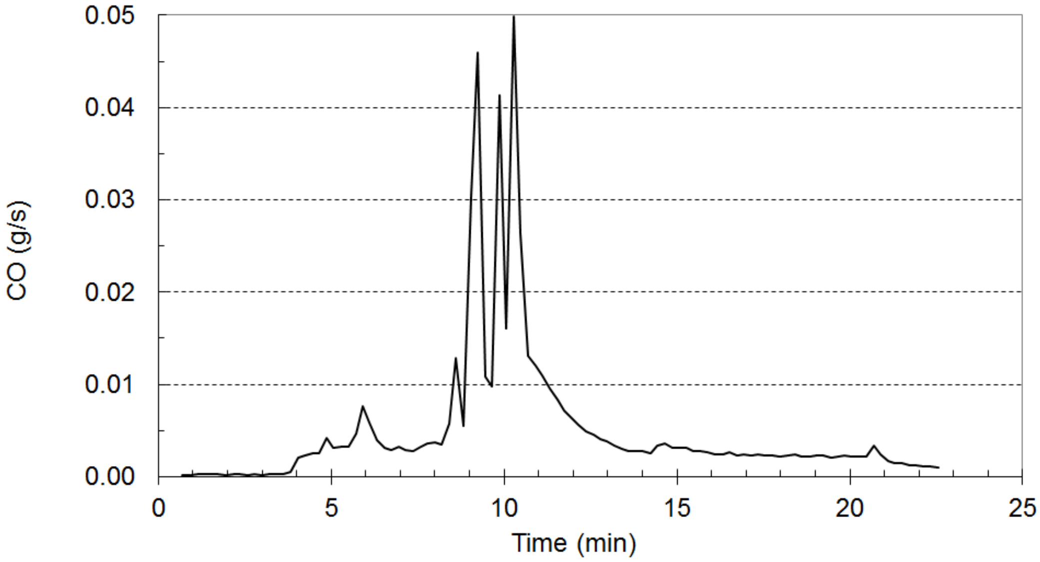

Figure 12 **Production rate of CO measured by FTIR in Test 3.**

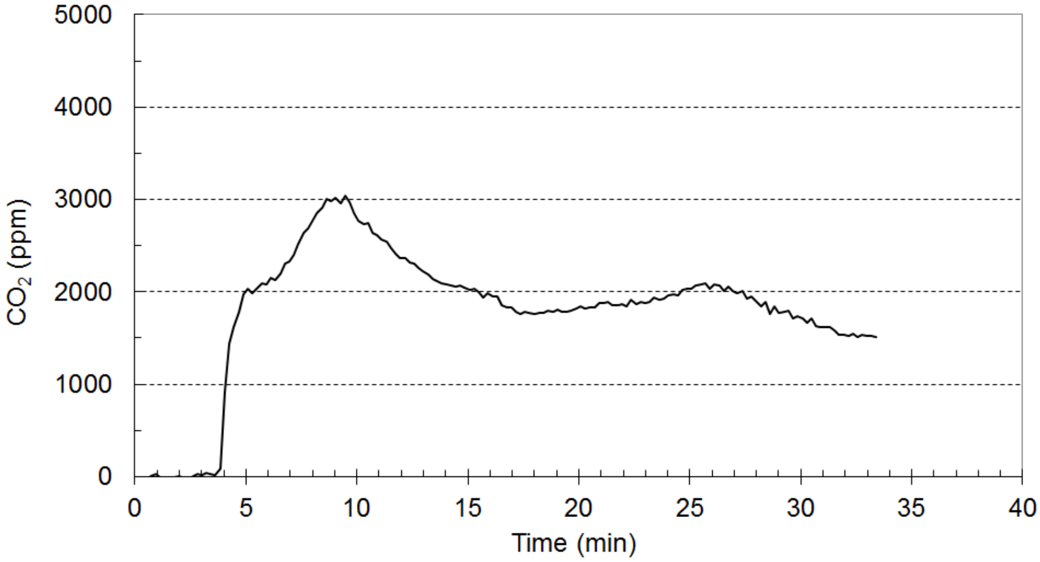

Figure 13 Concentration of CO_2 measured by FTIR in Test 4.

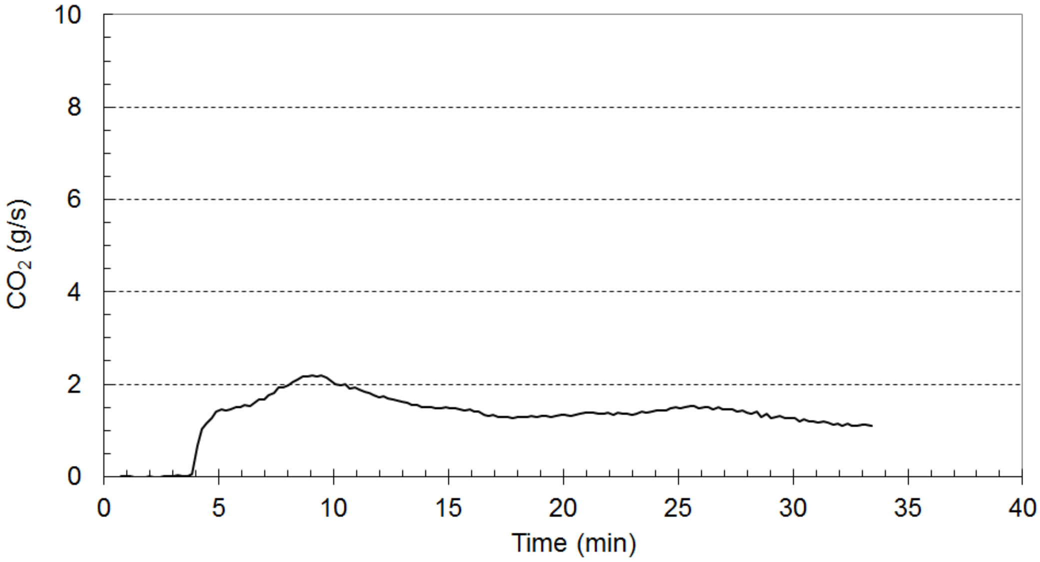

Figure 14 Production rate of CO_2 measured by FTIR in Test 4.

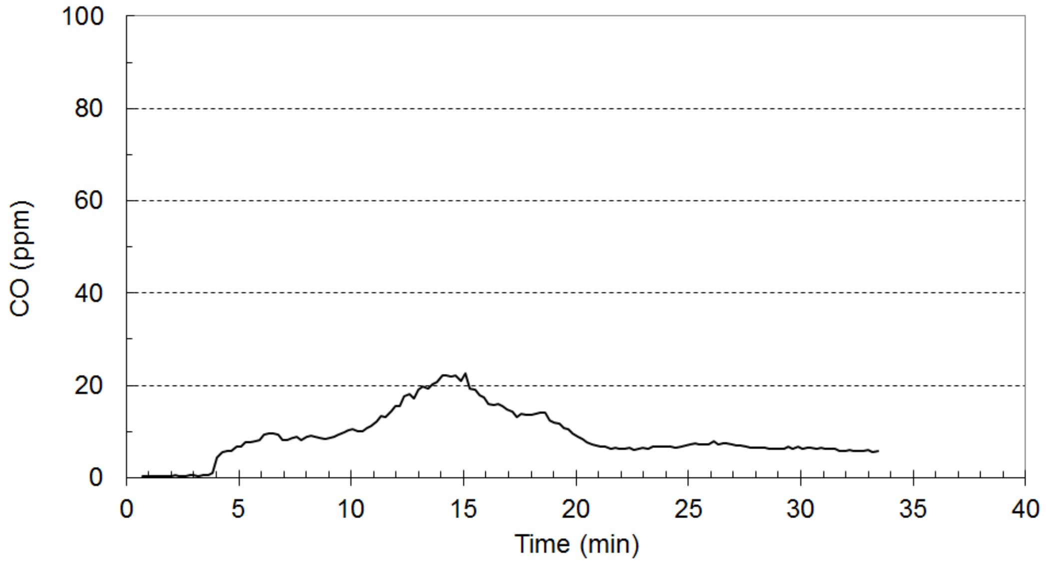

Figure 15 **Concentration of CO measured by FTIR in Test 4.**

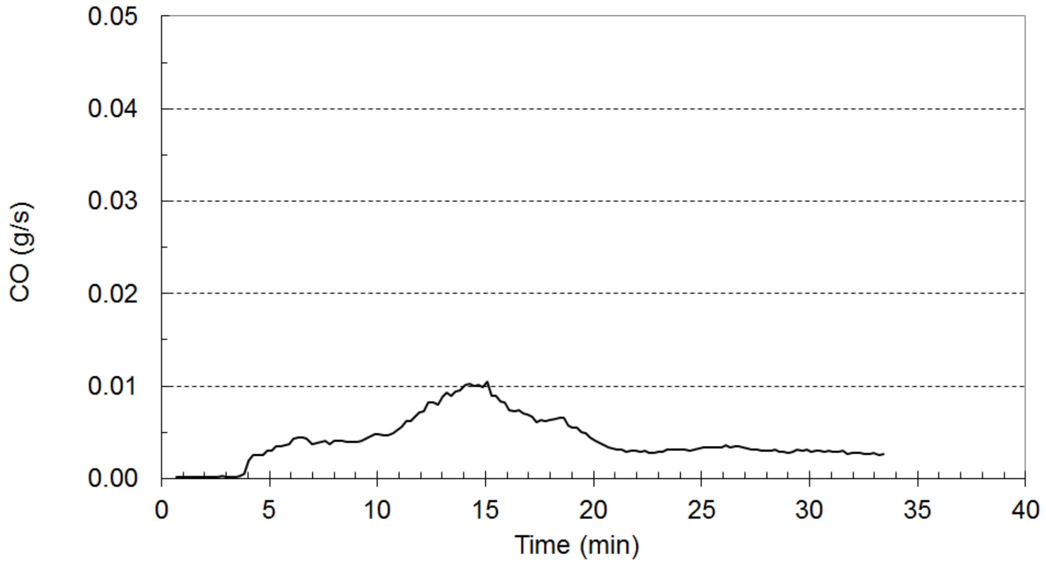

Figure 16 **Production rate of CO measured by FTIR in Test 4.**

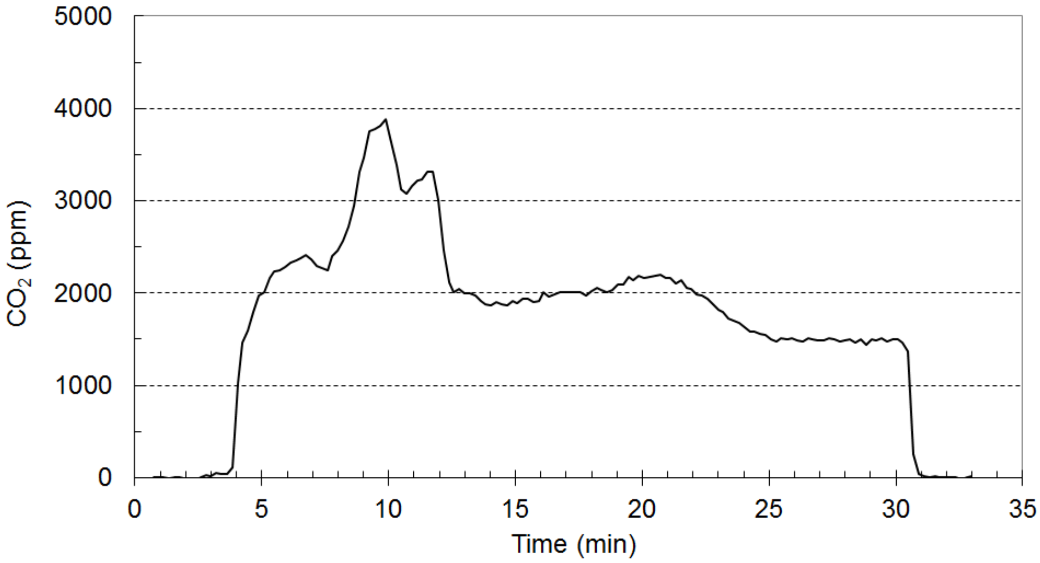

Figure 17 Concentration of CO_2 measured by FTIR in Test 5.

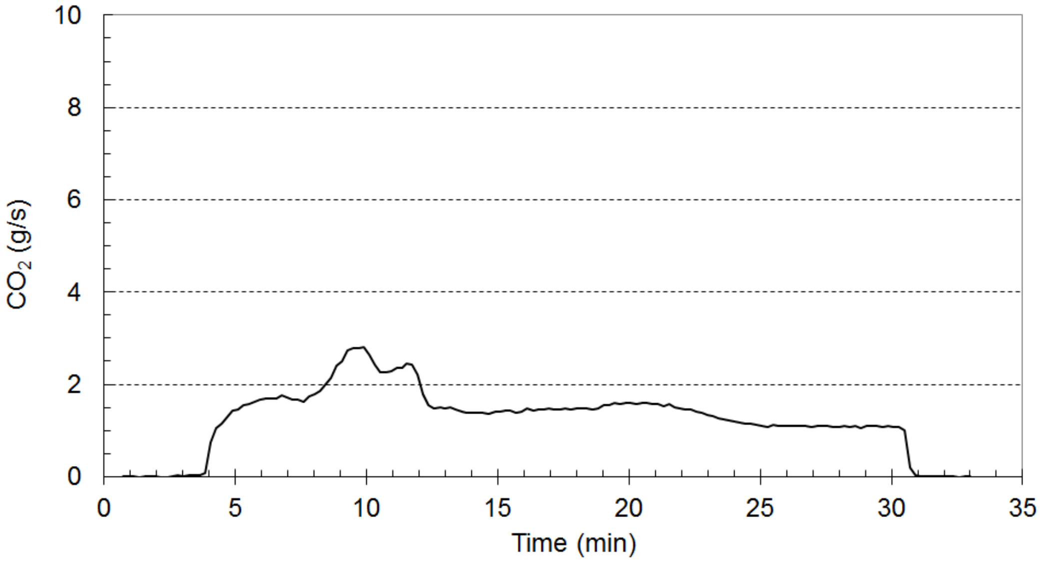

Figure 18 Production rate of CO_2 measured by FTIR in Test 5.

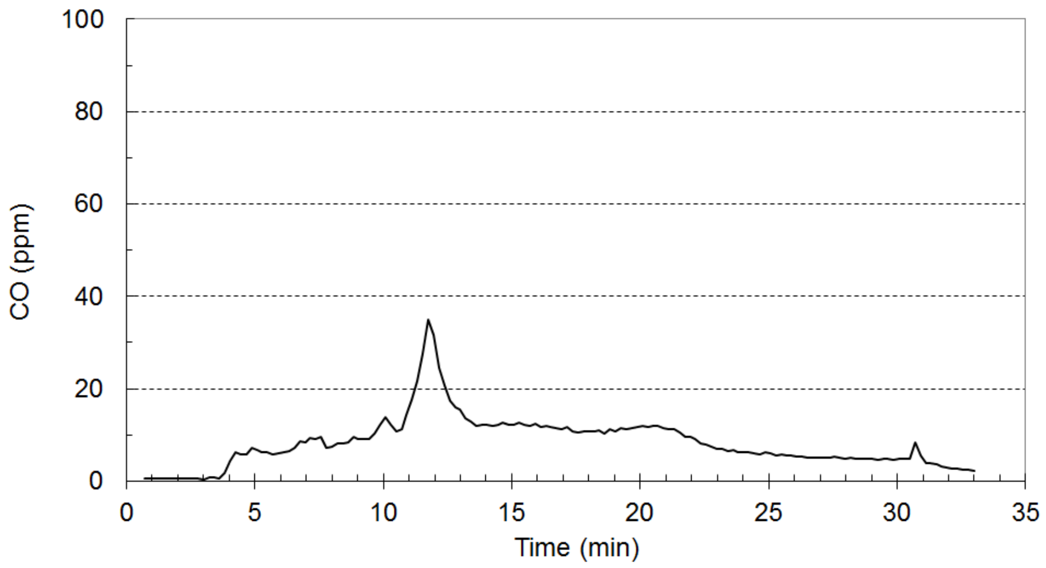

Figure 19 Concentration of CO measured by FTIR in Test 5.

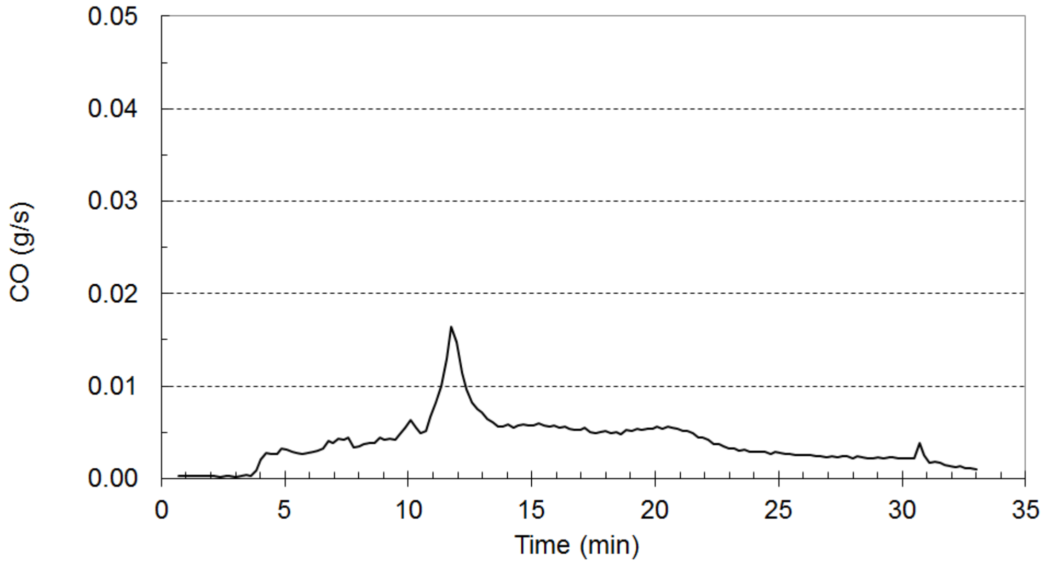

Figure 20 Production rate of CO measured by FTIR in Test 5.

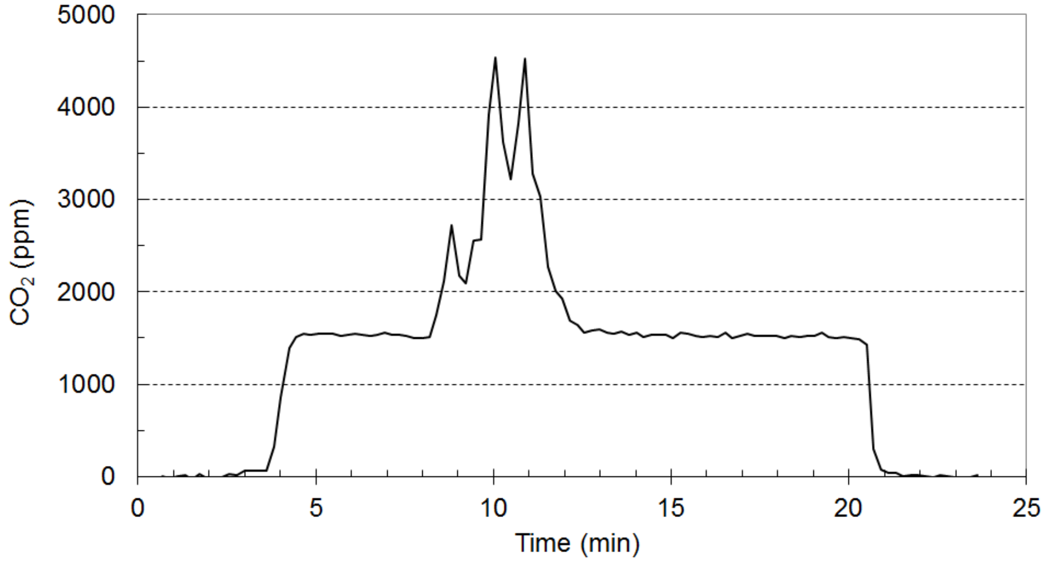

Figure 21 Concentration of CO_2 measured by FTIR in Test 6.

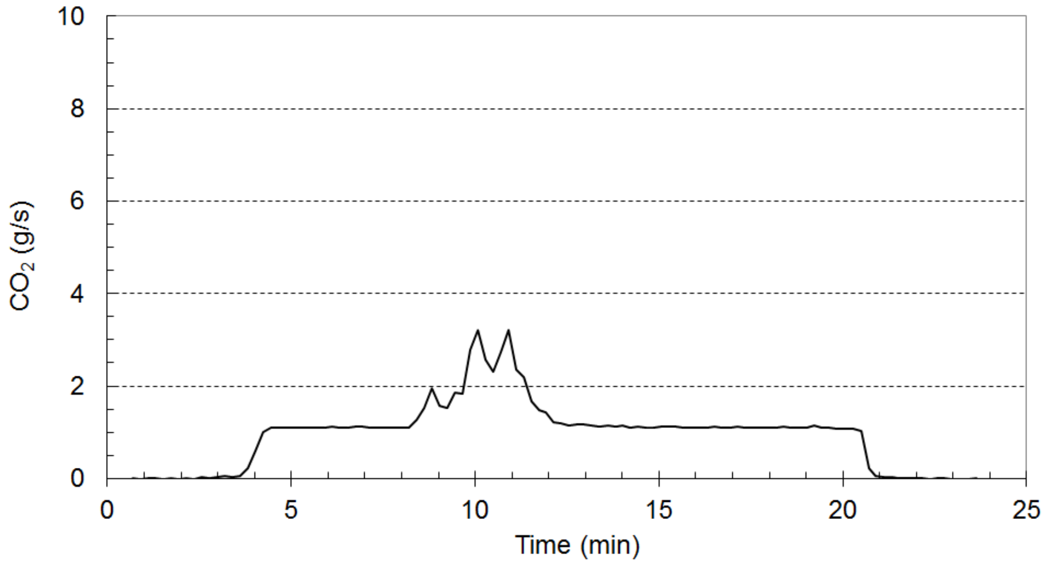

Figure 22 Production rate of CO_2 measured by FTIR in Test 6.

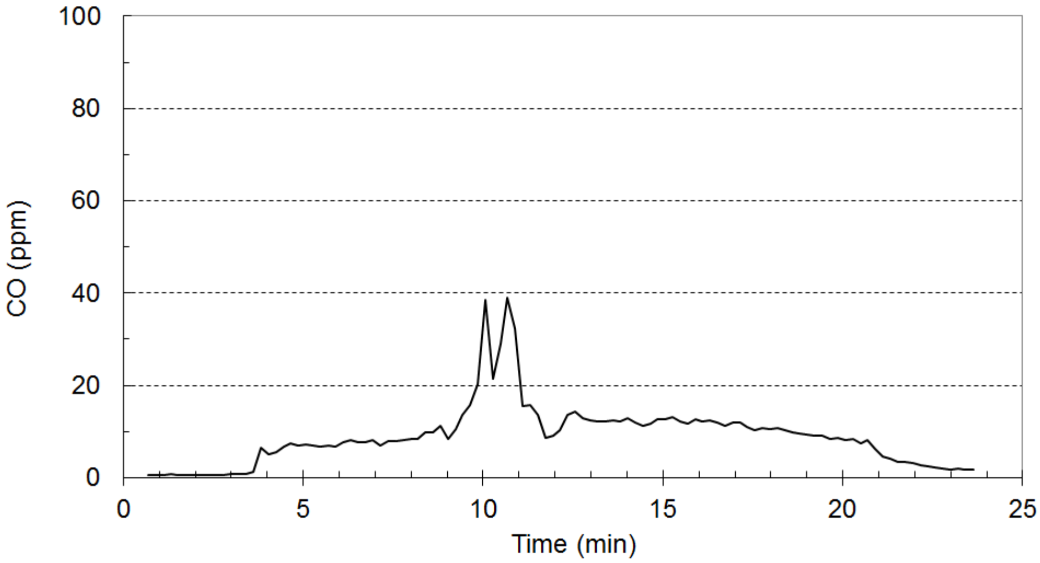

Figure 23 Concentration of CO measured by FTIR in Test 6.

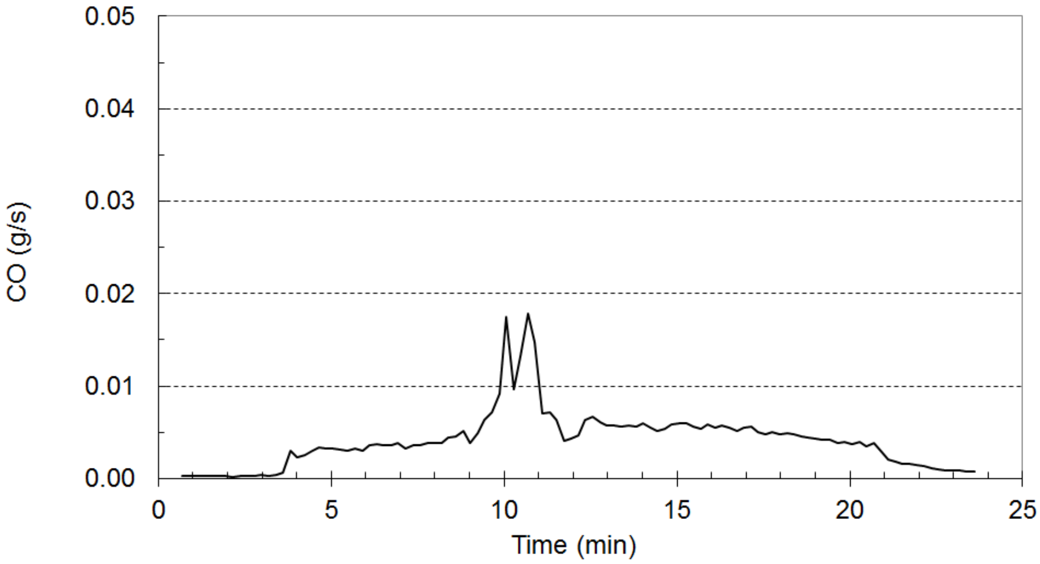

Figure 24 Production rate of CO measured by FTIR in Test 6.

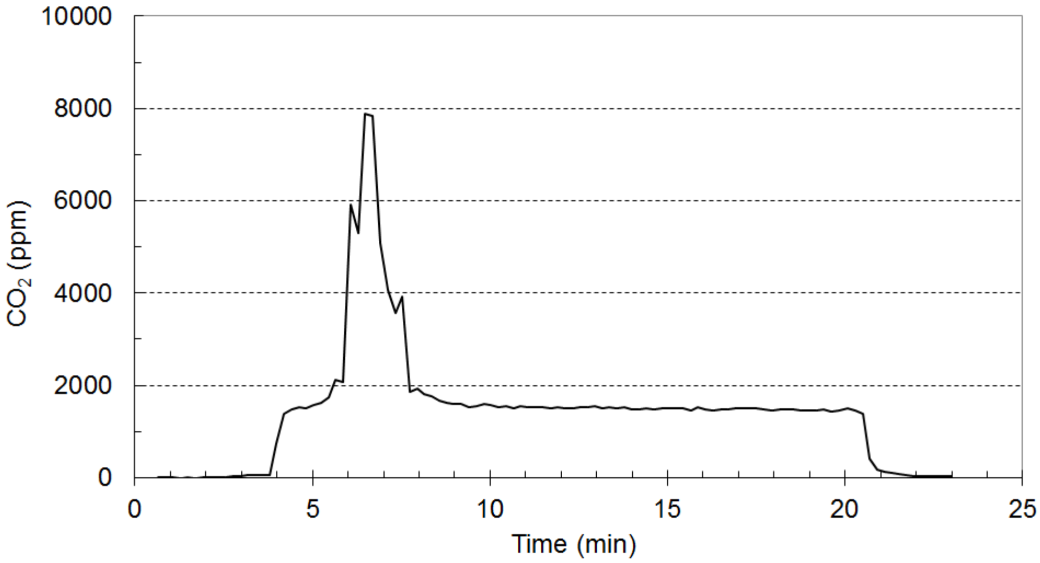

Figure 25 **Concentration of CO_2 measured by FTIR in Test 7.**

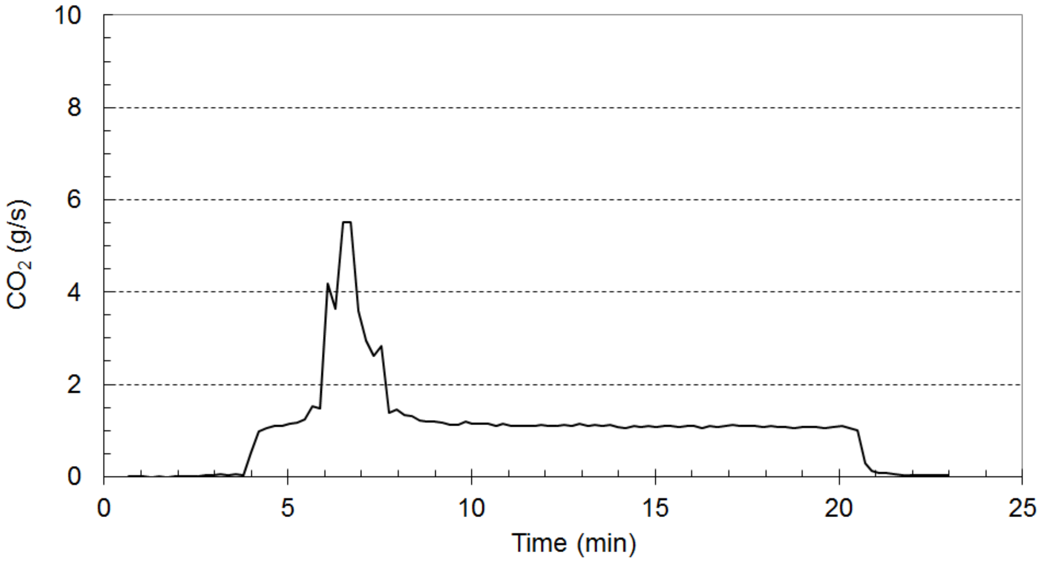

Figure 26 **Production rate of CO_2 measured by FTIR in Test 7.**

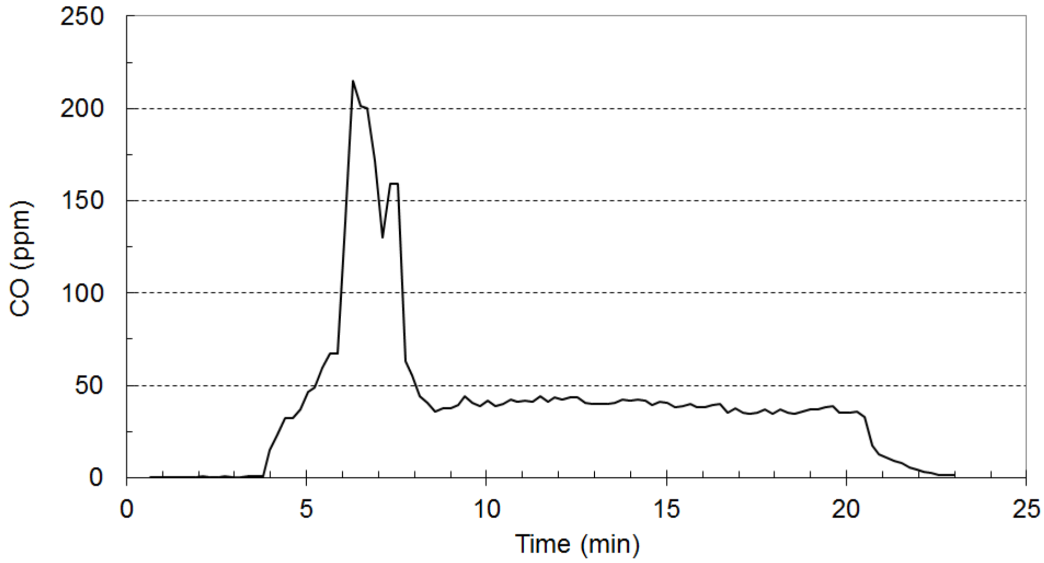

Figure 27 Concentration of CO measured by FTIR in Test 7.

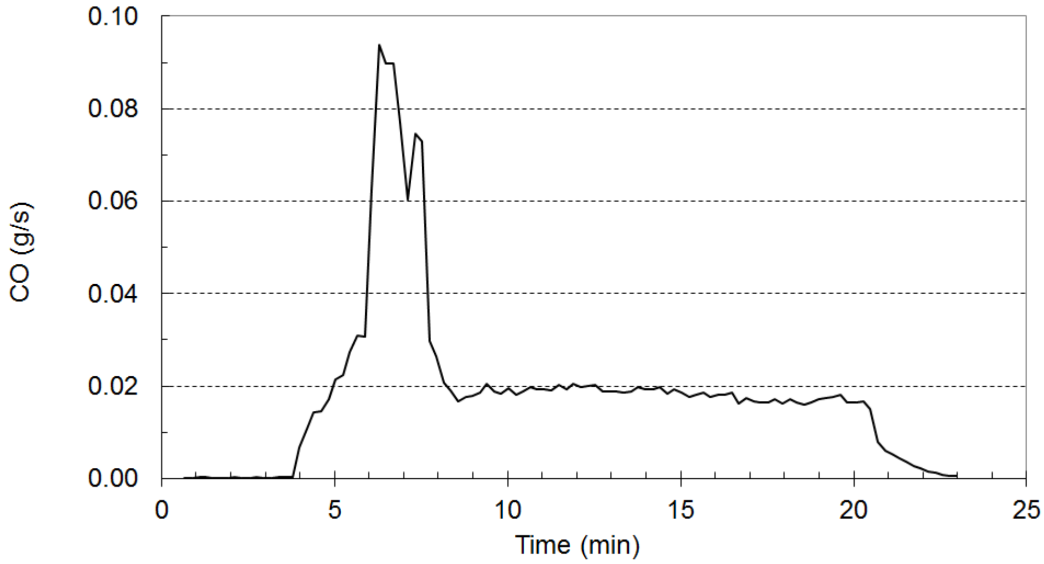

Figure 28 Production rate of CO measured by FTIR in Test 7.

Table 1 Results of CO_2 analysis with FTIR from test 1-5.

Test no	Total amounts with burner contribution subtracted (g)	Total yields (mg/g)
1	599	488
2	610	496
3	646	525
4	553	450
5	653	532

Table 2 **Results of CO analysis with FTIR from test 1-5.**

Test no	Max production rate (g/s)	Total amounts (g)	Total yields (mg/g)
1	0.041	6.0	4.9
2	0.038	6.2	5.0
3	0.050	6.7	5.4
4	0.011	8.4	6.8
5	0.016	7.6	6.2

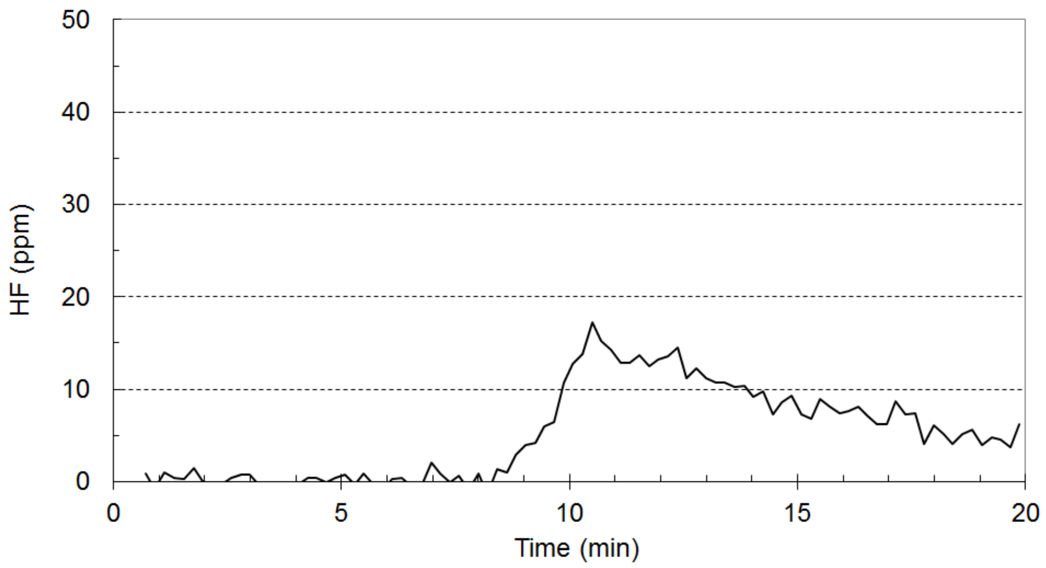

Figure 29 **Concentration of HF measured by FTIR in Test 1.**

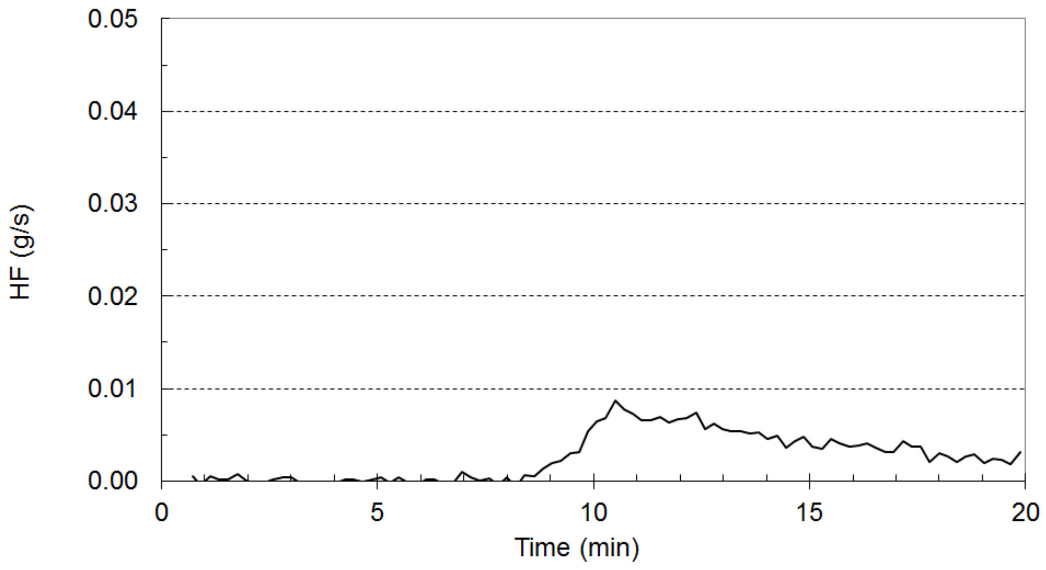

Figure 30 **Production rate of HF measured by FTIR in Test 1.**

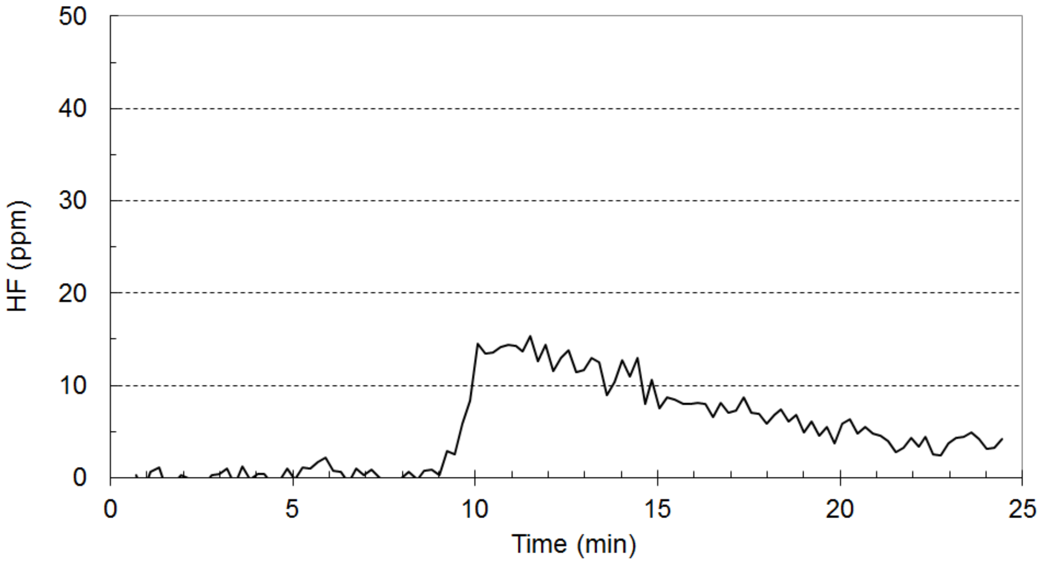

Figure 31 Concentration of HF measured by FTIR in Test 2.

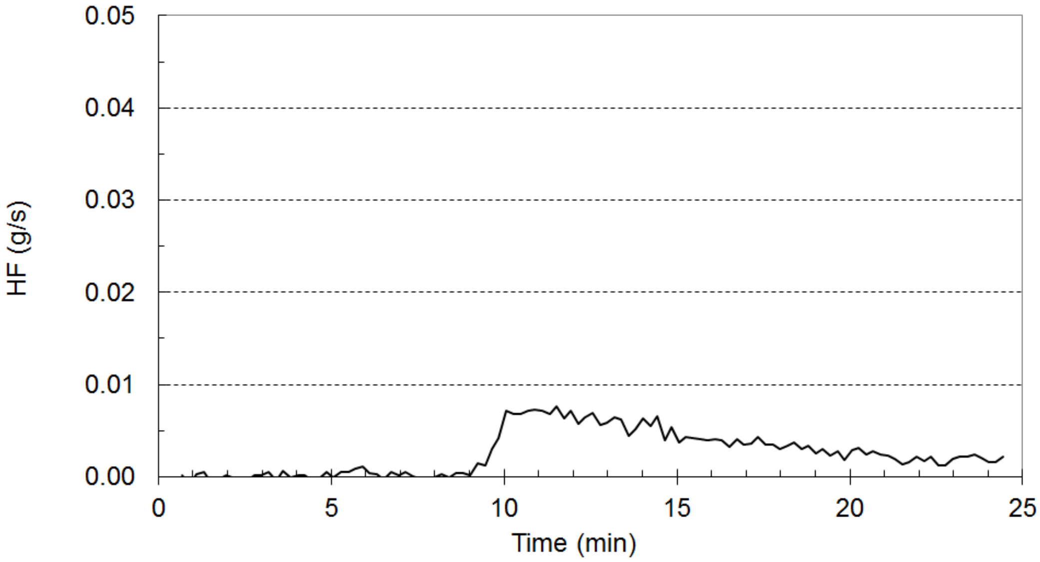

Figure 32 Production rate of HF measured by FTIR in Test 2.

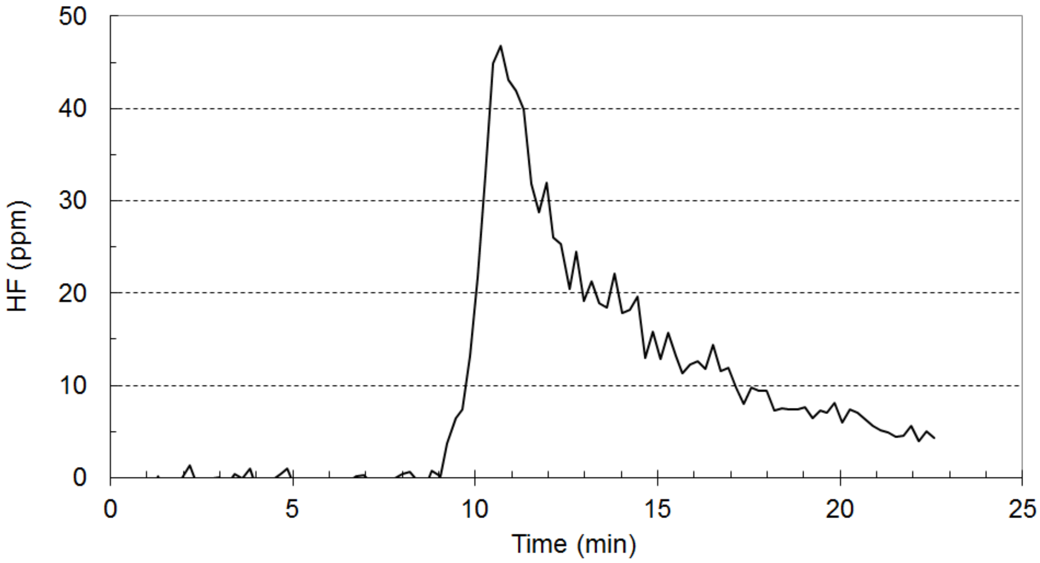

Figure 33 Concentration of HF measured by FTIR in Test 3.

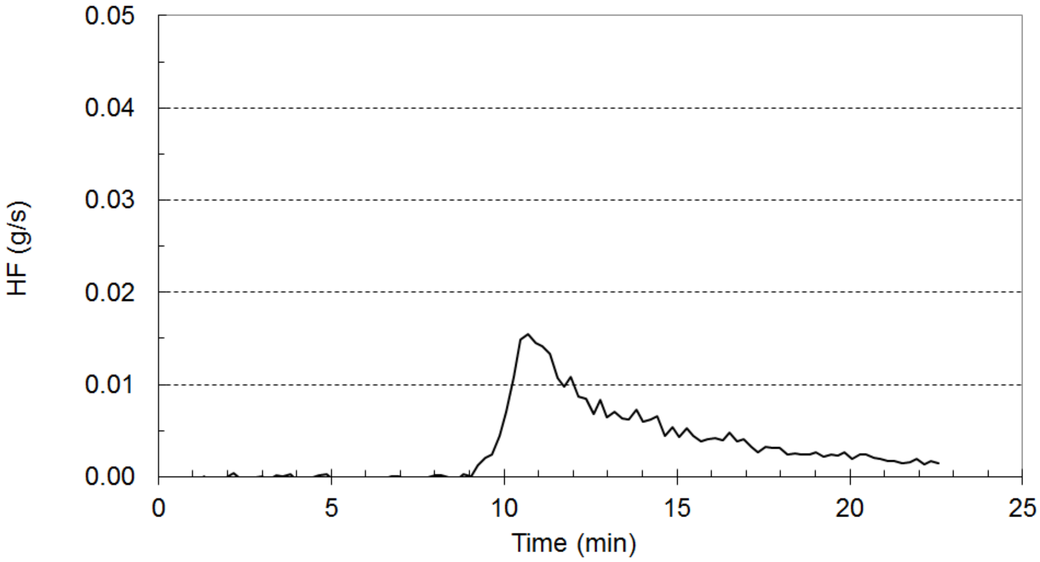

Figure 34 Production rate of HF measured by FTIR in Test 3.

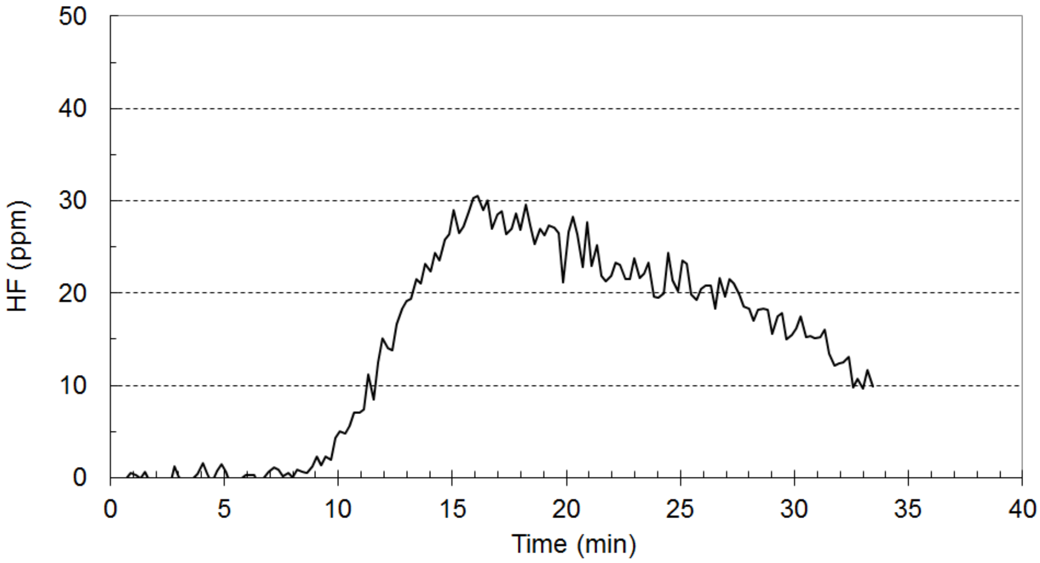

Figure 35 Concentration of HF measured by FTIR in Test 4.

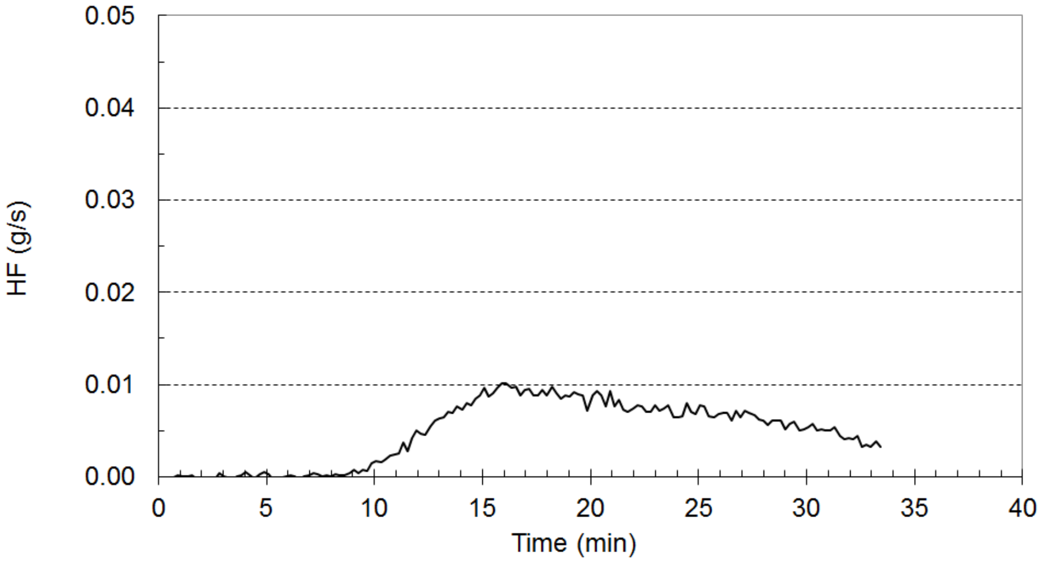

Figure 36 Production rate of HF measured by FTIR in Test 4.

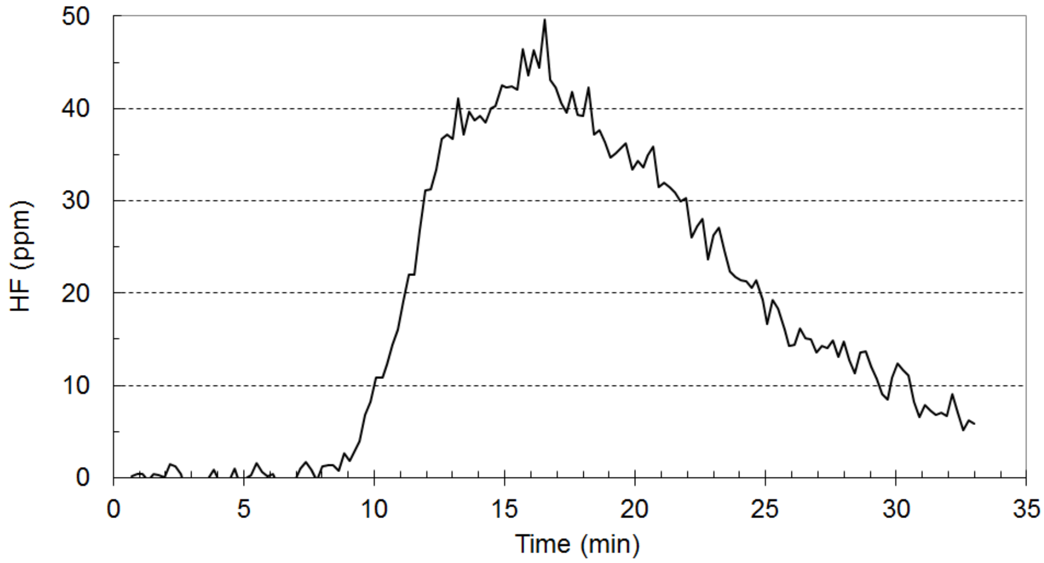

Figure 37 Concentration of HF measured by FTIR in Test 5.

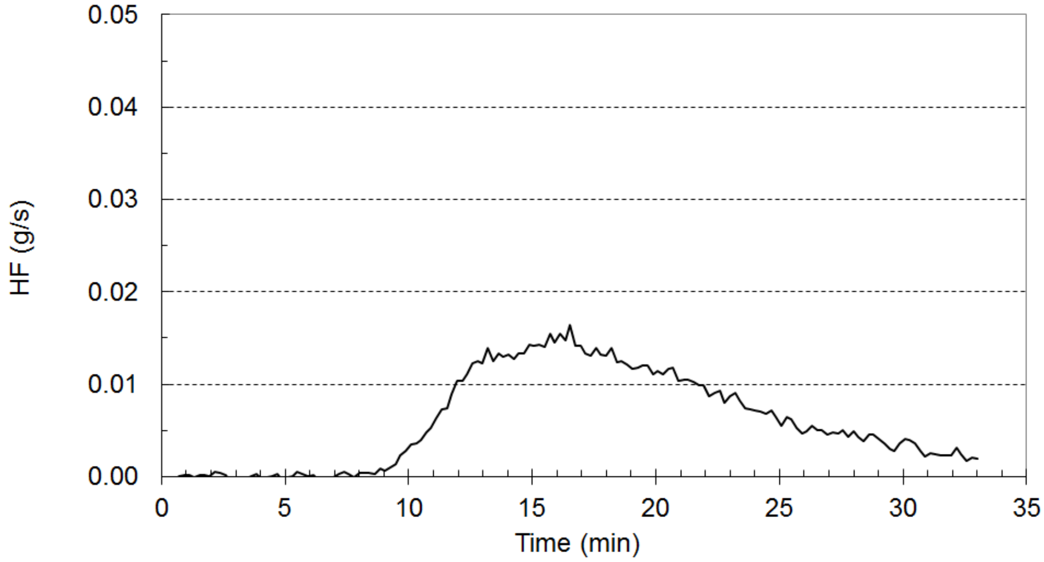

Figure 38 Production rate of HF measured by FTIR in Test 5.

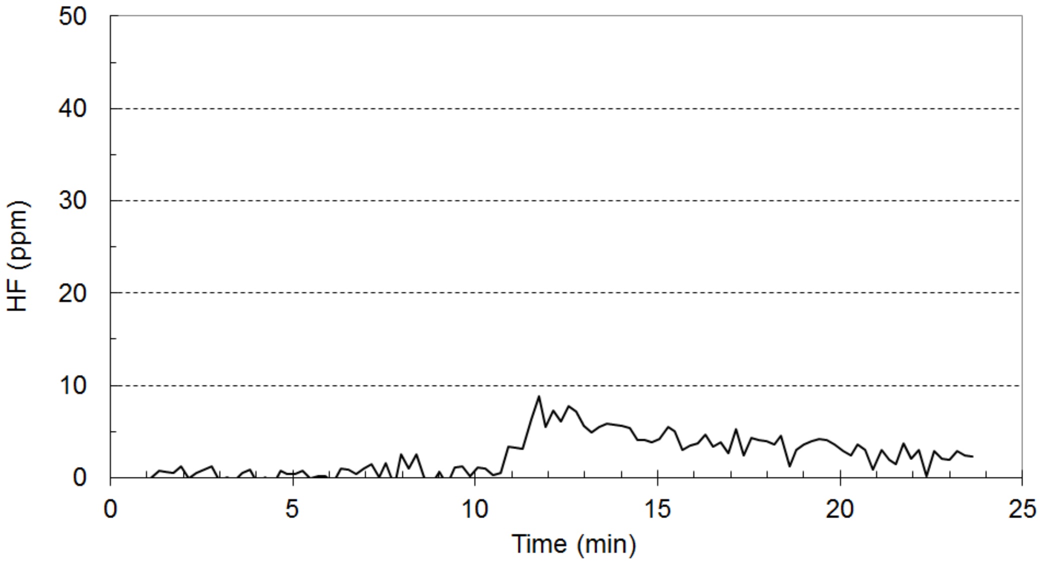

Figure 39 Concentration of HF measured by FTIR in Test 6.

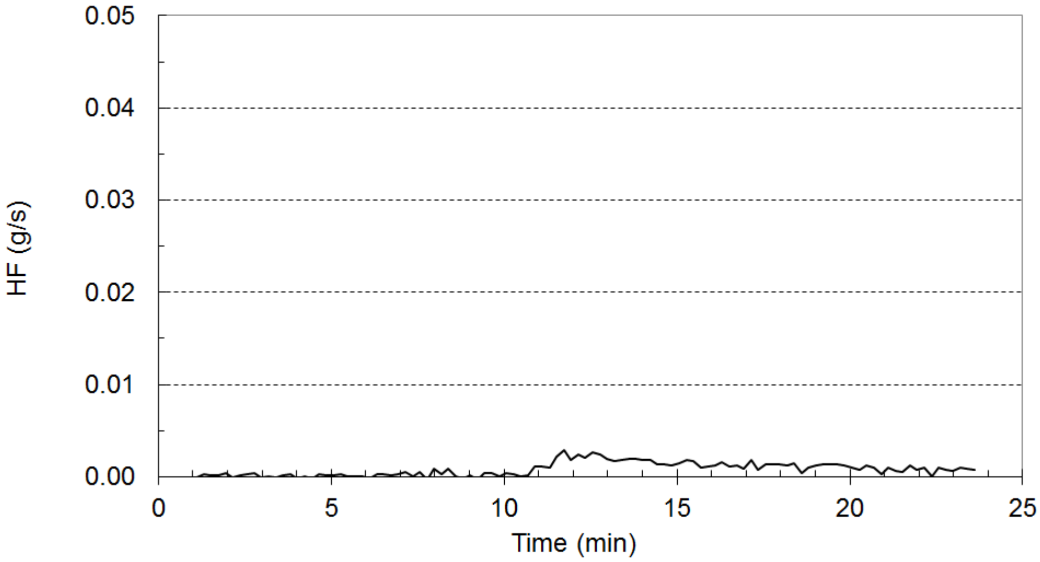

Figure 40 Production rate of HF measured by FTIR in Test 6.

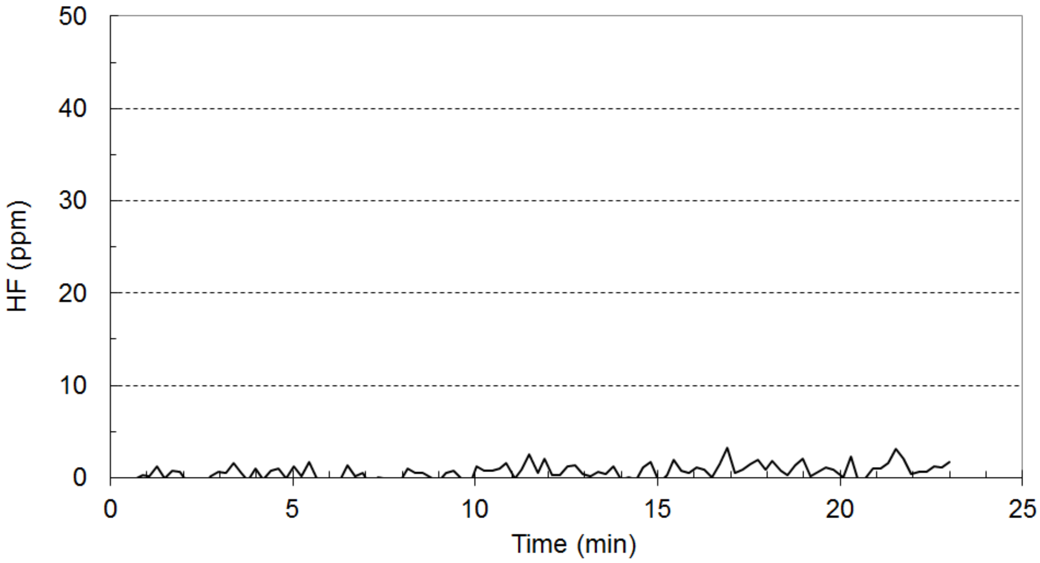

Figure 41 Concentration of HF measured by FTIR in Test 7.

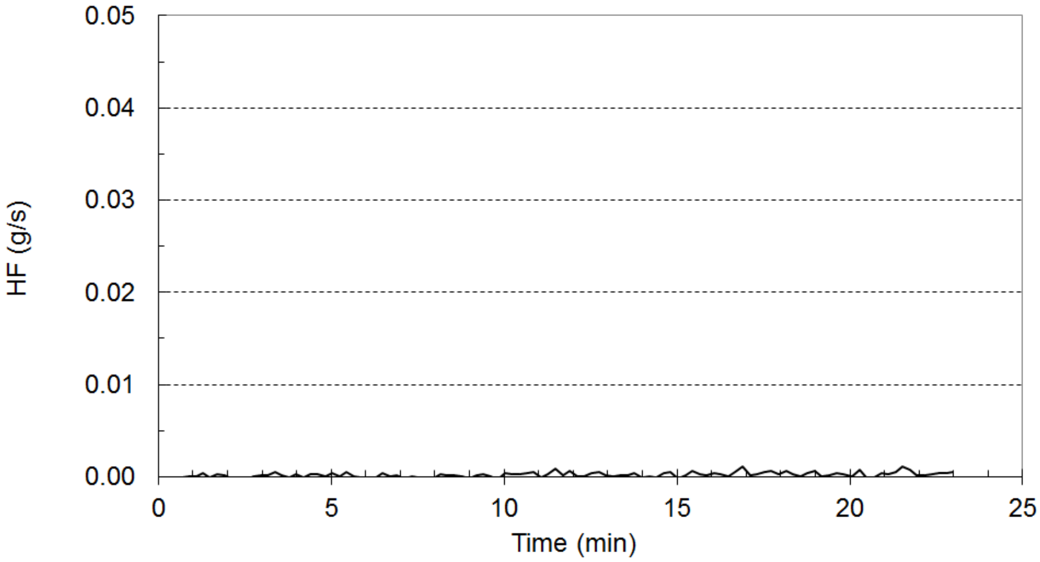

Figure 42 Production rate of HF measured by FTIR in Test 7.

Appendix C Photos from cell experiments

Figure 1 Burner during blank test 1

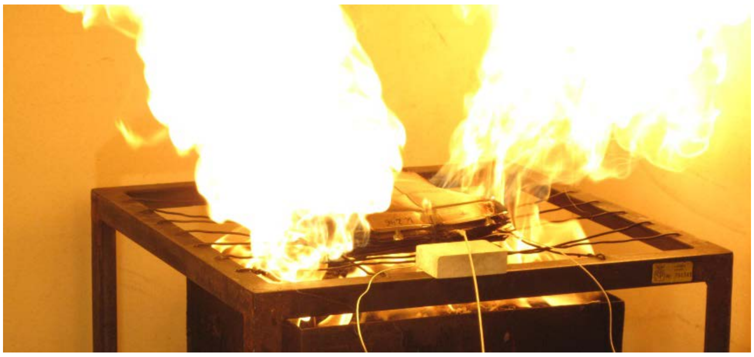

Figure 2 Typical outburst test 1

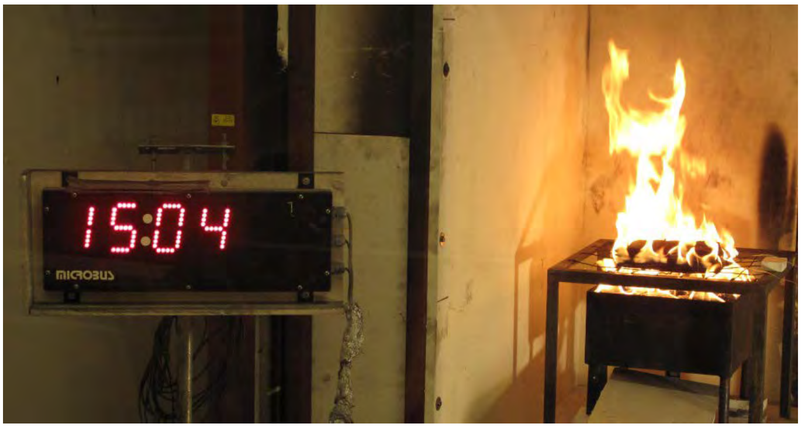

Figure 3 Later stage of fire Test 1

Figure 4 Outburst example test 2

Figure 5 Close up of test 2.

Figure 6 After test 2

Figure 7 Applying water test 3

Figure 8 Applying water test 3

Figure 9 Applying water test 3

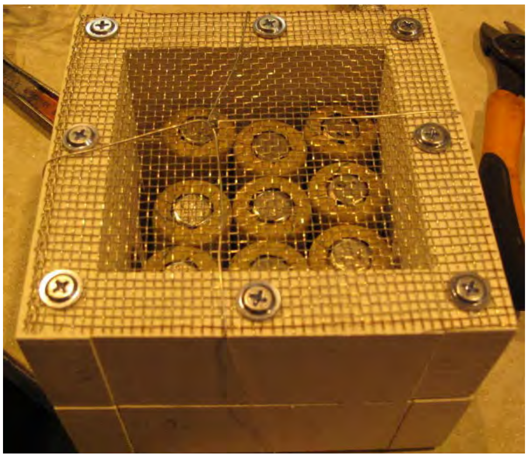

Figure 10 Cells for test 6 in their test container

Figure 11 Test 6

Figure 12 Test 6

Figure 13 Laptop cells in their container placed on burner before test 7

Figure 14 Outburst example test 7

Figure 15 Outburst example test 7

Figure 16 Outburst example test 7

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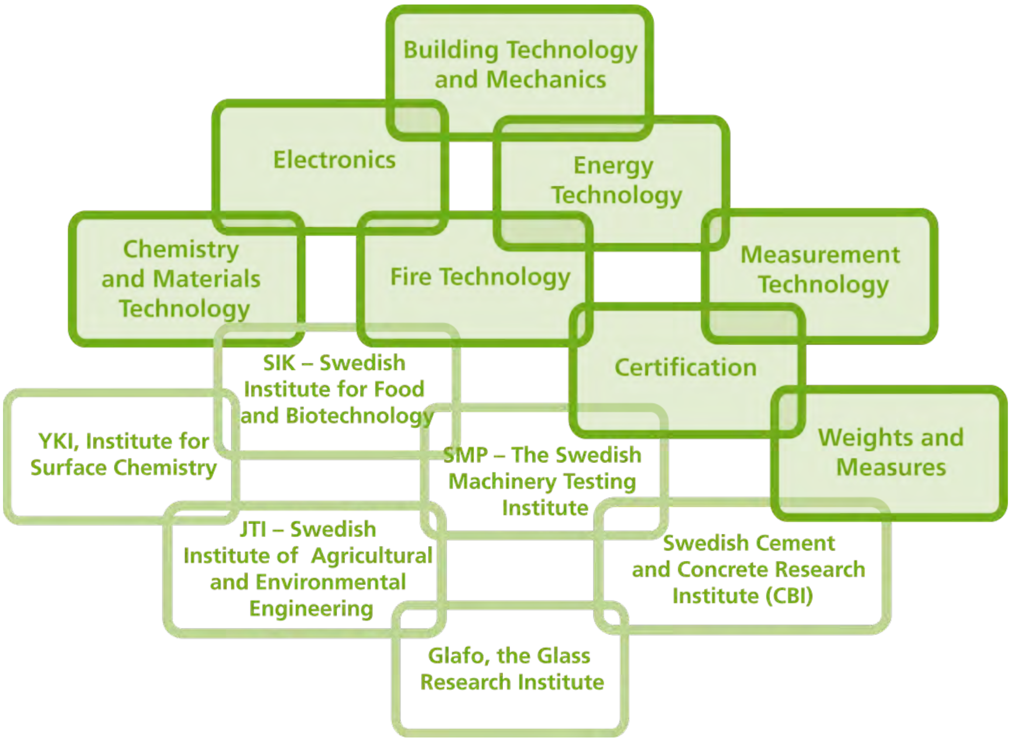

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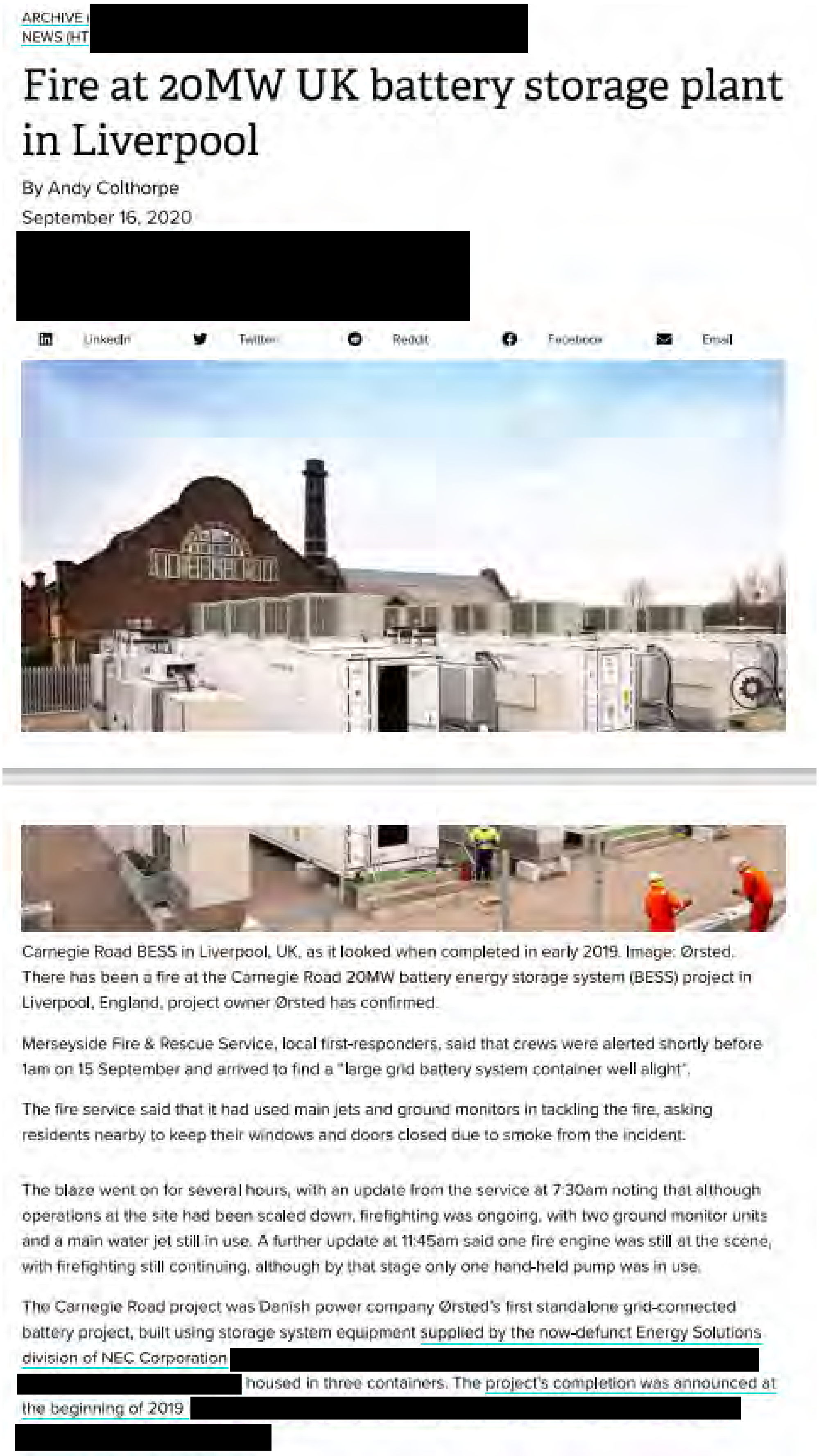
Appendix 6

News reports for references 14-16. Media coverage of Lithium ion BESS thermal runaway incidents in Australia (Big Battery) and Liverpool (Carnegie Road)

A) Energy storage news report – Liverpool incident



ARCHIVE
NEWS (HT [redacted]

Fire at 20MW UK battery storage plant in Liverpool

By Andy Colthorpe
September 16, 2020

[redacted]

Carnegie Road BESS in Liverpool, UK, as it looked when completed in early 2019. Image: Ørsted.

There has been a fire at the Carnegie Road 20MW battery energy storage system (BESS) project in Liverpool, England, project owner Ørsted has confirmed.

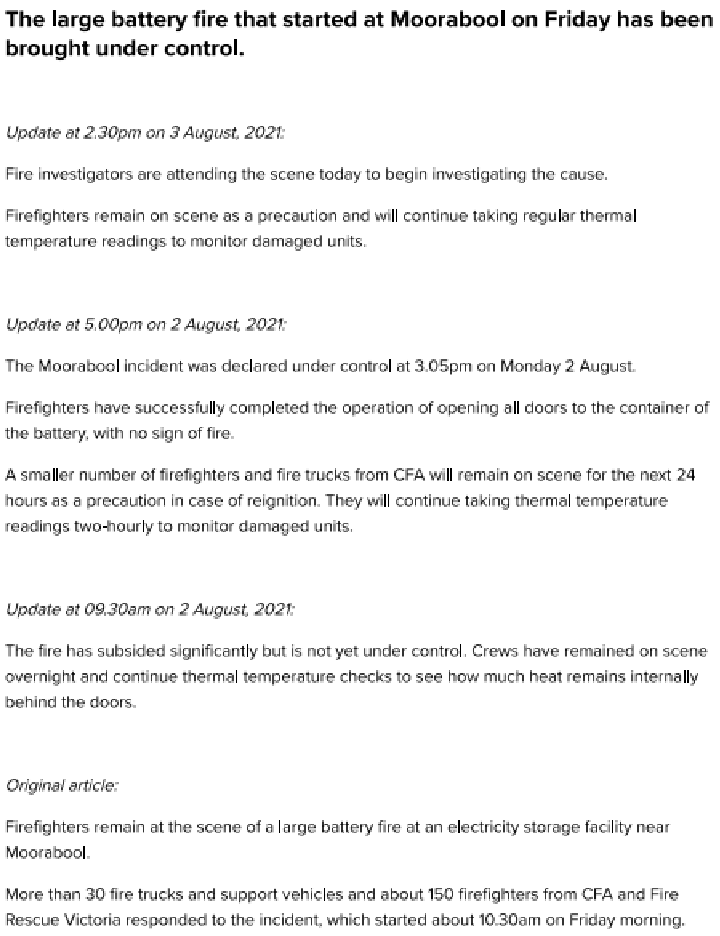
Merseyside Fire & Rescue Service, local first-responders, said that crews were alerted shortly before 1am on 15 September and arrived to find a "large grid battery system container well alight".

The fire service said that it had used main jets and ground monitors in tackling the fire, asking residents nearby to keep their windows and doors closed due to smoke from the incident.

The blaze went on for several hours, with an update from the service at 7:30am noting that although operations at the site had been scaled down, firefighting was ongoing, with two ground monitor units and a main water jet still in use. A further update at 11:45am said one fire engine was still at the scene, with firefighting still continuing, although by that stage only one hand-held pump was in use.

The Carnegie Road project was Danish power company Ørsted's first standalone grid-connected battery project, built using storage system equipment supplied by the now-defunct Energy Solutions division of NEC Corporation [redacted] housed in three containers. The project's completion was announced at the beginning of 2019 [redacted]

B) CFA (Country Fire Authority) updates regarding Big Battery incident



The large battery fire that started at Moorabool on Friday has been brought under control.

Update at 2.30pm on 3 August, 2021:

Fire investigators are attending the scene today to begin investigating the cause.

Firefighters remain on scene as a precaution and will continue taking regular thermal temperature readings to monitor damaged units.

Update at 5.00pm on 2 August, 2021:

The Moorabool incident was declared under control at 3.05pm on Monday 2 August.

Firefighters have successfully completed the operation of opening all doors to the container of the battery, with no sign of fire.

A smaller number of firefighters and fire trucks from CFA will remain on scene for the next 24 hours as a precaution in case of reignition. They will continue taking thermal temperature readings two-hourly to monitor damaged units.

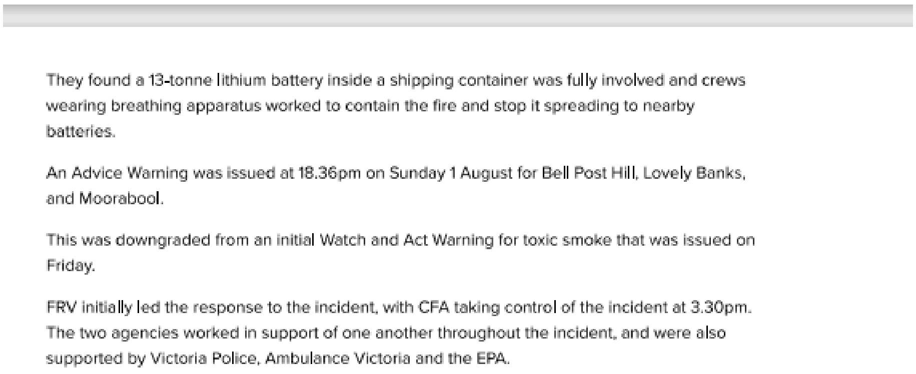
Update at 09.30am on 2 August, 2021:

The fire has subsided significantly but is not yet under control. Crews have remained on scene overnight and continue thermal temperature checks to see how much heat remains internally behind the doors.

Original article:

Firefighters remain at the scene of a large battery fire at an electricity storage facility near Moorabool.

More than 30 fire trucks and support vehicles and about 150 firefighters from CFA and Fire Rescue Victoria responded to the incident, which started about 10.30am on Friday morning.



They found a 13-tonne lithium battery inside a shipping container was fully involved and crews wearing breathing apparatus worked to contain the fire and stop it spreading to nearby batteries.

An Advice Warning was issued at 18.36pm on Sunday 1 August for Bell Post Hill, Lovely Banks, and Moorabool.

This was downgraded from an initial Watch and Act Warning for toxic smoke that was issued on Friday.

FRV initially led the response to the incident, with CFA taking control of the incident at 3.30pm. The two agencies worked in support of one another throughout the incident, and were also supported by Victoria Police, Ambulance Victoria and the EPA.

c) Wind Watch article about Big Battery incident

« Later Post • News Watch Home • Earlier Post »

filed: August 1, 2021 • Australia

Fire breaks out at Tesla Big Battery; toxic smoke warning issued

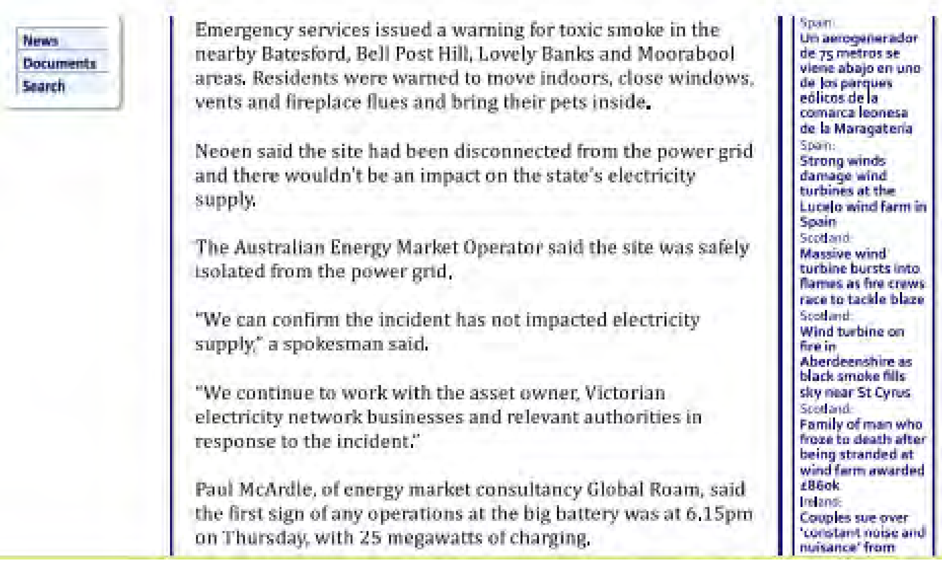
Credit: By Nick Toscano - July 30, 2021 - [redacted]

Emergency services are warning of toxic smoke after a fire erupted at Victoria's new Tesla Big Battery, the largest lithium-ion battery in the country.

One of the Tesla megapack batteries at the site in Moorabool, near Geelong, caught fire during testing shortly after 10am on Friday, according to French renewable energy giant Neoen.

"We can confirm that during initial testing today at approximately 10-10.15am a fire occurred within one of the Tesla Megapacks at the Victorian Big Battery," Neoen Australia managing director Louis de Sambucy said. "No one was injured and the site has been evacuated."

Neoen and Tesla are working with emergency services to manage the situation.



Emergency services issued a warning for toxic smoke in the nearby Batesford, Bell Post Hill, Lovely Banks and Moorabool areas. Residents were warned to move indoors, close windows, vents and fireplace flues and bring their pets inside.

Neoen said the site had been disconnected from the power grid and there wouldn't be an impact on the state's electricity supply.

The Australian Energy Market Operator said the site was safely isolated from the power grid.

"We can confirm the incident has not impacted electricity supply," a spokesman said.

"We continue to work with the asset owner, Victorian electricity network businesses and relevant authorities in response to the incident."

Paul McArdle, of energy market consultancy Global Roam, said the first sign of any operations at the big battery was at 6.15pm on Thursday, with 25 megawatts of charging.

Appendix D

Sunnica Energy Farm (EN010106) Deadline 3a

24 November 2022

Peter Danks – Reading Agricultural Consultants:

Comments on the Applicant's responses to First Written Questions from the Examining Authority (EN010106/APP/8.8)

Instructions

Reading Agricultural Consultants Ltd (RAC) is instructed by Say No To Sunnica Action Group Ltd (SNTS) to review and report on the agricultural elements of Sunnica Ltd's (the Developer) application for a Development Consent Order (DCO) for, and associated documents relating to, the construction, operation and decommissioning of Sunnica Energy Farm. The development includes an extensive ground-mounted solar photovoltaic (PV) array, battery energy storage systems (BESS) and supporting infrastructure with a stated capacity exceeding 500MW.

These comments have been prepared by Peter W Danks, Senior Director of RAC.

Applicant's Response to the First Written Questions

Q1.5.80:

This question deals with construction codes of practice.

The response lists those codes and standards commonly used in construction but omits topic-specific guidance on soil handling as set out in the Construction Code of Practice for the Sustainable Use of Soils on Construction Sites (2009) (https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/716510/pb13298-code-of-practice-090910.pdf), published by the Department of Environment, Food and Rural Affairs, which is generally accepted as the leading guidance on handling to minimise damage to soils. Further guidance can be found in the Good Practice Guide for Handling Soil 2000, published by MAFF (https://webarchive.nationalarchives.gov.uk/ukgwa/20130402200857/http://archive.defra.gov.uk/foodfarm/landmanage/land-use/soilguid/index.htm).

The documents accompanying the application do not include a code of construction practice for the management of the soi resource.

Q1.9.2:

This question seeks to address the multiple 'service' roles that land under solar PV may play, specifically agricultural production and energy production, although carbon sequestration and enhanced biodiversity might also be included in this area, in terms of reduced operating costs.

The Applicant's response agrees that services in addition to solar PV will reduce overall operational costs but fails to state in detail how and to what degree cost reductions will be achieved.

The outputs from agricultural and other activities carried out in parallel with energy production are not described or quantified in any way. In the absence of robust evidence from existing solar developments, experience suggests that it is not possible to simply 'graze sheep' on a solar farm and expect uniform grazing or reliable output from stock. The height of the array governs which breeds of sheep can be grazed and many sheep selectively graze between panels, not under them. The levels of productivity do not compare with traditional grazing on open fields. By quantifying both baseline and outputs it would be possible more accurately to compare developed with undeveloped land and assess the benefit of each use.

Neither baseline nor anticipated future output have been quantified in the documents supporting the application.

Q1.9.6:

This question seeks to assess the likely impact of piles used in the scheme. Piles rammed up to 3.5m deep are required to support Solar PV Module Mounting Structures across the whole site and deeper piles may be associated with the BESS containers, battery stations, substations, and the Burwell National Grid Substation Extension.

The latter structural piles will remain in place on decommissioning and that part in the upper one metre of the soil profile will be excavated and removed to leave clear access to the majority of agricultural machinery in routine operations.

The support structures for solar arrays will be drawn from the ground using similar machinery used for installation. No assessment has been made of the amount of disturbance caused in the soil profile during driving and drawing operations. It is likely that there will be a degree of mixing of subsoil and topsoil material when a long, relatively large diameter, well established, driven steel posts are removed from the ground. Any mixing of subsoil material or chalk with topsoil is likely to be spread laterally across the field surface with routine cultivations. The degree and impact of mixing is not accounted for in advance of the production of a Decommissioning Environmental Management Plan, which assumes a negligible impact without evidence to support this assumption.

Q1.9.7:

This question seeks clarification of the use of the term ‘operational life’ and what this means in terms of the restoration of land to agricultural production and residual infrastructure following restoration to agriculture.

The response relies on the production of an approved Decommissioning Environmental Management Plan (DEMP) to be approved prior to decommissioning under requirement 22 of the draft DCO. In the absence of a comprehensive and accurate baseline survey of the agricultural land, as is currently the case, it will not be possible to restore the land to its current condition.

Chapter 12 Socio-Economics and Land Use [APP-044] fails to demonstrate that there will be a negligible effect on soil resources, which the EIA considers not to be significant. Rather, it makes unproven assumptions that lead to this conclusion, including increased soil organic matter and no damage to soils during construction, operational and decommissioning phases.

In referring to the ‘operational’ phase, the applicant fails to account for the variable lengths of time spent constructing, commissioning and decommissioning the site. Thus, any assessment should take account of the unavoidable, unquantified ‘fallow’ periods of zero production of food or energy that may occupy up to 25% of some, unidentified, parts of the site.

This is of particular concern where land has been in agricultural production and there is a commitment in the CEMP (Table 3.7) to “*establish and maintain a grass sward over the Solar PV area before trafficking over by construction plant and delivery vehicles*”. A grass sward as described in the CEMP can only be established after the antecedent crop has been harvested and cultivation operations carried out to produce a suitable seedbed. Following sowing, the grass seed may need to be irrigated to ensure germination and establishment, and then managed for an indeterminate period to establish a sward capable of withstanding trafficking by construction and delivery vehicles. This may take up to two years from the granting of permission to go ahead with the development and add significantly to period that land is removed from production.

Q1.9.8:

This question seeks evidence to determine the baseline agricultural condition and output from the proposed development area.

The response fails to:

- quantify the relative areas of arable and pasture land;
- identify accurately the crops that have been grown across the area in the current or recent cropping years;
- quantify the area used for grazing livestock, which may vary from year-to-year. No average area grazed is given;
- quantify yields of crops grown and livestock kept on the land; and
- estimate the loss in yield due to the proposed development.

It is accepted that agricultural land is cropped in rotations and that crop yield vary from year-to-year. However, it is possible and valid to take a time series of cropping and yields to produce answers to all of the above questions. In the absence of farm-specific values, there are:

- multiple publications that provide standard yields, such as The John Nix Pocketbook for Farm Management and The Agricultural Budgeting and Costing Book.
- crop and region specific annual production statistics produced by the Agriculture and Horticulture Development Board (AHDB); and
- remote sensing derived data to provide annual land use statistics.

The Environmental Impact Assessment fails to account for the effects of loss of land in established use for the production of high value agricultural crops in terms of either economic loss to landowners and other affected enterprises, or loss of production in terms of UK productivity or wider security of supply of crops of food generally.

Appendix E

IN BROAD DAYLIGHT

Uyghur Forced Labour and Global Solar Supply Chains

LAURA T. MURPHY & NYROLA ELIMÄ

Sheffield Hallam University
Helena Kennedy Centre for International Justice

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MAY 2021

IN BROAD DAYLIGHT

Uyghur Forced Labour and Global Solar Supply Chains

LAURA T. MURPHY & NYROLA ELIMÄ

Sheffield Hallam University | Helena Kennedy Centre for International Justice

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EXECUTIVE SUMMARY

The People's Republic of China (PRC) has placed millions of indigenous Uyghur and Kazakh citizens from the Xinjiang Uyghur Autonomous Region (XUAR or Uyghur Region) into what the government calls "surplus labour" (富余劳动力) and "labour transfer" (劳动力转移) programmes. An official PRC government report published in November 2020 documents the "placement" of 2.6 million minoritised citizens in jobs in farms and factories within the Uyghur Region and across the country through these state-sponsored "surplus labour" and "labour transfer" initiatives. The government claims that these programmes are in accordance with PRC law and that workers are engaged voluntarily, in a concerted government-supported effort to alleviate poverty. However, significant evidence – largely drawn from government and corporate sources – reveals that labour transfers are deployed in the Uyghur Region within an environment of unprecedented coercion, undergirded by the constant threat of re-education and internment. Many indigenous workers are unable to refuse or walk away from these jobs, and thus the programmes are tantamount to forcible transfer of populations and enslavement.

It is critical that we examine the particular goods that are being produced as a result of this forced labour regime. This paper focuses on just one of those industries – the solar energy industry – and reveals the ways forced labour in the Uyghur Region can pervade an entire supply chain and reach deep into international markets. We concluded that the solar industry is particularly vulnerable to forced labour in the Uyghur Region because:

- 95% of solar modules rely on one primary material – solar-grade polysilicon.
- Polysilicon manufacturers in the Uyghur Region account for approximately 45% of the world's solar-grade polysilicon supply.
- Hoshine Silicon Industry, the metallurgical-grade silicon producer in the region with the highest production capacity, has participated in labour transfer programmes and has significant exposure to forced labour through its quartz supplier.
- All four of XUAR's polysilicon manufacturers – Daqo, TBEA (and subsidiary Xinte), Xinjiang GCL, and East Hope – have reported their participation in labour transfer or labour placement programmes and/or are supplied by raw materials companies that have.
- Daqo alone is a supplier to the four largest solar module manufacturers in the world – JinkoSolar, Trina Solar, LONGi Green Energy, and JA Solar.
- In 2020, China produced an additional 30% of the world's polysilicon on top of that produced in the Uyghur Region, a significant proportion of which may be affected by forced labour in the Uyghur Region as well.

In the course of this research, we identified

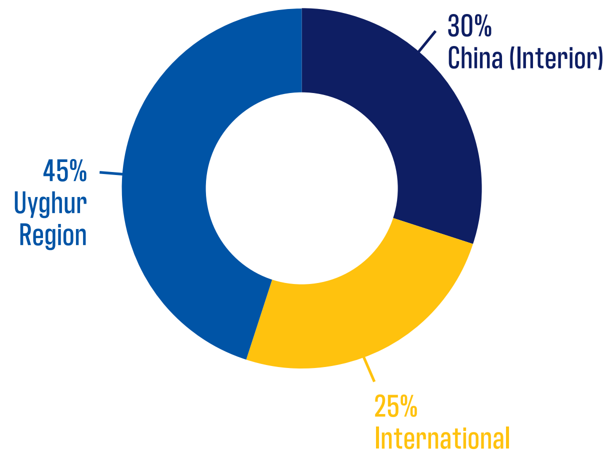
- 11 companies engaged in forced labour transfers
- 4 additional companies located within industrial parks that have accepted labour transfers
- 90 Chinese and international companies whose supply chains are affected

This report seeks to increase the knowledge base upon which the solar industry determines its exposures to forced labour in the Uyghur Region. We investigated the entire solar module supply chain from quartz to panel to better understand the extent to which forced labour in the Uyghur region affects international value chains. The examples of engagement in these programs are meant to provide stakeholders with the evidence base upon which to judge risk of exposure to forced labour in the solar supply chain.

While Xinjiang accounts for 45% of the world's solar-grade polysilicon supply, 35% more of it comes from other regions of China, and 20% from outside of China. Experts agree that this is enough to supply the United States and Europe's needs for solar modules. However, this does not account for the companies in the interior of China and internationally whose supply chains are likely affected by manufacturing in the Uyghur Region. The extent to which Xinjiang metallurgical-grade silicon and polysilicon pervades the market means that module manufacturers that want to avoid producing goods that are potentially tainted by forced labour in Xinjiang will have to scrutinise their supply chains thoroughly, all the way to the raw quartz materials, to determine if they are produced with forced labour or blended with affected materials. They will have to demand that the polysilicon that goes into the manufacture of their wafers is not sourced from companies engaged in forced labour transfers. This effectively leaves only a few Chinese alternatives with no confirmed exposure to forced labour in the Uyghur Region.

The solar supply chain is relatively easy to map, and identifying forced labour exposure in Xinjiang is less of a challenge than in industries such as textiles or agriculture. And doing so is critical, as it would not only address the forced labour issue in Xinjiang but would also substantially reduce the carbon emissions of the solar industry. From a human rights and climate perspective, the alternative of basing our green energy future on coal's high carbon emissions and on the forced labour of oppressed communities is a higher and longer-term price to pay.

2020 Polysilicon Market Share



A Note on Sources

Wherever possible, we provide official corporate documentation as evidence of the claims made in this paper. In some instances, we have had to rely on other publicly available sources, including state media, corporate publicity, and social media (including Weixin). These reports tend to reflect the interests of the companies investigated in our research, and so may at times exaggerate successes and/or the facts. However, we take company representatives and company websites and advertisements at their word regarding their participation in surplus labour and state-sponsored labour transfer programmes in the Xinjiang Uyghur Autonomous Region.

I. INTRODUCTION

Forced Labour in the Uyghur Region

In the spring of 2018, significant evidence began to emerge that the People's Republic of China (PRC) government understood its system of detention centres and internment camps as merely one part of a massive transformation of the Xinjiang Uyghur Autonomous Region (XUAR or Uyghur Region) into a docile and lucrative economic hub.[1] While continuing to hold indigenous citizens of the region in internment camps without trial, regional and local governments shifted their focus to the creation of an enormous forced labour regime. This system had the explicit goal of employing practically every adult citizen and was accompanied by the justification that the programme would increase both the economic productivity and the "stability" of the region.

To those ostensible ends, the Chinese Communist Party (CCP) has placed millions of indigenous Uyghur and Kazakh citizens from the XUAR into what the government calls "surplus labour" (富余劳动力) and "labour transfer" (劳动力转移) programmes. An official PRC government report published in November 2020 documents the "placement" of 2.6 million minoritised citizens in jobs in farms and factories within the Uyghur Region and across the country through state-sponsored "surplus labour" initiatives.[2] By the CCP's own calculations, this represents a 46.1% year-on-year increase in the number of XUAR citizens "transferred" for work. If the government's figures are correct, this indicates that approximately a fifth of the Uyghur and Kazakh population of XUAR is engaged in labour relocation programmes.

Workers manually crush silicon in Jingang Circular Economy Industrial Park, Ili Prefecture, Xinjiang. Source: Kokodala News via Weixin.

The government claims that these programmes are in accordance with PRC law and that workers are engaged voluntarily, in a concerted government-supported effort to alleviate poverty. However, this expansive labour transfer system as it is practiced in the Uyghur Region represents something more complex and coercive than the government might suggest. Employing government documents and state media reports, researchers have clearly identified that, as they are practiced in the XUAR, these so-called "surplus labour" and "labour transfer" initiatives are in fact mechanisms of a massive programme of compulsory labour.[3] Evidence reveals that labour transfers are deployed in the Uyghur Region within an environment of unprecedented coercion, undergirded by the constant threat of re-education and internment. Many indigenous workers are unable to refuse or walk away from these jobs, and thus the programmes are tantamount to forcible transfer of populations and enslavement.

The first evidence that people held in the camps were being forced to work in factories was revealed by PRC state media, which celebrated the transformation of the internment camp victims into model citizens through labour in factories located on the premises of the camps.[4] First-person testimony of people who have been held in the camps, worked as security guards or teachers within the camps, or have relatives in the camps confirms that Uyghur, Kazakh, and other minoritised citizens held in internment camps have been compelled to work as part of their daily schedules.[5]

People who are purportedly "released" or "graduated" from the internment camp system are often required as part of their release to work in factories near the camps in which they were once interned.[6] Journalists, scholars, and independent researchers who exposed this situation relied on public information – including government speeches and directives – to make their claims. For instance, Shohrat Zakir, Chairman of the XUAR, stated in October 2018 that "trainees" who completed their terms in the internment camps (called "vocational skills training education centres" by government sources)[7] would be placed in jobs with "settled enterprises" through a "seamless link between learning in school and employment in society."[8] Reporters have identified at least 135 camps that are co-located with or are proximate to factories.[9] In April of 2018, Kashgar regional government alone reported that they had plans to transfer 100,000 people from "vocational training" to employment, providing significant subsidies to the companies that took on these forced labourers.[10] First-person testimony of survivors of the camps and stories relayed through family members of released detainees who have been forced to work has indicated that participation in the programmes is not voluntary for camp detainees and is coerced through threats of further imprisonment.[11]

> Labour transfers are deployed within an environment of unprecedented coercion, undergirded by the constant threat of re-education and internment.

In addition to compelling internment camp victims to work, the CCP has designated as "surplus labour" those citizens living outside the camps who lack jobs, are seasonally employed, work as small-scale farmers, or are retired. Government-sponsored surplus labour transfer programmes have long existed in the XUAR, but the efforts have expanded and intensified in recent years. In 2018, the XUAR government announced a programme to "transfer" 100,000 workers to jobs within and outside the region within three years.[12] Local governments are required to identify all "surplus labourers" and induce them to take jobs in factories either close to home or further afield. As one 2018 county-level government directive indicated, in some regions, government agents or labour recruiters go household to household and assign each Uyghur or Kazakh person a point value and one of three categorisations – "controlled," "general," or "assured." These categories determine how far a person's work placement will be from home: those who need to be controlled are sent for "training;" all others are sent to work, either close to home or across the country. No one is exempt: "All surplus labour force in the jurisdiction shall be managed by a quantitative points system, so as to ensure that all the surplus labourers in the jurisdiction who should be trained are trained, and all who should be employed are employed." It continues: "If, during organization, publicity campaigns, and mobilization efforts of all villages and townships, there are people who are discovered to be able to participate in training but are unwilling to participate in training, or who are able to go elsewhere for employment but are not active in seeking employment, or have outdated concepts or stubborn thinking, the corresponding points should be deducted."[13]

The recruitment strategies deployed by government agencies on behalf of corporations suggest significant coercion. Interviews with a government cadre and a former detainee revealed that people with family members in the internment camps were coerced into working in factories when government officials promised that their labour would improve their detained family members' scores and hasten their release. The former detainee said "I learned that if one family [member] was in a camp you have to work so father or husband can get out quickly."[14] State media and government-funded reports provide evidence that government and private labour agencies repeatedly intervene in the lives of rural villagers until they relent to being transferred – often first through language and ideological training and surveillance, and then through repeated attempts to "encourage" them to leave their villages for industrial labour in spite of any personal or financial investments they may have in land, homes, family, or communities.[15] State media reported the story of an elderly farmer who was pressured to adopt sheep by workers stationed with the Xinjiang Production and Construction Corps. Even though he repeatedly resisted because he knew nothing about raising sheep and in the end was compelled to spend significant money to buy the unwanted sheep when the government subsidy was not enough to cover the full cost of the ten sheep, he was nonetheless compelled to purchase and raise the sheep. It was only through repeated visits and insistence that the farmer participated in the state-sponsored labour programme.[16] A Chinese media (CCTV) broadcast told another story of several young women who were distraught at the thought of leaving their families and lives behind to go work thousands of miles away, but government officials and labour agents harassed the women for days, promising them the ability to return home at any time and great wealth in order to convince them to go, which they only did reluctantly.[17] In order to "relieve migrant labourers of their worries," the government has created nurseries and elder care facilities to manage the families who are left behind by transferred labourers.[18] The government also transfers land into its own possession (for a small rental fee), purportedly to free farmers to move away from their hometowns.[19]


[redacted]

Lop County #4 Re-Education Camp.
Source: Xinjiang Justice Department via Weixin

State reports and directives regarding these labour transfer programmes promote the idea that the indigenous people of the region are lazy and unproductive and committed to their own poverty. The reports state that labour transfers are meant to discipline minoritised people and train them to be productive citizens, even if they are otherwise uninterested in these personal changes. In the local government labour transfer directive mentioned above, labour agencies were directed to "have organizational discipline in place and implement militarised management to make people with employment difficulties get rid of selfish distractions, to change their long-cultivated lazy, idle, slow, and inconstant behaviours of personal freedom, to abide by corporate rules and regulations and work discipline, and to devote themselves fully to daily production. The government should use iron discipline to ensure that worker cooperation results in a 1+1>2 result."[20] A PRC government-funded study conducted by Nankai University concluded that one of the impediments to the success of the surplus labour transfer strategy was that, "fettered by traditional concepts, there are still some labourers who are unwilling to move far away from home and have serious homesickness," despite "the government's serious guiding efforts over the past several years," indicating that these programmes are not voluntarily chosen by all who are employed by them.[21]

Though state-sponsored labour transfers and so-called "poverty alleviation" (扶贫) strategies (and indeed forced labour) have long existed in the Uyghur Region[22] and also operate in other parts of the PRC, they are now operating in the XUAR against a backdrop of mass internment and extra-judicial imprisonment, which make refusal to participate a non-option. While there may be some people who would choose to be deployed to a factory through a labour transfer, in the XUAR, it is impossible for a citizen to refuse these supposed opportunities for "poverty alleviation" because if they do, there are dire consequences. In a lengthy justification of the labour transfer programmes released in September 2020, the CCP claimed that "terrorists, separatists, and religious extremists" incite the region's indigenous citizens to "refuse to improve their vocational skills, economic conditions, and the ability to better their own lives" as a justification for requiring local governments to implement these labour transfers at a mass scale.[23] Thus, the programmes are grounded in the logic of labour as a strategy of anti-terrorism. For Uyghur people to resist state-sponsored programmes purportedly designed to encourage vocational skills and "poverty alleviation" would be to align themselves with the above named "three evils," which are the rationale for the CCP's crackdown and criminalization in the Uyghur region, including the camp system.[24] Han "relatives," who are assigned to visit and even live in Uyghur homes to educate them in appropriate behavior and monitor them carefully for signs of deviation from party ideology, are required to report anyone who resists "poverty alleviation" programmes such as the labour transfers.[25] These practices of surveillance support the logic of anti-terrorism that undergirds the labour transfer system. Together, they ensure that minoritized citizens do not have a legitimate opportunity for choice when asked to participate in state-sponsored labour transfer programmes.

As further evidence that these are not voluntary programmes that are designed to lift people out of poverty, there is the fact that many of the people who work in the camps are trained professionals and business people (e.g. university graduates, film makers, dentists, nurses, medical professionals, restauranteurs, business owners, engineers, marketing professionals, or retirees) who are not under-employed and who would not otherwise work in factories.[26] Nonetheless, they are forced to work in what the CCP calls "labour-intensive" industries. Others are forced to be complicit in the work of the camps, assigned to work as teachers (a leaked government list names several camp graduates recruited as teachers) or security guards in the camps, despite sometimes having been victims of the camps themselves.[27] Again the Nankai report is helpful in contextualizing why this might be the case – the report indicates that the labour transfer regime "not only reduces the Uyghur population density in Xinjiang but is also an important method to influence, integrate, and assimilate Uyghur minorities," (感化，融化，同化)[28] thus poverty alleviation is not the sole or even likely the primary motivating factor for the programme.

> These programmes deny citizens the human right to free choice of employment afforded by Article 23 of the U.N. Declaration of Human Rights.

Many of the factories employing supposedly free XUAR citizens are surrounded by razor-wire fences, iron gates, and security cameras, and are monitored by police or additional security, while Han workers' mobility is unrestricted in the workplace and in the ability to return home.[29] In many cases, Uyghur and Kazakh workers are not allowed to leave the factories voluntarily.[30] First-person reports indicate that people working in the camps are either unpaid, paid far less than the minimum wage, or have their salaries reduced with the explanation that they owe a debt to their employers for food or transport to work.[31] Reports suggest that local police hold workers' identification cards, controlling their movement.[32] The restriction of the rights to free movement and to walk away from employment are indicators of forcible transfer and human trafficking. Some who have escaped this forced labour regime have explicitly described it as "slavery."[33]

The evidence regarding labour transfers for the indigenous people of the XUAR points to clear indicators of human trafficking and compulsory labour as defined by international conventions regarding labour rights. Indeed, these programmes deny citizens the human right to free choice of employment afforded by Article 23 of the U.N. Declaration of Human Rights.[34] The United Nations' Palermo Protocol prohibits "the threat or use of force or other forms of coercion, of abduction, of fraud, of deception, of the abuse of power or of a position of vulnerability, or of the giving or receiving of payments or benefits to achieve the consent of a person having control over another person, for the purpose of exploitation."[35] These labour transfer strategies clearly suggest the indicators of forced labour identified by the ILO, including (at a minimum): abuse of vulnerability, deception, restriction of movement, isolation, intimidation and threats, retention of identify documents, withholding of wages, and potentially debt bondage.[36] The International Labour Organization's (ILO) Forced Labour Convention of 1930 defines forced or compulsory labour as: "all work or service which is exacted from any person under the threat of a penalty and for which the person has not offered himself or herself voluntarily,"[37] and in 1957 they further prohibited member states from employing compulsory labour

- (a) as a means of *political coercion or education* or as a *punishment for holding or expressing political views* or *views ideologically opposed* to the established political, social or economic system;
- (b) as a method of mobilising and using labour for purposes of *economic development*;
- (c) as a means of *labour discipline*;
- (d) as a punishment for having participated in strikes;
- (e) as a means of *racial, social, national or religious discrimination*.

It is clear from the evidence presented above that the CCP's labour transfer programme in the Uyghur Region is used to punish people with oppositional ideological views, to create a regime of economic development built on compulsory labour, and to discipline the masses whom they deem to be inherently deficient because of their race and religion. While the PRC government justifies these programmes as "poverty alleviation" strategies, the spectre of internment camps looms, creating a situation in which no Uyghur or other minoritised citizen could refuse participation in these government-run programmes without risk of being sent to the camps. This clearly contravenes the ILO convention, to which the PRC is subject because all member states must comply with the four fundamental principles of the ILO, which includes the abolition of slavery.[38]

Because the Chinese government has invested vast resources in this unprecedented system of compulsory labour and because that system so clearly contravenes the conventions that govern labour rights internationally, it is critical that we examine the particular goods that are being produced as a result. This paper focuses on just one of those industries – the solar energy industry – and reveals the ways forced labour in the Uyghur Region can pervade an entire supply chain and reach deep into international markets.

Xinjiang Production and Construction Corps

The Xinjiang Production and Construction Corps (also called the XPCC or bingtuan) is a state-operated paramilitary corporate conglomerate that had a gross production value of nearly CNY 275 billion in 2019.[39] It might be most easily understood as a prefectural government; it governs 2.43 million people across 10 distinct cities and 37 towns, dispersed across the vast Xinjiang Uyghur Autonomous Region like an archipelago. In addition to operating local governments, the XPCC also owns and operates a corporate empire that includes 14 publicly listed companies and (by one estimate) as many as 862,600 direct and indirect holdings.[40] One metric of its importance in the Chinese economy is the fact that the XPCC grows 30% of the PRC's cotton.[41]

The XPCC has come under increased scrutiny in recent years because it is also involved in operating and supporting some of the internment camps where minoritised citizens are being held for re-education in the Uyghur Region, and it facilitates forced labour transfers.[42] As a result of its deployment of re-education, internment, and forced labour, the XPCC has been subject to a U.S. government Withhold Release Order that bans the importation of all cotton products produced in whole or in part by the state conglomerate.

While the XPCC does not directly own or operate any metallurgical-grade silicon or solar-grade polysilicon facilities, they do operate many of the industrial parks within which the manufacturers are located. The XPCC promises significant benefits to companies that locate in their industrial parks, with the motto of "You build the project; we will handle the formalities."[43] Those formalities can include anything from reduced rents and utilities for manufacturing sites to providing logistics, warehousing, and transport of finished goods. We have included corporate engagement with the XPCC in this report to illustrate the ways the XPCC may have affected the solar supply chain.

The Making of a Solar Panel

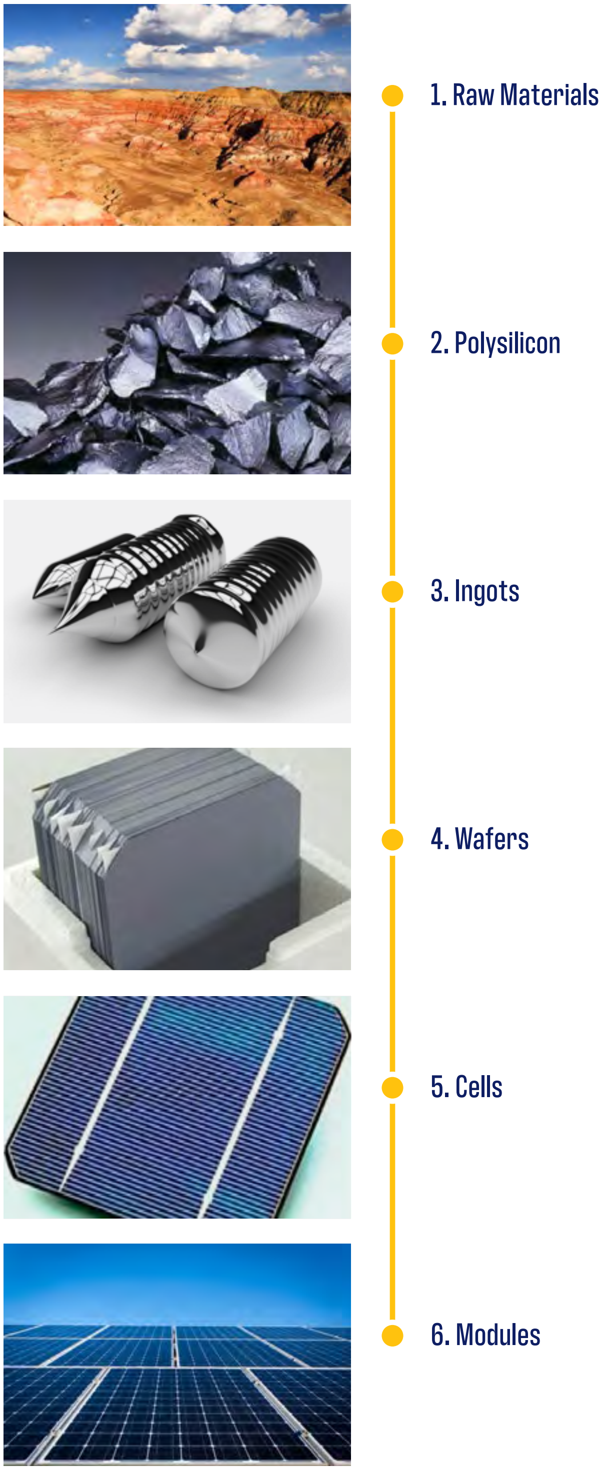


Image credits: raw materials: Zhundong Economic and Technological Development Zone promotional video (still); polysilicon: Daqo New Energy; ingots: Peter Soboley via 123rf; wafers: DS New Energy; cells: U.S. Department of Energy; modules: DSM Functional Coatings (PR001) via Flickr.

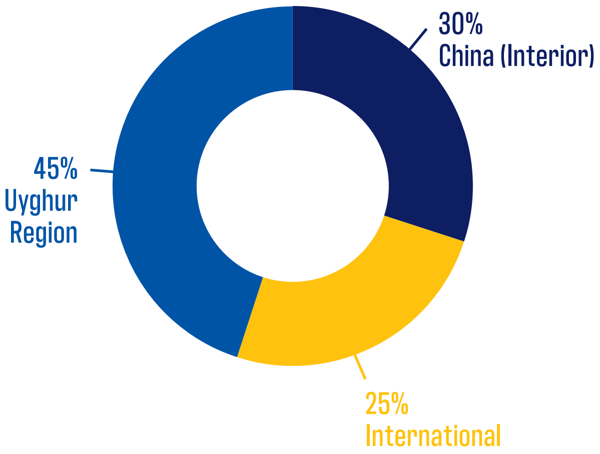
Incentivizing Solar in the Uyghur Region

Around 95% of solar modules rely on one primary material – solar-grade polysilicon.[44] Until 2005, seven companies headquartered in the United States, Germany, and Japan made practically all of the polysilicon needed to manufacture solar modules for the world; the People's Republic of China had almost no presence in the polysilicon market. One Chinese company, Emei Semiconductor, produced a very small amount of polysilicon, not even enough to begin to address China's own domestic requirements, where solar energy generation plants were increasingly under development.

After only fifteen years in the industry, the PRC now dominates the global solar energy supply chain.[45] In 2020, China produced nearly 75% of the world's polysilicon (including solar-grade and electronic-grade). The four largest producers in Xinjiang alone account for around 45% of the world's solar-grade polysilicon supply. The journey to this extraordinary market share only took 15 years, and it saw rapid acceleration in the last five. As polysilicon expert Johannes Bernreuter put it, the top six producers of polysilicon alone "reached a production capacity of 470,000 MT in 2020 – almost as much as all polysilicon manufacturers had in total worldwide at the end of 2015."[46] Five of those companies are in China; four of them have facilities in the Uyghur Region.

The first major polysilicon company to emerge in China, GCL-Poly Energy Holdings, started manufacturing in 2007 in Xuzhou and was the world's leading supplier of polysilicon by 2013. Other companies soon followed suit. Tongwei Solar Company's subsidiary Sichuan Yongxiang broke into the polysilicon competition in 2008 and has since risen to become the polysilicon producer with the highest production capacity in the world. Daqo New Energy began operations the next year and quickly became a significant supplier of polysilicon for a wide range of downstream manufacturers. Tebian Electric Apparatus Stock Company's (TBEA) subsidiary Xinte New Energy Company began producing polysilicon in 2009. The Chinese polysilicon industry began significantly expanding capacity after 2013, when the PRC government imposed duties on U.S. polysilicon imports, which currently remain in effect.[47] With those duties in place, Tongwei, Daqo, and Xinte all significantly expanded their polysilicon production capacity to meet domestic need.

2020 Polysilicon Market Share



TBEA was the first of the solar industry manufacturers to recognise that the abundant natural resources in the Uyghur Region was a benefit to business and would lower prices far below that of international manufacturers. TBEA headquartered its subsidiary TBEA Silicon Industry Company (renamed Xinte Energy in 2012) on the distant outskirts of the XUAR's capital Urumqi in 2008, and it built a coal-fired power plant in the Zhundong Economic and Technological Development Zone in 2009 to take advantage of the Uyghur Region's resources. The company simultaneously invested in a massive industrial park and logistics centre that would become a hub for the transport of the new energy materials being manufactured in the region. Daqo relocated all of its polysilicon production from Chongqing to Shihezi, XUAR in 2011/2012, to be closer to the raw materials used in the manufacturing process.

In the fall of 2016, the Xinjiang Party Committee and People's Government began promoting the expansion of several industries (including silicon and polysilicon) in Xinjiang as part of the "Made in China 2025" strategy.[48] In the "13th five-year plan on national economic and social development of the Xinjiang Uyghur Autonomous Region," the regional government encouraged companies to take advantage of the Uyghur Region's rich resources to become internationally competitive in industrial production, with a special emphasis placed on the development of the non-ferrous metals, polysilicon, and mono- and polycrystalline wafers that are essential components of solar module production. The five-year plan cited explicit concerns about the "fragility" of the ecological environment, the "lack of water resources," and the economic, social, and educational inadequacies of the workers to be "transferred" to the industries that would move into the region.[49] One significant solution to these challenges outlined within the five-year plan was to provide companies with subsidies that would allow them to better "absorb employees" through training programmes and insurance subsidies. Companies were directed to "give full play to the enterprise's principal role in promoting employment."[50] In 2017, the Xinjiang government declared that two main regions to be the only two sites for new development of silicon industry projects – the Turpan Shanshan Industrial Park for raw materials and the Zhundong Economic and Technological Development Zone for polysilicon manufacturing. Corporate development in these sites promised significant tax incentives and additional "added value" from the government.[51]

These programmes and incentives initiated a rush to build in the Uyghur Region. By 2018, the Uyghur Region had seen a significant expansion of the polysilicon industry. GCL-Poly built facilities within and on the outskirts of the massive Zhundong Zone, in a joint venture with Zhonghuan Semiconductor (the world's second largest producer of solar wafers). Polysilicon newcomer East Hope New Energy built an industrial park for a new production facility, which also began operation in the Zhundong coalfield in 2018. The company also established a metallurgical-grade silicon manufacturing subsidiary in the same park, locating all of the production steps in one small area, deliberately keeping down transportation and fuel costs. Xinte Energy expanded their manufacturing in the XUAR as well, locating its Crystalline Silicon Co. manufacturing site only a few miles outside Zhundong in 2018. Add to that the fact that JinkoSolar, the world's second largest solar module manufacturer, completed the final phases of the construction of its Xinjiang ingot production facility in 2018, and it is clear that Xinjiang was indeed effectively transformed into a significant centre for solar energy manufacturing as predicted.

Polysilicon Capacity 2020

RANK	COMPANY	CAPACITY (IN TONS)
1	Tongwei	96,000
2	GCL-Poly	90,000
3	Wacker	84,000
4	Daqo New Energy	80,000
5	Xinte Energy	80,000
6	East Hope	40,000

From Dernreuter Research

By 2020, smelting and processing of non-ferrous metals (which includes metallurgical-grade silicon and polysilicon) accounted for more than 5% of Xinjiang's gross industrial output, and the generation of electricity (which many of these companies also engage in) accounted for 20% – all of this due in part to the expansion of the polysilicon industry into the region.[52] It was the capitalization on cheap energy prices that were unavailable to international competitors (at least in part because energy costs multiple times more in other countries) that allowed China's polysilicon manufacturers to grow so quickly and to rank as five of the top six highest-capacity producers in the industry by the end of 2020. Two Korean companies, OCI and Hanwha Solutions, had been riding a similar upward trajectory in the 2010s, but they could not compete with China's cheap production costs. In February of 2020, both companies declared that they would shutter their polysilicon production facilities in Korea (though OCI still runs a polysilicon plant in Malaysia), leaving the PRC in a position to dominate the industry almost entirely.[53]

It is perhaps not a coincidence that the period between 2016 and 2018 saw a significant expansion of the polysilicon industry in the Uyghur Region. Low energy prices were indeed a draw for many companies. In fact, a wide variety of industries were expanding into the XUAR at that time, in part in response to cheaper production costs in the region. However, it was not cheap coal alone that lowered the costs and increased the incentives of doing business in the Uyghur Region.

The Competitive Advantage of Forced Labour

The solar industry is not alone in its rapid expansion into the XUAR. The CCP has set ambitious targets for the growth of its industries, and they have determined that the Uyghur Region will be a strategic centre for development of their exports to the West, as well as for their national security, stability, and "unity of the motherland."[54] In an effort to facilitate the expansion of industry in the Uyghur Region, XUAR prefectural governments have provided significant financial and tax incentives to corporations that move to or build facilities in Xinjiang. Starting as early as 2010, governments exempted companies that moved into the "difficult regions of Xinjiang" from all corporate income tax from their first to second year and it was reduced to 50% from their third to fifth year.[55] Local prefectures added to the incentives. In Ili Prefecture (where JinkoSolar's Xinjiang factory is located), for instance, new companies that made at least 50% of their sales from products for export, and existing companies that made at least 70% of their sales from products for export, were granted exemptions for local corporate income tax, property tax, and urban land use tax for five years.[56] In addition to similar exemptions, some companies located in the Xinjiang Production and Construction Corps' (XPCC) Shihezi Industrial Park (where metallurgical-grade silicon producer Hoshine Silicon and polysilicon manufacturer Daqo New Energy both operate facilities) receive free office space, chairs, desks, computers, and internet and they qualify for annual monetary rewards.[57] These government incentives encouraged many companies to build plants or launch subsidiaries in the Uyghur Region, despite the significant bias against Uyghur labourers that dominates Chinese corporate culture, as a researcher from Peking University documented.[58]

> In the Uyghur region, companies create green energy by consuming cheap, carbon-emitting coal. They aim to improve climate conditions but sacrifice humane labour conditions in the bargain.

The compulsory labour transfers described above went hand-in-hand with this expansion. In 2015, the government introduced "rewards for towns, villages and other basic-level organizations, public employment service agencies, labour dispatch agencies, labour brokers, and other institutions and individuals that have successfully implemented the organised transfer and employment of rural surplus labour" to these new and expanding enterprises.[59] After 2016, by which time the camp system had begun to emerge, companies that "absorbed" "surplus labourers" to work in their facilities received significant incentives, including subsidies for the cost of building new factories, transport of the products made there to the coast, training for the new labour recruits (including Chinese language training), transport of new workers, and salaries of workers. Companies were "encouraged and guided" to hire these surplus labourers and to act as arbiters of ethnic unity in order to assist the government in its ambition of achieving 2.2. million "transfers for employment" of rural surplus labour per year on average from 2016 to 2020.[60] In Turpan (where another of Hoshine Silicon's facilities is located), for instance, the government provides subsidies for each worker that a company "absorbs" and trains as well as "tax reductions and exemptions" for those companies that "undertake social training tasks and provide practical training and internships" for "personnel participating in vocational training."[61]

What made the period between 2016 to 2018 a particularly lucrative time for solar and other industries to expand into the XUAR, then, was the new government-sponsored corporate incentives programmes that were introduced at the national, provincial, and local levels, including the incentives to employ "surplus labour transfers," which were enthusiastically embraced by many of the raw material and polysilicon manufacturers in the region, as this report will show. While BloombergNEF researcher Jenny Chase argued recently that labour costs only account for "a small component" of the cost of producing polysilicon and therefore using "unskilled and unhappy" forced labourers represents a negligible incentive for companies, that does not mean that companies are not benefiting from the exploitation of indigenous workers.[62] As discussed above, the Xinjiang government introduced a suite of corporate incentives in an explicit effort to attract polysilicon and other "labour-intensive industries" (劳动力密集产业) to move into the region and simultaneously directed corporations to understand the absorption of surplus labour as a social responsibility. Because they are associated with high-priority government efforts, these compulsory labour programmes are almost as difficult to avoid for companies as they are for the workers who are compelled to work within them. The corporate subsidies and other incentives thus serve to facilitate the implementation of the government's expansive labour transfer strategy. While companies may not see a significant and directly attributable decrease in their production costs due to the labour transfers, the extensive package of subsidies affiliated with operating in the Uyghur Region, where the government has instituted this ethnically-discriminatory forced labour regime, do indeed add up to a significant financial benefit.

The Purpose of This Report

The PRC's development of this vast, intertwined system of mass internment and forced labour has only occurred in the last several years. The solar industry seemed to first take notice of the potential implications of its significant investment in the XUAR in 2020,[63] and companies have since been trying to determine the extent to which they are exposed to the forced labour regime in operation there. The U.S.-based Solar Energy Industries Association (SEIA) released a call to action to manufacturers through which 245 companies have committed to "helping ensure that the solar supply chain is free of forced labour."[64] The SEIA has encouraged signatories of the pledge be divested from Xinjiang by June 2021 and has also committed to "industry-led solar supply chain traceability protocol as a tool for identifying the source of primary raw materials and inputs and tracking their incorporation into finished products, including solar modules."[65] Nonetheless, Mark Widnar, chief executive at U.S. manufacturer First Solar has indicated that it is "going to be tough" for panel manufacturers that source polysilicon products from the PRC to "really understand where [their] exposure is."[66]

This report seeks to increase the knowledge base upon which the solar industry determines its exposures to forced labour in the Uyghur Region. We investigated the entire solar module supply chain from quartz to panel to better understand the extent to which forced labour in the Uyghur region affects international value chains. To understand the context of the issue, we conducted a rapid assessment of experts in the field of forced labour, supply chains, the history of the Uyghur Region, and PRC policy, as well as with members of the affected community. We consulted with experts in the field of solar energy to shape our portrait of the process by which and conditions within which modules are manufactured. Our team of forced labour and supply chain experts fluent in Chinese, Uyghur, and English then examined hundreds of publicly available corporate disclosures, government directives, state media campaigns, social media posts, and industry reports. In the end, we investigated over 30 companies involved in the Chinese solar energy supply chain to determine any potential exposures each may have to the compulsory labour programmes instituted by the PRC government in Xinjiang.

Based on our determination that engagement in state-sponsored labour transfers is indeed a form of forced labour that contravenes international conventions on labour rights, our investigation determined that many of the major Chinese producers of raw materials, solar-grade polysilicon, ingots and wafers integral to solar module manufacturing are operating facilities in the Uyghur Region that have employed forced labour transfers of the indigenous people of the region and that many of these manufacturers have beneficial relationships with the Xinjiang Production and Construction Corps. These manufacturers' adoption of compulsory labour has a significant impact on downstream producers of solar modules and for the governments, developers, and consumers who buy them. The examples of engagement in these programs are meant to provide those stakeholders with the evidence base upon which to judge risk of exposure to forced labour in the solar supply chain.

The global demand for solar energy has encouraged PRC companies to go to great lengths to make our climate responsibility as inexpensive as possible, but it comes at great cost to the workers who labour at the origin of the supply chain. In the Uyghur Region, companies create green energy by consuming cheap, carbon-emitting coal. They aim to improve climate conditions but sacrifice humane labour conditions in the bargain.

2. RAW MATERIALS

The primary raw material used to produce photovoltaic cells is quartz, which is found in the vast deserts of the Uyghur Region. Indeed, one industry estimate indicates that Xinjiang holds 10% of the PRC's reserves of vein quartz used in the manufacture of metallurgical-grade silicon.[67] To create polysilicon, quartz is mined and then crushed, and then heated to remove the oxygen, leaving metallurgical-grade silicon (sometimes referred to as "silicon metal" or "industrial silicon" in China). The last ten years has seen the rapid expansion of the metallurgical-grade silicon manufacturing sector in the Uyghur Region, with one company – Xinjiang Hoshine Silicon Industry Co. – dominating all of the others. Hoshine (also known as Hesheng) and many of its competitors in the Uyghur Region engage in state-sponsored labour transfer programmes, affecting the entire solar module supply chain.

Xinjiang Hoshine

Xinjiang Hoshine Silicon Industry Co., Ltd (新疆西部合盛硅业有限公司)is a wholly-owned subsidiary of Zhejiang's Hoshine Silicon Industry Co. Xinjiang Hoshine is the world's largest metallurgical-grade silicon producer and perhaps the world's largest producer of siloxanes.[68] Xinjiang Western Hoshine operates from Shihezi, Xinjiang. The company established its Xinjiang Eastern Hoshine Co. in Piqan (Chinese: Shanshan 鄯善) outside of Turpan in 2016. There, Hoshine built the "Silicon-based New Material Circular Economy Industrial Park of Hoshine Silicon Industry" as its mining and manufacturing base within the Shanshan Stone Industrial Park. According to a description of the park, "experts" announced "China's stone material depends on Xinjiang, and Xinjiang stone material depends on Shanshan."[69]

Participation in Labour Transfers: There is evidence that Hoshine has actively recruited and employed "transferred surplus labour" from rural villages around Turpan to its Shanshan facility.[70] The company's labour recruitment process promises "transformation of surplus rural labour into industrial workers and urban dwellers, making them become fresh combat troops for industrialization, urbanization, and agricultural modernization."[71] A Hoshine recruitment fair in 2017 included a visit to the County National Unity Education Hall nearby, where the recruits "unanimously agreed that Xinjiang has always been an inalienable part of the motherland, and that people of all ethnicities have staunchly resisted the incursions of foreigners for over one hundred years."[72] Political indoctrination is an integral aspect of the ideological transformation imposed on rural farmers who are subject to labour transfer.[73]

> Their labour recruitment process promises "transformation of surplus rural labour into industrial workers and urban dwellers, making them become fresh combat troops for industrialization, urbanization, and agricultural modernization."

Xinjiang Hoshine relies on government programmes that place rural labourers deemed to be "surplus" in factory work. In its 2019-2021 vocational skills implementation plan, the Turpan government explicitly names Hoshine as a "key enterprise" in the "vocational skills training platform."[74] One effort early in Hoshine's development in the Uyghur Region suggests the potential scale of that collaboration. In 2017, the Turpan Bureau of Human Resources assured the media that the agency had adjusted its training of 9,800 surplus rural labourers to provide them with skills required by Hoshine and would be able to "fully meet [Hoshine's] employment needs" for 5,000 trained labourers.[75] Hoshine further received subsidies from the XPCC to provide its own surplus labour vocational skills training, as a part of an extensive Turpan government multi-agency effort to employ indigenous workers in labour-intensive industries.[76] Guidance from the Turpan government referred to in the Xinjiang Hoshine annual report in relation to labour transfer subsidies indicates that the payments are meant to provide vocational training for "rural surplus labourers" who will be "transferred" to companies in need of workers.[77]

State-sponsored recruitment efforts on Xinjiang Hoshine's behalf depend on coercive strategies that suggest non-voluntary labour. For instance, one media report depicts a married couple from rural Dikan Township who were targeted for "poverty alleviation." They were provided a government-determined "income-increasing package," which began with the assignment of a cadre who instructed them in Chinese language skills "to pave the way for them to leave their hometown to work." The regional work team then assigned the couple to vocational skills training to learn to be welders in the farming off-season. The couple followed the directives of the cadre, while the regional work team still provided "encouragement and help" for them to do "pre-employment training for the surplus rural labour force," after which they were transferred to work at Xinjiang Hoshine. Though the couple owned seven acres of grape fields that would need tending, the government "relieved the two of their worries," by transferring their land use rights (流转) to the state. The couple was transferred to Xinjiang Hoshine, more than 50 kilometers away from home, to work as a mechanic and a product inspector in the Shanshan County Hoshine Silicon Industry factory, leaving behind their children and ill parents. Though the report indicates that the couple have a bright and spacious house in their village, the photos accompanying the story suggest that the couple now lives in a bunk house with other employees at Xinjiang Hoshine and only rarely return home.[78]

Couple recruited through labour transfer program in a bunk room at Hoshine Silicon Industry facility.Source: Weixin

Hoshine's "surplus labour" recruitment programme explicitly strives to "change the employment concept of residents" and for the "transformation of the poor labour force's thinking" to "strengthen the endogenous motivation of poverty alleviation."[79] This implies that their inherent beliefs are opposed to poverty alleviation and that they are in need of correction that labour can provide. Hoshine's recruitment practices thus present labour transfers as a necessary ideological disciplining process.

These recruitment efforts appear to have been successful in transferring workers to Hoshine.[80] In 2020, Hoshine's parent company won an award as a "social support and caring enterprise," for its efforts to "fight against poverty, enable local people to increase employment and income, and promote local industrial upgrading" in Shanshan County, Xinjiang.[81]

Open worker recruitment advertisements from Hoshine suggest other discriminatory hiring practices. "Minority" workers must be able to speak Chinese and have “no bad political records.” Manual laborers are paid a piece rate of CNY 42 per ton to manually crush silicon, whereas other jobs get paid a salary.[82]

Supplier Exposures: The Shanshan Stone Industrial Park, in which Xinjiang Hoshine is operating, is separated into two sections, the north and the south, which are six miles apart. Xinjiang Hoshine’s facilities all appear to be located in the north section of the park, which Google Earth satellite imagery shows was barren desert as of 2015 but has been built up by Hoshine since and appears to house the industrial aspects of its operations.[83]

The southern part of the Stone Industrial Park[84] was a stone processing site as early as 2005, more than a decade before Hoshine’s facilities were built six miles to the north. The southern section of the Shanshan Stone Industrial Park is a site for the mining and processing of quartz stone; 98% of Shanshan’s stone processing companies are located in this park.[85] Hoshine Silicon Industry (Shanshan) Co, Ltd.’s Environmental Impact report notes that the company “purchases stone from Shanshan and carries out intensive processing in the park to smelt quartz stone,”[86] creating the metallurgical-grade silicon that the company sells downstream to polysilicon manufacturers. Furthermore, in a response to an online investor query, Hoshine indicated that it outsources for the quartz stone they use for manufacturing metallurgical-grade silicon.[87] This information suggests that when the company does not mine and process the quartz itself, it is almost certainly coming from the park that processes 98% of stone in the region. Google Earth imagery further confirms that the coordinates provided in Hoshine’s corporate document regarding sourcing of stone align with the southern Shanshan Stone Industrial Park.

If Hoshine is indeed sourcing its raw materials from the southern Shanshan Stone Industrial Park (as is likely the case), this fact is significant because the park engages in labour transfers and because two internment camps identified by the Australian Strategic Policy Institute (ASPI) are located within the bounds of that park.

Media reports confirm that there are coercive strategies being used to recruit labourers to the Shanshan Stone Industrial Park. In 2018, five cadres were assigned to nearby villages and had “mobilized the surplus labour in the region, especially the residents who were unwilling to go out to work and guided them to change their minds.” One of the people who was mobilized was a 28-year-old man whose home had been demolished by the government. He was visited by all five team members in turn, who each performed “ideological work” on him so that he eventually “abandoned his fear of enduring hardship” in manual labour. Among the companies he could have been employed by was Hoshine Silicon Industry. The team of labour recruiters reported “transferring” 59 “surplus labourers” in all.[88]

The southern Shanshan Stone Industrial Park is the site of two internment camps. Satellite imagery reveals that the northeastern site identified by ASPI (see map) as a “Tier 1 Re-education Facility” appeared to be the site of factories alone until 2018.[89] In 2018, however, a building that may be a dorm was built on the northern perimeter of the site, and a double layer of significant exterior walls and interior fencing was erected. By 2019 additional interior fencing was added near the dorm-like facilities. By 2021, much of the fencing was removed, but the facility still seems to be in operation. While it is unknown whether detainees are (or were) deployed to work in the park, the addition of high-security fencing on the inside of exterior walls suggests potential detention of people within the facility. Additional due diligence would be necessary to determine the relationship of this high-security facility to the stone processing facilities both within and outside the facility’s walls. Given that there is evidence of other internment camps providing labour for co-located companies (see introduction), this co-location raises the risk of additional forced labour in Hoshine’s supply chain.

Southern Shanshan Stone Materials Industrial Park. Source: Google Earth Pro

Satellite imagery of the ASPI-identified internment camp/factory co-location in the northeastern corner of southern Shanshan Stone Industrial Park. Source: Google Earth Pro

The camp in the southwestern corner of the southern Shanshan Stone Industrial Park was first identified by researcher Shawn Zhang, who located the resume of a local government official that indicated that as part of his job, he was "responsible for de-radicalization (去极端化) and anti-infiltration (防渗透) work in the field of education and training" and "responsible for vocational skills service management (stone factory)."[90] This suggests that the re-education camps are likely supplying laborers for the stone industry in the Shanshan Stone Industrial Park.

[redacted]

In addition to the Shanshan supplier exposures, Xinjiang Hoshine is exposed to labour transfers through its chemicals supplier Xinjiang Tianye Co., Ltd. Xinjiang Tianye is a state-owned enterprise of the 8th Division of the XPCC.[91] Xinjiang Tianye's 2018 annual report indicates participation in a wide array of so-called poverty alleviation programmes, including labour transfers and vocational training programmes. The company reports that it has "absorbed" (吸纳) 100 local workers, which typically is a euphemism for labour transfers.[92] Furthermore, a state media report in 2020 provides evidence that the company has been the recipient of "poverty alleviation" surplus labour transfers as a "paired poverty alleviation work unit" (对口帮扶单位).[93] It may be that Tianye primarily supplies Hoshine's downstream sealant projects and not their metallurgical-grade silicon projects;[94] nonetheless, this again raises the likelihood of labour transfers in Hoshine's supply chain.

Relationship with the XPCC: Xinjiang Hoshine is a private company, but it benefits significantly from its relationship with the Xinjiang Production and Construction Corps. Hoshine's Xinjiang headquarters is in the XPCC's 8th Division city of Shihezi, in the XPCC-operated Shihezi Economic and Technological Development Zone, where its customer Daqo is also located. Hoshine has invested more than CNY 4 billion recently in the expansion of their facilities in this Shihezi Park.[95] Xinjiang Hoshine's latest expansion of its sealant and metallurgical-grade silicon production facilities was touted recently as the largest investment attraction project of the XPCC in 2019-2020.[96] Xinjiang Hoshine's website once boasted that the company's significance is evidenced by the fact that "it can make use of Xinjiang's rich mining resources to fill the gaps in XPCC's industrial products."[97]

Xinjiang Hoshine receives significant subsidies and support from the XPCC. In its 2019 annual report, Hoshine indicated receipt of financial incentives/investments from the XPCC in the amount of CNY 40,140,411, and it listed an additional on-going special subsidy from the XPCC that originated in 2012 for the amount of CNY 26,855,298.[98]

Potentially Affected Supply Chain: Hoshine supplies more than 33% of Daqo New Energy Corporation's raw materials, according to Daqo's 2021 corporate filings.[99] Daqo in turn supplies polysilicon to the solar module manufacturers with the world's largest market share (as discussed in the next section). Official corporate documents indicate that Hoshine's other major customers include some of the industry's major players, Jiangsu Zhongneng (a subsidiary of GCL-Poly),[100] Asia Silicon,[101] and Wacker Chemie AG.[102] Hoshine also indicated in an online investor forum in February 2021 that its customers include Tongwei, Xinte, East Hope, and Korea's OCI (though these companies do not appear in Hoshine's annual reports as primary customers).[103]

Investors asked Hesheng Silicon (603260) :

Check the company's prospectus and find out that Jiangsu Zhongneng, a subsidiary of silicon manufacturer GCL-Poly, was the company's largest industrial silicon customer in the first quarter of 2017. Check the company's prospectus and find out that Hesheng Silicon is also its third largest supplier. Supplier, does the company supply other polysilicon materials companies?

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Hesneng Silicon (603260) answered investors :

Dear investors, the company is the largest industrial silicon manufacturer in the country. Industrial silicon is the main raw material for the production of organic silicon, polysilicon and silicon aluminum alloy. The main customers of the company's industrial silicon products in the downstream polysilicon industry include domestic polysilicon The main manufacturers Tongwei, Daquan, Xinjiang GCL, Xinte Energy, Eastern Hope, Jiangsu Zhongneng, Asia Silicon, etc., as well as foreign polysilicon manufacturers such as Wacker, OCI, etc., thank you for your attention to the company! (From: Shanghai Stock Exchange)

2021-02-08 15:11:54

Other Raw Materials Suppliers

Xinjiang Sokesi New Materials Company (aka Sokos, 新疆索科斯新材料有限公司) supplies 47% of Daqo's raw materials, according to 2021 corporate filings.[104] State media reports announced that Sokesi also participates in the state-sponsored "organised transfer of labour from poor families in ten deeply impoverished counties in the three prefectures of southern Xinjiang." The labourers work in Sokesi's facilities in the Changji High-tech Zone within the Zhundong Economic and Technological Development Zone, which "transferred" more than 700 labourers from Hotan through "surplus labour" programmes in March 2020 alone. State media reported Sokesi would sign three-year contracts for surplus labourers in 2020.[105] There is not much more information about Sokesi accessible in publicly available documents. [See textbox about Zhundong Economic and Technological Development Zone]

Production of Xinjiang Metallurgical-Grade Silicon

RANK	COMPANY	TONS/PER YEAR
1	Xinjiang Hoshine Silicon Industry	498500
2	Changji Jisheng New Building Materials	114800
3	Xinjiang China Silicon Technology	46400
4	Xinjiang Jingweike New Energy	33950
5	Xinjiang Yusi Technology	31200
6	Xinjiang Jagesen New Energy Materials	30000
7	Xinjiang Jierong Silicon Industry	19850
8	Xinjiang Xintao Silicon Industry	19600
9	Xinjiang Jinteng Silicon Industry	16350
10	Yili Jinjing Silicon Industry	16000

Source: Ferroalloy Online

Zhundong Basin

Aside from Daqo's two main suppliers, there are a number of other smaller enterprises engaged in producing the metallurgical-grade silicon that is essential in the production of polysilicon. An industry website ranked the top ten metallurgical-grade silicon producers in Xinjiang in terms of their 2020 production, and Hoshine ranked first, with a total production that amounted to more than four times the amount of its closest competitor. Indeed, Hoshine produced 52% more than the amount produced by all nine competitors combined. Information about these other smaller raw materials producers in Xinjiang is more difficult to come by and we are not able to find much more than the corporate addresses for a few of these companies. Nonetheless, investigation of these companies provides some evidence of additional potential risk of forced labour and XPCC involvement in the photovoltaic raw material industry.

Xinjiang East Hope developed its own raw materials subsidiary, **Changji Jisheng New Building Materials Company** (昌吉吉盛新型建材有限公司), which ranks as Hoshine's distant second place competitor. Their raw materials base is located adjacent to its main polysilicon processing facility, as part of the company's ambition to keep the entire process as cost efficient as possible.[106] As is documented in the discussion of East Hope in the polysilicon section below, East Hope's XUAR campus significantly benefits from the utilization of labourers transferred through state-sponsored programmes operating in rural regions of southern Xinjiang.

Xinjiang China Silicon Technology Company (also known as Zhonggui, 新疆中硅科技有限公司), reports having received critical support from the XPCC to transport raw materials during the COVID-19 pandemic.[107] A local CCP organization committee reported via their official social media that Xinjiang China Silicon participated in a job recruitment fair for "surplus labourers."[108] The company also advertised that "local ethnic minority" citizens account for 68% of all their employees, and that the company has "played an important role in solving the employment of local surplus labourers."[109]

Xinjiang Jingweike New Energy Development Company (新疆晶维克新能源发展有限公司) and **Xinjiang Jingxin Silicon Industry Company** (新疆晶鑫硅业有限公司) jointly own Xinjiang Fuxin Energy Company (新疆富鑫能源有限责任公司) with the XPCC (through its Shihezi Guoneng Energy Investment Company), according to the PRC's National Enterprise Credit Information Public System (NECIPS).[110] Xinjiang Jingweike engaged in surplus labour transfer job fairs.[111] In October 2019, when Xinjiang Jingweike recruited new hires, the company specifically indicated that it was hiring 40 "general workers" who would be responsible for "silicon smashing" and working the furnace, for which the workers would be paid CNY 2000 a month and CNY 40 per ton of silicon crushed. While it was unclear whether the company was recruiting "surplus labourers" for these positions, the advertisement specified no ethnicity requirement for those labour-intensive jobs. Tellingly, for all of the professional-level jobs (such as warehouse managers, accountants, cashiers, lab technicians, sales and office clerks), Xinjiang Jingweike required the candidates to be Han nationality.[112] This is clearly indicative of racially discriminatory hiring practices. Xinjiang Jingxin was reported to have employed "surplus labour" by local state government via their social media, which also details that the labourers in question are subjects of a land transfer scheme run by the government to transfer rural farmers' land use rights to the government, while transferring the farmers into industrial labour.[113]

Several raw materials processing companies are located in the Xinjiang Production and Construction Corps' Jingang Circular Economy Industrial Park (新疆伊犁州巩留县七十三团金岗工业园): Xinjiang China Silicon Technology Company, **Xinjiang Yusi Technology Company** (新疆宇硅科技有限公司), **Xinjiang Jiagesen New Energy Materials Co., Ltd.** (新疆嘉格森新能源材料股份有限公司), and **Xinjiang Guopeng Technology Co., Ltd.** (新疆国鹏科技有限公司), along with several other raw material manufacturers.[114] The park is the "Xinjiang Silicon Industry Base," with silicon raw material mining and manufacturing as one of its primary industries, and is intended to become the largest silicon production base in the XUAR.[115] The park is a joint development of the Tokkuztara County (Chinese: Gongliu 巩留) government and the 73rd Regiment of the 4th Division of the XPCC, as a model of "military-land integration."[116] It was designed to make the 73rd Regiment a "'stabilizer' for the frontiers, a 'melting pot' for gathering people of all ethnic groups, and a 'demonstration zone' for advanced productivity and culture."[117] Over 130 workers from Kashgar have been transferred to this park.[118] The park has documented engagement in surplus labour programmes, and the company has indicated to state media that 485 of their 946 employees hail from local villages.[119] When Xinjiang Yusi posted an open recruitment advertisement for workers in 2017, safety and financial personnel jobs were limited to Han people only; manual labour jobs such as silicon crushing were open to ethnic minorities who were "able to bear hardships and hard work" and had "no bad record,"[120] indicating a clear discriminatory policy toward minoritized citizens.

The raw materials supplier with the eighth highest reported capacity is **Xinjiang Xintao Silicon Industry Co., Ltd.** (新疆鑫涛硅业有限公司). In 2019, Xinjiang Xintao indicated that the company's "labour demand is about 300 people, which can effectively solve the employment of surplus labour in the surrounding area."[121] Until 2019, Xinjiang Xintao's shareholder was Western Oasis International Industry Group (西部绿洲国际实业集团有限公司), a wholly-owned subsidiary of the XPCC, according to NECIPS.[122] According to a November 2020 press release, Xinjiang Xintao's customers include Xinte Energy, Beijing Zelin, Qinghai Baitong, Xuzhou Zhengxu, Shanghai Chaojin.[123]

Beijing Dadi Zelin Silicon Industry Company (北京大地泽林硅业有限公司) has a silicon powder production base in Changji High-Tech Industrial Development Park[124] and is a supplier for Asia Silicon.[125] Several Chinese media reports document labour transfers to this industrial park, though none name this particular company.[126] Satellite imagery reveals a camp, detention centre, and prison in the midst of construction across the street from this industrial park.

It is important to note that GCL-Poly and East Hope (both discussed in the polysilicon section below) operate raw materials processing facilities in the Uyghur Region that provide at least part of the feedstock for their manufacturing.

Implications

Xinjiang Hoshine Silicon presents a useful case study for understanding how the deployment of compulsory labour transfers can potentially put an entire supply chain at risk. Hoshine has benefited from a wide variety of government-sponsored incentives programmes designed to require the industrial employment of all indigenous people of the region deemed employable by the government, and the company has actively engaged in the ideological re-education efforts associated with those programmes. The company has accepted the government's assistance in seeking impoverished rural workers to work in its facilities, exploiting the rural poors' vulnerability to such mandatory government programmes. The "transferred" labourers are put to work directly in the production of the silicon, manning the furnaces and inspecting the final products. Furthermore, Hoshine likely sources its quartz from companies likely engaged in labour transfers and perhaps employing detainees from internment camps. Because Hoshine's metallurgical-grade silicon is sold directly to Daqo, who supplies the four top-selling module manufacturers in the world, this has significant effects on the entire supply chain.

While the rest of the raw materials producers in the Uyghur Region have less of a public presence through which we can examine labour practices, it is clear that several of them are also engaging in labour transfers. Many of them are significantly supported by the XPCC, which itself employs and facilitates forced labour transfers, though we cannot be sure if it does so for these particular silicon manufacturers. Some raw materials companies appear to be bringing on minoritised workers for the significant manual labour of crushing the silicon for processing, which is not necessarily forced labour but is an indicator of discriminatory hiring practices that should be carefully examined in corporate due diligence. Furthermore, these recruitment advertisements also give clear proof that the multi-stage process of producing silicon is not so technologically advanced as to preclude the employment of unskilled surplus labourers as some in the industry have suggested.[127]

The widespread adoption of state-sponsored labour programmes in the Uyghur Region means that it is nearly impossible to avoid forced-labour-tainted raw materials if they are being sourced in the XUAR under the current regime. Wherever the raw materials originate, however, there is an even further forced labour risk in the next step of production in the solar module supply chain – the manufacture of polysilicon.

3. POLYSILICON

Once quartz has been processed into metallurgical-grade silicon, it is then ground up and purified even further. The purification process requires extraordinarily high temperatures, which consumes significant electricity,[128] making the Uyghur Region's coal fields an ideal location for polysilicon producers. The Uyghur Region's coal reserves account for 40% of the PRC's reserves and is one of the largest untapped reserves in the world.[129] The mono-grade or multi-grade polysilicon that results from this purification process is a major export of the XUAR region.

As was described in the introduction, the last ten years (and in particular the last three or four years) has seen significant growth in polysilicon ingot and wafer manufacturing in the Uyghur Region. By 2020, four of the six highest-capacity polysilicon producers were companies with significant manufacturing bases in the XUAR – Daqo New Energy Corp, GCL-Poly, TBEA/Xinte, and East Hope. All four of them utilise state-sponsored labour transfers, the end products of which are sold into the international solar module market.

Because polysilicon can be blended and ingots can be made from several feedstocks, companies downstream of these polysilicon giants run significant risk of having their supply chains tainted by Xinjiang forced labour.

Daqo New Energy Corp

Daqo New Energy Corp's (大全新能源股份有限公司) main product is high-purity polysilicon. The company's XUAR subsidiary is located in the XPCC 8th Division city of Shihezi. Daqo began building a polysilicon plant with the support of the Shihezi government in the XUAR in 2011.[130] While Daqo is a publicly-traded company (NYSE: DQ) and not state-owned, the company is significantly subsidised by the Xinjiang Production and Construction Corps.In 2013, Daqo negotiated a deal with the 8th Division Deputy Party Secretary and acting mayor of Shihezi to invest an additional CNY five billion in developing the Daqo Photovoltaic Industrial Park inside the Shihezi Economic and Technological Development Zone. It was planned to be the company's only solar-grade polysilicon production base.[131]


Daqo polysilicon production facility. Source: Daqo New Energy Corp

100% of Daqo's now 80,000 MT polysilicon capacity is produced in its Shihezi, Xinjiang facility.[132] In 2020, Xinjiang Daqo claimed it held 19% of the domestic market share of polysilicon.[133] This indicates that Daqo's direct engagement in labour transfers or any forced labour in its own supply chain represents a significant exposure for the solar market.

Participation in Forced Labour Programmes: In 2020, in the IPO prospectus for Xinjiang Daqo, a principal operating subsidiary controlled by Daqo New Energy, the company indicated that it had received subsidies for "labour placements" (劳动力安置) from the Chinese government, which may indicate that the company employs state-sponsored labour transfers in its own facilities, as "placement" is a term the central government and Xinjiang local and regional governments sometimes use for labour transfers.[134] There is no additional information available that elaborates on the nature of those placements.

In response to accusations that the company had employed forced labour in its factories or within its supply chain, Daqo CEO Zhang Longgen reported in April 2021 that only 18 of Xinjiang Daqo's 1,934 employees are from communities designated as minorities in the PRC.[135]

Supplier Exposures: Daqo's two primary raw material suppliers, Hoshine Silicon and Xinjiang Sokesi, are both engaged in state-sponsored labour transfer programmes, putting Daqo's downstream supply chain at risk.[136]

Relationship with the XPCC: Xinjiang Daqo and the XPCC are in a long-term, mutually beneficial relationship. In return for its investment in the XPCC's Shihezi Industrial Park, Xinjiang Daqo has continuously received subsidies, incentives, energy, and special price negotiation dispensations from the XPCC. These XPCC subsidies include, most recently, corporate social security subsidies post-Covid. [137] XPCC subsidies to Xinjiang Daqo are significant and include CNY 77.36 million in financial subsidies from the Shihezi government in 2018 and CNY 35.14 million in 2019.[138] The company operates several research and innovation programmes in collaboration with the XPCC.[139]

Xinjiang Daqo purchases the majority of its energy from Xinjiang Tianfu Energy Co Ltd, an XPCC company, which is co-located in the same industrial park and which offers Daqo special pricing. The ultimate controller of Tianfu is the State-owned Assets Supervision and Administration Commission of the 8th Division of the XPCC.[140]

Potentially Affected Supply Chain: Xinjiang Daqo supplies Chinese companies with polysilicon, which those companies then manufacture into ingots, wafers, and cells for sale into the domestic and international markets. Supply chain mapping indicates that its polysilicon is likely to pervade much of the solar market. Nearly every Chinese company that sells solar panels is in one way or another downstream of Daqo. The company has confirmed current contracts with the top four solar module producers in the world – LONGi Green Energy Technology (through 2022),[141] JinkoSolar Holding (through 2021),[142] Trina Solar (through 2023),[143] and JA Solar (through 2023)[144] – as well as the second largest producer of silicon wafers in the market, Tianjin Zhonghuan Semiconductor Co (through 2023).[145] The company also has current contracts with Wuxi Shangji Automation (through 2024),[146] and Gaojing Solar (through 2024).[147] The company's recent SEC filings suggest a broader downstream market, including supplying Eaton Corp PLC (US).[148] Sunshine Energy Holdings/Solargiga (TW), and Huantai Group.[149]

In a response to a request for comment, Daqo's representative for investor relations and board secretary, Kevin He, indicated that the labour placements (安置) listed in Daqo's IPO document were "a very common subsidy scheme utilized by local governments globally." He claimed that in the context of their IPO, "placement" was a mistranslation of 安置, which he suggested is better understood as "helping to settle down (from another place) securely and peacefully." Furthermore, He indicated that with "Xinjiang being in a remote location, the availability of talent is generally limited, and the government provides employment related incentives and subsidies to attract skilled labor to work in the Xinjiang area." He said that Daqo's hiring process is entirely independent of the state and that Daqo has "NEVER" participated in any poverty alleviation, surplus labour, or labour transfer programs of minority citizens. He reiterated that they only have 18 ethnic minority citizens working at their factory in Xinjiang. He further indicated that Daqo has zero tolerance for forced labour, has sent a formal statement articulating their policies to their suppliers, and has received written reassurance from their suppliers that they are not engaged in forced labour. He wrote, "We don't see any clear evidence of forced labor issue in their plants."

GCL-Poly Energy Holdings Company

GCL-Poly Energy Holdings Company (保利协鑫能源控股有限公司) considers itself the world's leading supplier of photovoltaic materials. The company produces polysilicon chunks and granules and mono-crystalline and multi-crystalline wafers that are incorporated into the manufacture of solar modules. In September 2016, Xinjiang Changji Hui Autonomous Prefecture signed a cooperative agreement with Xinjiang GCL to invest CNY 30 billion in the construction of the GCL Silicon-based Industrial Park,[150] located in the enormous Zhundong Economic Development Zone (see text box about Zhundong).[151] Around half of GCL-Poly's polysilicon production capacity is located in its XUAR facilities;[152] the company also produces polysilicon in Xuzhou, Jiangsu province.


[redacted] [redacted]

Caption from original source: "Xinjiang GCL New Energy Material Technology Co., Ltd. conducts military posture training for transferred personnel." Source: Worker Times

Participation in Labour Transfers: An XUAR-based subsidiary of GCL-Poly, Xinjiang GCL, employed coerced surplus labourers as part of a scheme that brought "more than 1,800 poor labourers [who] are all beneficiaries of the organised transfer of labour from poor families from ten deeply impoverished counties in three prefectures of southern Xinjiang." According to state media, the workers "were placed in Xinjiang state-owned enterprises affiliated with the region or central government enterprises based in the region, while enterprises in Urumqi's seven districts and one county as well as the three county-level cities in Changji prefecture and three industrial parks had organized transfer for employment."[153] The article about the transfers depicted the labourers being trained in "military posture" and in "etiquette" by Xinjiang GCL.

In late 2018, within the first few months of operation, GCL-Poly's facility in Changji had employed more than 60 people through surplus labour transfers. A state media report about the transfer explained that workers at the facility, including those from the XUAR, live far from family, as the location is the most remote among all enterprises in the industrial park.[154]The company's party committee magazine highlighted the isolation of one of the transferred labourers in its factories who commented that when she returns home, she'll treat her parents and daughter to a new Chinese food she learned about, a sign that she had to leave her family behind for work.[155]

According to GCL's promotional materials on corporate sustainability, by December 2019, Xinjiang GCL had achieved a ratio of nearly 50% local workers on staff, having recently recruited 121 "minority" employees. The company achieved this in part through "acceptance of poor minority people from southern Xinjiang," which is likely a state-sponsored labour transfer.[156]

Supplier Exposures: Xinjiang GCL has its own operation in the desert of the Zhundong Economic and Technological Development Zone, where it produces its metallurgical-grade silicon. Hoshine's corporate filings report that it has been a supplier to Xinjiang GCL and GCL subsidiary Jiangsu Zhongneng.[157]

Relationship with the XPCC: In June of 2020, GCL-Poly subsidiary Henan GCL and the 13th Division of the XPCC brokered a CNY 2.15 billion deal.[158] The nature of this investment is unclear, but it is likely connected to the development of photovoltaic power generation plants. Yili GCL Energy Co., Ltd. is owned 56.51% and 43.49% by Suzhou GCL New Energy and the XPCC, respectively. The address of the registered office and principal place of business of GCL Ili is the XPCC Division of Khorgas Economic and Technological Development Zone, Ili Prefecture.[159]

Potentially Affected Supply Chain: GCL-Poly has significant current contracts with many of the major producers of solar wafers, including LONGi Green Energy Co (CN) (through 2023),[160] Wuxi Shangji Automation Co (CN) (through 2021),[161] and Tianjin Zhonghuan Semiconductor Co (CN) (through 2026).[162] GCL-Poly also signed contracts in 2019 to supply wafers to Canadian Solar (CA),[163] Astronergy/Chint Solar, Daycare Photovoltaic, and Akcome Optoelectronics.[164]

TBEA Co. & Xinte Energy Co

TBEA Co. (特变电工) specialises in the research and development of photovoltaic energy products and silicon-based new materials.[165] The company has two additional listed subsidiaries, both of which are located in the XUAR: Xinjiang Zhonghe/Joinworld (新疆众和股份有限公司), and Xinte Energy (新特能源公司). The company's polysilicon production capacity has increased by nearly four times since 2016.[166]

Unlike many of its competitors, TBEA's headquarters are located in Xinjiang. The company has two primary locations, one in the capitol Urumqi, in the Ganquanbao Economic and Technological Development Zone and another in the Zhundong Economic and Technological Development Zone in Changji Prefecture.

As indicated in the sections below, TBEA Group has taken extensive advantage of the PRC's Xinjiang policies and "poverty alleviation" programmes, through locating its facilities in government industrial parks, receiving significant government subsidies, and receiving "surplus labour" transfers. It is unclear from company media campaigns and the C.E.O.'s speeches regarding labour transfers to what extent Xinte Energy, its polysilicon-manufacturing subsidiary, is the direct recipient of the transfers or a party to the pairing programmes that match TBEA employees with indigenous labourers for ideological indoctrination. However, it is clear that the parent company is heavily invested in these programmes, and it may be the case that these programmes are employed throughout and supported by all of its Uyghur Region subsidiaries and facilities.

Participation in Forced Labour Transfers: Of all the companies studied, TBEA has most enthusiastically heeded the call to engage in Xinjiang's "poverty alleviation" programmes. By May of 2020, TBEA had invested a total CNY 30 million in various "poverty alleviation" programmes in the Uyghur Region and significantly engaged in surplus labour transfers.[167]

Zhang Xin, TBEA's C.E.O., is Secretary of the Party Committee of TBEA and a representative of the National People's Congress.[168] He is an enthusiastic promoter of the Xinjiang government's so-called "poverty alleviation" and "Becoming Family" (结对认亲) programmes.[169] TBEA has adopted two villages in Hotan where it engages in extensive "poverty alleviation" and labour transfer social engineering experiments.

[redacted]

TBEA poverty alleviation walnut processing plant in remote Hotan village. Banner reads: "Employ one person, alleviate poverty for a household; Labour is great; Getting rich is glorious; Let's unite as one and run toward a well-off life together." Source: Tencent Video

TBEA announced in 2018 that it had "developed employment positions," for which the company transferred 200-300 poor people into work.[170] TBEA was one of four companies that were recipients of 139 eighteen- to sixty-year-old "transfer labourers" from Jimsar County [Chinese Jimusaer 吉木萨尔] for work in the company's power plant in the Zhundong Economic and Technological Development Zone. The labourers were assigned Han minders/trainers that were dubbed fictive "in-laws" to ensure their enculturation in the new site.[171] The company's factories engage in political education that is explicitly meant to pacify Uyghur dissent. Zhang Xin noted in 2018 that TBEA "launched a series of activities to educate and guide all employees to clearly oppose national separatism [and] insisted on maintaining stability as the overriding priority."[172]

TBEA plays an active role in the "Thousands of Enterprises Help Thousands of Villages" (千企帮千村) programme, through which TBEA promised to assist "360 impoverished households or 1,600 people" from two poor villages in Hotan to "fully overcome poverty" before 2020.[173] TBEA adopted these two rural villages in Hotan in 2017,[174] where the company has invested CNY 1 million in agricultural businesses that employ rural labourers recruited from the town.[175]


[redacted]
[redacted]

Image of Uyghur family from Chinese media about TBEA's engagement in poverty alleviation programmes, including redesigning Uyghur domestic spaces and providing televisions to watch state media. Source: Tencent Video.

In addition to conscripting the villagers into manual labour, TBEA has instituted much more invasive "poverty alleviation" programmes. They have instituted a programme whereby they redecorate the villagers' houses with Chinese furniture and restructure the living spaces to better resemble Han practices. The company's "poverty alleviation" teams also restructured the courtyards of hundreds of Uyghur homes – a traditional space of family gathering. TBEA has installed 921 televisions in Uyghur homes in a programme explicitly designed for "spreading the voice of the Party and modern culture to every household" and to "stimulate endogenous motivation" for poverty alleviation. TBEA also had to build an elder care facility to care for the elderly who have been left behind by their family members who have been recruited to work outside the village through the state-sponsored surplus labour programmes. TBEA workers "regularly carry out education to encourage being grateful to the party, listening to the party, and following the party."[176]

The company actively participates in the "Becoming Family" programme, whereby a Han TBEA employee is assigned to be a "relative" to a Uyghur household. In their visits, they are assigned to educate and monitor their assigned family. CEO Zhang Xin himself has adopted a family that he monitors in the name of "poverty alleviation."[177]

Zhang has authored a report called "Recommendations on further deepening the Xinjiang government's 'Thousands of Enterprises Helping Thousands of Villages' targeted "poverty alleviation work."[178] Speaking to reporters at the 2020 Two Sessions, he encouraged the government to "continue to intensify its efforts in industrial poverty alleviation, to combine the advantageous industrial capabilities of the central and eastern regions [of the PRC] with Xinjiang's resource advantages to even more vigorously promote the improvement of hematopoietic capacity."[179] Hemotopoeisis (造血) is a term used to describe the positive effect that "poverty alleviation" and labour transfers are supposed deliver, namely, a metaphorical shift from the people of the region needing a "blood transfusion" (输血) to their "producing their own blood' (造血).

Supplier Exposures: Xinte sources its metallurgical-grade silicon from Xinjiang Xintao Silicon Industry Co., which may engage in labour transfers. [180]

Relationship with the XPCC: TBEA has a strategic cooperative agreement with the XPCC 2nd Division in Tiemenguan City. Since at least 2017, the company has provided power generation and infrastructure construction support "to meet the development needs of Tiemenguan City."[181] The 2nd Division Tiemenguan government has brought in transferred surplus labourers from Kashgar to work in a textile factory and likely have transferred other workers as well.[182]

Potentially Affected Supply Chain: TBEA and its subsidiary Xinte have confirmed current contracts with JA Solar (through 2025),[183] Qinghai Gaojing Solar Energy Technology Co. (through 2025),[184] Beijing Jingyuntong Technology Co (through 2021),[185] LONGi Green Energy Technology Co (through 2025),[186] and Wuxi Shangji Automation Co/Hongyuan New Materials (Baotou) Co. (through 2025).[187] TBEA has otherwise primarily served a vast PRC-based corporate customer base in the recent past, according to SEC filings, which may affect additional downstream customers.

East Hope Group

East Hope Group (东方希望) produces metallurgical-grade silicon and solar-grade polysilicon, as well as other chemical and metallurgical products.

In 2010, Shanghai-based East Hope heeded "the national 'Go West' call," (西部大开发) establishing Xinjiang East Hope Nonferrous Metals and Xinjiang East Hope Photovoltaic Technology Co., Ltd. with the deliberate intention of taking advantage of the Zhundong region's significant coal deposits. The company has invested more than CNY 30 billion in the XUAR and intends to reach CNY 100 billion in investments in its industrial park there.[188] East Hope's ambition in Zhundong is to produce the cheapest (though not necessarily the purest) polysilicon on the market, aiming for cash costs under CNY 25/kilogram (US $3.85/kilogram) as opposed to Daqo's approximately US $5/kilogram. Recent global average prices have run as high as US $20/kilogram and are likely to continue to rise.[189]

Participation in Forced Labour Transfers: East Hope has engaged in "surplus labour" programmes since at least 2017.[190] In that year, the Zhundong Economic and Technological Development Zone's official social media reported on job fairs to recruit rural surplus labourers[191] and the prefectural public security's official social media account reported on visits to check on the well-being of the surplus labourers working for East Hope.[192] The report indicated that 95 labourers from southern Xinjiang had been "transferred" to this site. The Qira County (Chinese: Cele, 策勒) citizens who had been transferred approximately 1,500 km from their homes were instructed to remember, know, appreciate, and repay the kindness of the Party and to "observe discipline and promote unity" in their work placements.[193]

In 2018, East Hope engaged more transferred labourers, pairing them with "teachers" to train them, in an effort to "transform [them] into qualified industrial workers as soon as possible."[194] The company held "national family unity" (民族团结一家亲) programming in which "the southern Xinjiang labour transfer personnel are encouraged to continue to study, work diligently, and exchange sweat for a better tomorrow."[195]

In March 2020, Xinjiang East Hope reported that it had recently employed at least 235 transferred labourers in its plants.[196] It appears that in March of 2020,

Suntech International Clean Energy Ltd. representatives visit transferred labourers at East Hope Zhundong facility. Source: Weixin.

there were “express transit” programmes running from rural villages to industrial parks in the midst of COVID-19 train stoppages, and East Hope was a beneficiary of this mass forced migration in the midst of the pandemic.[197]

On its corporate social responsibility page, East Hope Group announced that it has also invested CNY 800,000 for the transformation of rural villages in Kashgar through the “Fang Huiju” (访惠聚 or 访民情, 惠民生, 聚民心, translation: “Visit the People, Benefit the People, and Get Together the Hearts of the People”) visitation programme, whereby Han cadres go for required surveillance visits in Uyghur homes.[198]

Supplier Exposures: East Hope Group established Changji Jisheng New Materials Building Co. in the Zhundong Economic and Technological Zone to process its metallurgical-grade silicon. The company positioned the raw materials facility adjacent to the East Hope polysilicon manufacturer to maximize efficiency.[199]

Potentially Affected Supply Chain: Despite ambitions to produce the world’s cheapest polysilicon, East Hope has not provided much in the way of publicly available evidence of its customers. The company has not managed to reach the production capacity it had anticipated in 2017,[200] so it may be that the company is consuming its own supply in its solar generation plants. However, if East Hope is able to increase its production as anticipated in 2021, it could become a major source of polysilicon for the solar module supply chain.

Non-Xinjiang-Based Polysilicon Suppliers

Despite the XUAR’s dominance in the manufacture of polysilicon, 35% of the world’s polysilicon still comes from regions of China outside of the XUAR. While critical attention must be paid to the polysilicon manufacturers that operate facilities in the Uyghur Region, other significant polysilicon suppliers may be purchasing raw materials that originate in the XUAR. And because both metallurgical-grade silicon and the more refined polysilicon can be blended from different sources, products sourced from the Uyghur Region could be integrated into the polysilicon and silicon ingots produced by companies outside the region. For this reason, BloombergNEF solar expert Jenny Chase recently declared that “any silicon-based solar panel may have at least a small amount of Xinjiang silicon.”[201]

Tongwei Solar Company (通威股份) produces high-purity polysilicon and solar cells.[202] According to Bernreuter Research, Tongwei is the manufacturer with the highest capacity for polysilicon production in the world, and thus represents a significant share of the PRC’s non-Xinjiang-sourced polysilicon.[203] Tongwei seems in many ways like the safest bet in the Chinese polysilicon market. Nonetheless, there are some potential risks in Tongwei’s supply chain that merit further investigation.

Tongwei sources its raw materials from Sichuan Hengye Silicon Industry Co (四川恒业硅业有限公司).[204] There are no discernable links between Hengye and Xinjiang or forced labour. It is unclear if Hengye is the sole or primary raw material source for Tongwei’s polysilicon. However, if Hoshine Silicon’s claims in the online investor forum (discussed above) are correct, then Tongwei is a customer of raw materials from Hoshine, which engages in labour transfers. However, it appears that Tongwei’s raw materials are typically sourced from companies proximate to their polysilicon facilities, which could rule out Hoshine as a primary supplier.[205]

Tongwei’s corporate filings do indicate that the company is a customer of LONGi Green Energy, Tianjin Zhonghuan, and JinkoSolar,[206] all of which have upstream suppliers that are engaged in labour transfers (see the next chapter for information regarding these manufacturers). These relationships seem to involve a circular transaction. Tongwei supplies polysilicon to LONGi, for instance. LONGi then turns the polysilicon into ingots and wafers for resale back to Tongwei.[207] Then Tongwei uses the wafers in the manufacturing of solar cells. This does not present a risk unless LONGi blends the Tongwei polysilicon with polysilicon purchased from suppliers Daqo, Xinte, or Xinjiang GCL for resale back to Tongwei subsidiaries. Since polysilicon from multiple suppliers is often blended, an investigation into those practices could be critical in understanding Tongwei's exposure.

In terms of the employment of forced labour or labour transfers, there is nothing that suggests that Tongwei itself is involved. Tongwei did win an award for "absorbing" "more than 10" workers through a "poverty alleviation" labour transfer programme outside of the XUAR, but it is unclear where the workers originated from. Without further information, this is not conclusive evidence.[208]

Determining the source of all of Tongwei's raw materials is critical to determining the company's exposure to forced labour. This is important because Tongwei does supply some of the world's most significant solar module manufacturers with polysilicon. The company has current contracts with JinkoSolar Holding Company (through 2023),[209] Trina Solar (through 2023 and joint venture),[210] Tianjin Zhonghuan Semiconductor Company (through 2021),[211] Jiangsu/Baotou Meike Silicon Energy Company (through 2023),[212] and LONGi Green Energy Technology Company (through 2023).[213]

Asia Silicon (Qinghai) Company (亚洲硅（青海）有限公司) is a manufacturer of solar-grade polysilicon materials.[214] The company is registered in the PRC and majority-owned by Australian citizens. Asia Silicon's most significant exposure to labour transfers is through the company's immediate suppliers of raw materials, Hoshine,[215] Beijing/Qinghai Dadi Zelin Silicon Industry,[216] and Xinjiang Guopeng Technology.[217] Asia Silicon is currently expanding its Xining polysilicon production site, but as it stands, raw materials sourcing is what determines Asia Silicon's (and its customers') exposure to forced labour. Asia Silicon has a confirmed contract to supply wafer manufacturer LONGi Green Energy through 2025.[218]

Implications

The metallurgical-grade silicon made by Hoshine and its competitors significantly impacts the solar supply chain, but the Uyghur Region-based polysilicon manufacturers add significantly more risk. All four of the major companies located in Xinjiang participate in state-sponsored labour transfer programmes, and some of them are engaged in programmes that promote the invasive transformation of rural Uyghur life across the XUAR. While Asia Silicon does not have a polysilicon facility in the Uyghur Region, it does appear to be transporting raw materials out of the XUAR to its Qinghai locations. This is a reminder that XUAR raw materials are being shipped to polysilicon manufacturing facilities elsewhere, tainting even the polysilicon produced outside of the region. Thus, the reach of forced-labour-tainted metallurgical-grade silicon is clearly much wider than a portrait of the XUAR-based companies alone can reveal. This finding suggests that the larger Chinese supply chain requires close investigation to identify further downstream exposure to Xinjiang's state-sponsored forced labour programmes.

To that end, the next chapter will show that while the XUAR is home to only one ingot/wafer production facilities and one (possibly shuttered) module manufacturing facility, the forced-labour-tainted polysilicon produced in the region reaches many other solar module manufacturers in the interior of China.

Zhundong Economic and Technological Development Zone

Spanning 15,500 square kilometers across the Gobi Desert, the Zhundong Economic and Technological Development Zone provides the vast coal reserves – 7% of the PRC's total coal reserves – necessary for the cheap production of a wide range of industrial products.[219] Ironic though it may seem, Xinjiang regional and local governments advertise the Zhundong coalpits as a lure for renewable energy manufacturing. As of 2020, the Zhundong Zone had the capacity to produce 94,000 tons of polysilicon, which constituted 46% of the Uyghur Region's output and 22% of the PRC's.[220]

Zhundong Economic and Technological Development Zone.
Source: Wo Ai Zhundong Promotional Video.

To encourage polysilicon companies to make the distant move out to the XUAR in the mid-2010's, the government promoted the development of the Zhundong Coal Power Base, which has powered the polysilicon giants that moved into the region (and will eventually power a great deal of the PRC).[221] To better facilitate the growth of the new energy economy in Zhundong, the government planned an expansion of the railroad and airports into the otherwise largely deserted region as well.[222]

Some of the PRC's leading new energy giants have taken full advantage of the benefits of proximate and cheap coal to fuel their polysilicon production. Xinjiang GCL and East Hope both call the region home. TBEA has a coal plant there, and their factories for both polysilicon manufacture and other electrical products they create are located just outside (though their official addresses use the closest urban area, Urumqi).

The Zhundong Zone employs 80,000 people.[223] The Zone also has a strong relationship with the local labour transfers programmes. The Wucaiwan Industrial Park, where East Hope is located, is just one park located inside the enormous Zone. It operates its own Wucaiwan Supply and Marketing Cooperative Member Service Center that "actively communicates with the transfer of labour in various towns and villages in Jimsar County" and with the corporations located in the park to determine matches between workers and available jobs. The Center had successfully matched companies with 9,000 rural surplus labourers by 2016, before the internment camp system was operational. Since 2016 and the increasing rise of repression in the Uyghur Region, labour transfers continued apace upon a backdrop of internment camps, supplying the PRC's solar industry with labourers who were compelled to participate.[224] The Human Resources and Social Security Bureau of Changji Prefecture boasted in 2018 that it had conducted 11,631 transfers of surplus labour to date.[225] The compulsory programmes continue even now, supported by incentives provided by the Bureau to companies within Zhundong for absorbing the transfers. By 2020, the Bureau announced that it had distributed "1.6 million yuan in rewards and subsidies to 52 labour service cooperation organizations, and allocated 800,000 yuan in special funds for small factories...to absorb poor labourers."[226]

Coal transport in Zhundong Economic and Technological Development Zone. Source: Wo Ai Zhundong Promotional Video.

4. INGOTS, WAFERS, CELLS & MODULES

Polysilicon is melted and shaped into ingots, which are in turn sliced into wafers, which are in turn used to construct photovoltaic cells. Many of the large Chinese solar module producers are vertically integrated from the ingot to the module. Alternately, a company might sell polysilicon to a wafer manufacturer who then sells the wafers back to the first company's module manufacturing subsidiary, as in the collaborative effort between Tongwei and LONGi described above.

Ranking of Market Share of Module Manufacturers

RANK	MANUFACTURER	HEADQUARTERS
1	LONGi Solar	China
2	Jinko Solar	China
3	JA Solar	China
4	Trina Solar	China
5	Canadian Solar	Canada/China
6	Hanwha Q-Cells	South Korea
7	Risen Energy	China
8	Astronergy/Chint Solar	China
9	First Solar	United States
10	Suntech	China

From Energy Sage

Of the top ten module producers in the world, there are seven Chinese companies (and one that is registered in Canada but manufactures in the PRC).[227] A significant proportion of the solar modules manufactured in the PRC are utilised domestically. The PRC government has set an ambitious target of 25% of the primary energy consumption being supplied by non-fossil-fuel-based energy by 2030.[228] However, 71% of the world's solar modules and 97% of the wafers that go in all of the world's modules are manufactured by Chinese corporations.[229] Nonetheless, Chinese solar companies export and often distribute their panels through their own international subsidiaries.[230] Many of them have international offices and even manufacturing plants. Because they export to their own subsidiaries, their customers are a bit more difficult to identify. However, based on corporate disclosures, it is clear that energy companies, developers, governments, and individual consumers have been buying solar panels that are at high risk of being at the end of a supply chain tainted by forced labour in the Uyghur Region.

JinkoSolar Holdings Company

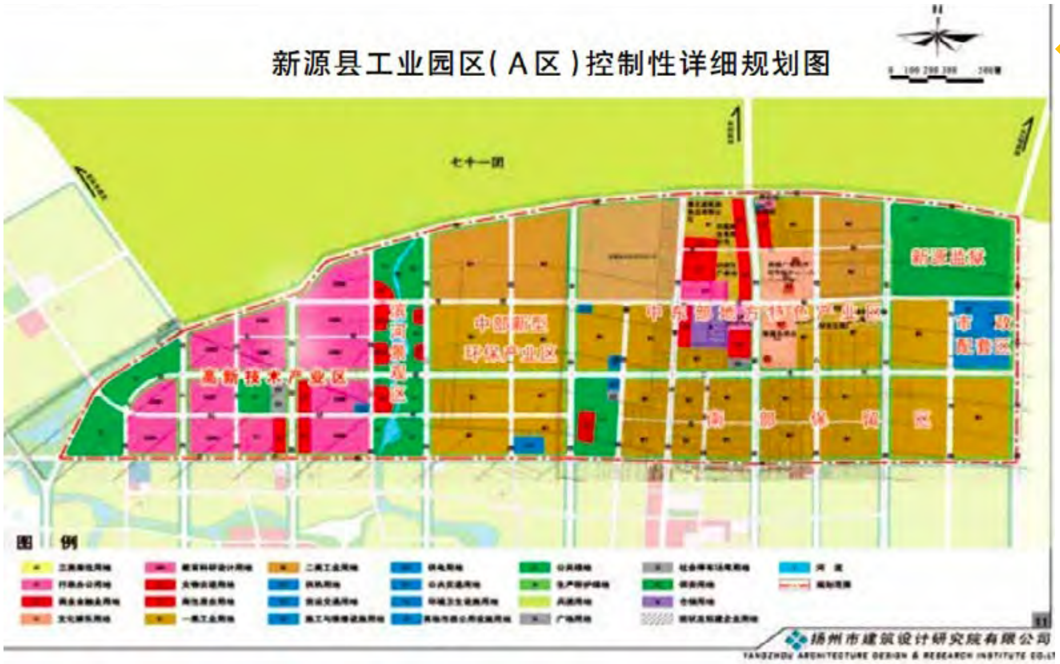
JinkoSolar Company (晶科能源控股有限公司) is one of the world's largest photovoltaic materials manufacturers. It is an international, vertically-integrated company concentrating on research and development, manufacturing, and sales of photovoltaic products, including wafers, cells, and modules. According to corporate reports, JinkoSolar held 12.6% of the global market share in solar modules in 2019.[231] JinkoSolar produces 42% of its ingots and the same proportion of its wafers in its XUAR facility.[232] JinkoSolar established its subsidiary in Xinjiang in 2016, just as the mass internment campaign against the Uyghurs and other ethnic minorities was beginning.

Participation in Labour Transfers: In the spring of 2020, Xinjiang JinkoSolar accepted 78 "registered unemployed personnel" from the Kunas County (Chinese: Xinyuan, 新源) government on one-year or longer contracts. Their names and educational levels, ranging from junior high to undergraduate, were publicly listed, suggesting that the company's employee requirements are not limited to highly skilled or educated technicians. According to a Kunas County government press release on the transfer, the recruits were given CNY 1,000 state subsidies to work at JinkoSolar.[233] In July 2020, Xinjiang JinkoSolar was awarded further subsidies for "accepting forty poor labourers from southern Xinjiang."[234] 2020 may not have been the earliest Xinjiang JinkoSolar received labour transfers; the relatively small Xinyuan Industrial Park in which JinkoSolar is located brought in rural surplus labourers starting at least as early as 2018.[235]

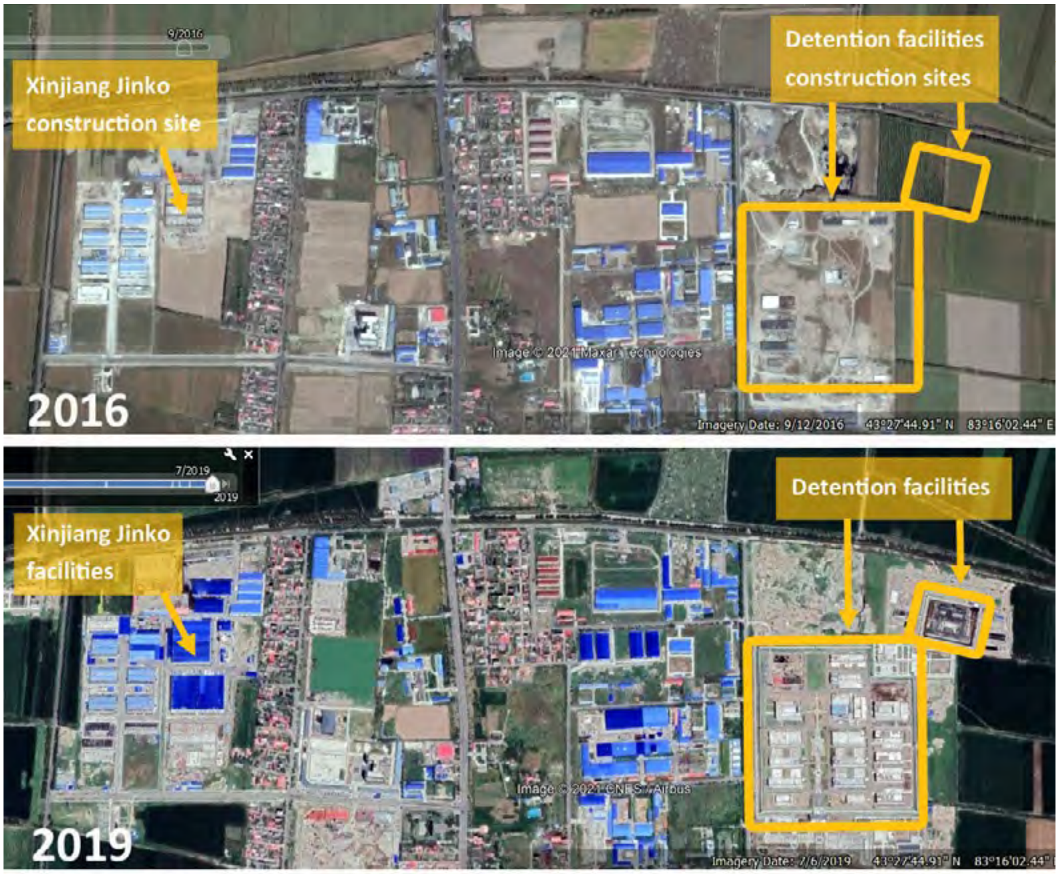
According to media reports, 54% of JinkoSolar's employees at its Kunas plant are ethnic minorities from the local area, including former farmers and herdsmen.[236] It is unclear how many of the workers are recruited through state-sponsored labour programmes, but it is clear from the above that at least some of its workers are. This is also interesting in light of claims that only highly skilled and highly educated workers are capable of working in polysilicon plants.

Co-Location with Detention Centre and Prison: Another potential issue for JinkoSolar is the fact that the company invested CNY 3 billion in the Xinyuan Industrial Park,[237] which houses the JinkoSolar factory complex as well as a high-security prison (identified by industrial park documents) and an internment camp (identified by ASPI).[238] This facility was by far the largest the company owned in the world at over 165,000 square meters, until they built the Leshan, Sichuan ingot production facility in 2019.[239] Historical satellite imagery from Google Earth reveal that at the same time as JinkoSolar's silicon ingot facilities were being built, the prison and detention centre were being built in the same industrial park, merely one and a half miles away. According to the early plans for the park, there are also local craft, textiles, agricultural and food factories across the street from the detention centre.[240] In 2015, the Kunas government invested CNY 400 million in building the high-security prison and CNY 3 million for a fund to reward citizens and employees who inform on others who undermine social "stability."[241] The prison appears to have opened in late 2017 using personnel from Urumqi.[242] There is no conclusive evidence that either the internment camp or prison provide labour for JinkoSolar, but because some companies co-located in industrial parks with camps have utilized forced labour of detainees (see introduction), JinkoSolar's co-location represents a heightened risk.

Supplier Exposures: JinkoSolar is also exposed to forced labour in its supply chain. According to Daqo's 2020 and 2021 corporate filings, JinkoSolar is its second largest customer.[243] In September 2019, Daqo signed a purchasing agreement with JinkoSolar through December 2022.[244] Xinjiang Daqo's 2021 IPO prospectus indicates that at least through 2020, Daqo supplied not only Xinjiang Jinko but also JinkoSolar's Sichuan subsidiary and JinkoSolar in Jianxi.[245] Because 100% of Daqo's polysilicon is produced in the Uyghur Region, and its direct suppliers are implicated in labour transfers, this is a significant exposure for JinkoSolar.



Schematic for Xinyuan Industrial Park. JinkoSolar facilities in pink on the left. Note site of Xinyuan Prison (新源监狱) is marked in green in top right corner. The blue box below the prison is designated for the Municipal Supporting Facilities Area (市政配套区). Source: Xinyuan Investment Guide.



Xinyuan Industrial Park Site 2016, 2019. Source: Google Earth Pro

Potentially Affected Supply Chain: Because JinkoSolar largely distributes its products through its own distributors, it is necessary to look at their corporate disclosures alone to ascertain which companies might be sourcing modules from JinkoSolar. In JinkoSolar's 2019 and 2020 annual reports, the company indicated that the following international companies were their most significant customers: Vivint Solar (US),[246] CIMIC Group (AU), Consolidated Edison (US), Consolidated Electrical Distributors (US), Copenhagen Infrastructure Partners K/S (DK), Decmil Group (AU), Elecnor SA (ES), Enel SpA (IT), Engie SA (FR), Fuji Electric Co (JP), Green Light Contractors Pty (AU), Henan Senyuan Electric Co (CN), Hengtong Optic-electric Co (CN), Innotech Corp (JP), Jiawei Renewable Energy Co (CN), Kenya Electricity Generating Co PLC (KE), MAONENG Group (AU), Metka-Egn (GB),[247] MVV Energie AG (DE), NextEra Energy (US), Sungrow Power Supply Co (CN), Swinerton Builders (US),[248] and Sustainable Power Group (US).[249]

LONGi Green Energy Technology Company

LONGi Green Energy Technology Company (隆基绿能科技股份有限公司) is mainly engaged in the research and design, production and sales of monocrystalline silicon ingots, silicon wafers, cells and modules.[250] It is the world's largest monocrystalline wafer producer, and when it expanded in 2019, became the world's largest solar module manufacturer.[251]

LONGi's production facilities are located across the PRC, but the company does not manufacture in the Uyghur Region. It does run solar power generation plants in the XUAR, however. LONGi does engage in "poverty alleviation" programmes in the Uyghur Region, but, as far as records reviewed for this report show, its poverty alleviation efforts generate power for the grid in that region and are not involved in any identified labour transfers.[252]

Supplier Exposure: LONGi is a customer of many of the polysilicon companies that are engaged in labour transfers in the Uyghur Region. In a deal brokered in early 2021, LONGi agreed to procure polysilicon from GCL-Poly for all of its seven monocrystalline ingot/wafer subsidiaries from March 2021 through 2023.[253] In late 2020, LONGi signed an agreement to purchase 270,000 tonnes of polysilicon from Xinte through 2025. LONGi also has a purchasing agreement with Daqo for 112,000 tons of polysilicon that lasts through December 2022.[254] In 2019, LONGi awarded Daqo with a "Strategic Partner Award," celebrating that it is one of Daqo's largest customers.[255] LONGi also has a long-term purchasing relationship with Asia Silicon, and in late 2020 signed a five-year agreement to purchase nearly 125,000 MT of polysilicon from that company through 2025.[256]

Relationship with the XPCC: Xian LONGi Clean Energy Co., Ltd has three solar energy generation plants in the Liushuquan Farm (Willow Springs Farm) of the 13th Division of the Kumul (Chinese: Hami 哈密) Xuanli Division of the Xinjiang Production and Construction Corps.[257] LONGi's Liurui New Energy Development Co., Ltd. (哈密柳瑞新能源开发有限公司) is also located in that park.

Potentially Affected Supply Chain: U.S. Customs records accessed via ImportGenius suggest that LONGi mainly ships directly to its own international distributors. Customs records also indicate that the company ships to a transport company called Amass International, as well as a Texas company called FC Felhaber. LONGi also recently announced that they sent a large shipment of modules to the Southhampton port in the United Kingdom, but it is unknown who the end customer for those panels will be.[258] Solar Supplies UK, Plug-inSolar, and Segen sell LONGi's modules online.[259] LONGi's 2020 half-year report includes the following companies as customers: Vina Cell (CN/VN), Shanghai EZ New Energy Technology Co, Ltd., Taizhou Zhonglai Optoelectronics Tech Co, and Jiangsu Runergy Photovoltaic Technology Co., Ltd.[260] LONGi also brokered a three-year deal to be a supplier to Astronergy. [261] A 2019 news report announced a LONGi deal with Sunnova (US).[262] LONGi also has a long-standing relationship with Tongwei, as described in the chapter above.

Trina Solar Energy Company

Trina Solar Company (天合光能股份有限公司) is a multinational corporation that produces silicon ingots and wafers, cells, and modules.[263] In 2014, Trina Solar began manufacturing photovoltaic modules in Toksun County (Chinese: Tuokexun, 托克逊), Turpan, Xinjiang, where the company invested CNY 180 million in a plant.[264] By January 2021, Cooper Chen noted in PV Magazine that it appears that the little module manufacturing that was happening in the Uyghur Region had been "halted," which would suggest that Trina's Xinjiang plant (the only module manufacturer in the region) may not be operating currently, but Trina's most recent corporate filings do not provide any specific confirmation of that.[265]

Participation in Labour Transfers: In the 2015 announcement of Trina's module production facility in the XUAR, the company explained its hiring strategy, which echoes much of the government labour transfer rhetoric. Trina committed to helping to "solve the employment problem of the local people of all ethnic groups." The company reported that the plant employs more than 150 people, of which "more than 120 local ethnic minority employees have been absorbed."[266] The language of "absorption" is often used to describe labour transfers in the XUAR. It is otherwise unclear to what extent Trina has been involved in labour transfers since its facilities opened and, importantly, since the system of mass internment has been developed.

Supplier Exposure: Trina Solar is primarily exposed to forced labour through its supplier, Daqo. Trina has a contract to purchase as much as 37,600 tons of polysilicon from Daqo through 2023.[267] Trina is also supplied by other companies with exposure to forced labour, including GCL-Poly, LONGi, Asia Silicon, and Tianjin Zhonghuan. Trina signed an agreement to buy 1.2 billion units of silicon wafers from Tianjin Zhonghuan at the end of 2020.[268] Tianjin Zhonghuan's own supply chain is affected by multiple suppliers reported above who employ labour transfers (see Tianjin Zhonghuan section below).

Relationship with the XPCC: According to Trina's corporate reports, subsidiary Wujiaqiu Energy rents land from the XPCC Sixth Division 106th Regiment 3rd Company for its Xinjiang corporate offices. [269] It is possible it also receives other subsidies for its operation of power plants in that city, which is governed by the XPCC. Trina's subsidiary Xinjiang Tianyuan Smart Energy Company also has a project in the Camel Circle Industrial Park of the 13th Division of the XPCC.[270]

There is no further indication as to whether the company's other power generation plants are supported by the XPCC. It is possible that the company does receive XPCC support because of the particular cities where its plants are located.

Potentially Affected Supply Chain: In April 2021, the UK Ministry of Defense announced that it had signed a purchasing agreement to install 4,248 Trina Vertex panels as part of Project PROMETHEUS at its Defense School of Transport, Leconfield.[271] SelectSolar, Sunstore, and Segen (among others) sell Trina's modules direct to contractors and consumers online.[272] In its 2020 IPO prospectus, Trina listed the following companies as customers: Xinjiang TBEA,[273] NextEra Energy (US), Sungrow (CN), Enel Green Power North America (US), Enviromena Power Systems (UAE), JGC Corporation (JP), X-ELIO Energy, S.L. (ES), Ortiz Energia, S.A. (ES), Greenko Group (IN), TOYO Engineering (JP), Hero Future Energies (IN),[274] WEG S.A. (BR), Greening Components B.V. (NE), BayWa r.e Renewable Energy GmbH (DE), Aldo Componentes Eletronicos Ltda (BR), Marubeni Corporation (JP), Sol Distribution Pty Ltd. (AU), Changzhou Shengping Photovoltaic Technology Co., Ltd. (CN), Sonepar Group (FR), IBC SOLAR AG (DE),[275] China DaTang Co. Ltd. (CN), Changjiang Huasheng Energy (CN), Saving Service Co., Ltd. (CN), Scatec Solar (NO), Solar City (subsidiary of Tesla, US), Downer Utilities Australia Pty Ltd. (AU), Cypress Creek Holdings (US), Zhejiang Energy Group Co., Ltd. (CN),[276] Hero Solar Energy Private Ltd. (IN), Niagara Renewable Energy Ltd. (CA), and COBRA Infraestructuras Internacional, S.A. (ES).[277] Newcomer Matrix Renewables (ES) has brokered a significant deal with Trina that runs through at least 2022.[278]

JA Solar Holdings Company

JA Solar Holdings Company (上海晶澳) manufactures silicon wafers, solar cells and solar modules.[279] The company is in a multi-year process of significantly expanding wafer production capacity.[280] JA Solar does not have any solar module manufacturing facilities in the Uyghur Region, and it does not appear to directly participate in any Xinjiang government "poverty alleviation" or surplus labour programmes. However, the company does have a long-term lease with the XPCC for land that JA Solar operates power generation plants on.

Supply Chain Exposures: JA Solar's most significant exposure to forced labour in Xinjiang is through suppliers Daqo, Xinte, and GCL-Poly. In September 2020, JA Solar agreed to buy 97,000 tons of polysilicon from Xinte through December 2025.[281] In December 2020, JA Solar agreed to buy up to 43,000 tons of polysilicon from Daqo.[282] A JA Solar report indicates that GCL-Poly is a supplier.[283]

Relationship with the XPCC: JA Solar runs several power generation plants in the XUAR (Beitun Haitianda Photovoltaic Power Generation Co., Ltd and Beitun Haitianda Photovoltaic Power Generation 184th Mission Branch) that operate in the 184th Regiment of the 10th Division of the XPCC. They have a lease with the XPCC through December 2040.[284] In April 2020, JA Solar created a new subsidiary, Tiemenguan JA Solar Co., Ltd., which is located in the XPCC's Tiemenguan city, where it operates a power station. It is possible that the XPCC provides other subsidies for the power plants.

Potentially Affected Supply Chain: ImportGenius/U.S. Customs records indicate that JA Solar mainly ships directly to its own subsidiaries and distributors in the United States, which makes it difficult to know precisely which international companies' supply chains are at heightened risk. Customs records indicate that JA Solar ships directly to a company in the Dominican Republic, Escala Solar Energias Renovables. JA Solar's recent corporate filings indicate that the company primarily supplies other Chinese solar companies, but it also reports selling to Acciona SA (ES),[285] Exel Solar SAPI de CV (MX),[286] Acciona Energie Chile (CL), Cypress Creek EPC (US), Iberdrola SA (ES), and the PRC's Sungrow, which has international distribution.[287]

Other Potentially Exposed Module Manufacturers Operating in the PRC

Tianjin Zhonghuan Semiconductor Company (天津中环半导体股份有限公司) is a state-owned manufacturer of silicon ingots and wafers. Tianjin Zhonghuan owns a 27% stake in Xinjiang GCL and purchased CNY 900 million of "new energy materials" (likely polysilicon) from them in 2019.[288] Additionally, Zhonghuan's subsidiary signed a purchasing agreement with GCL-Poly for 350,000 tons of granular polysilicon materials from GCL's subsidiary Jiangsu Zhongneng in Xuzhou and its future plant in Leshan through 2026.[289] Zhonghuan also has a purchasing agreement with Daqo through 2024.[290] Zhonghuan is a "long-term partner" of French oil and gas company Total's subsidiary SunPower (US) and has recently taken a minority share (28.8%) of Maxeon Technologies (US).[291] Its annual reports do not indicate customers, so it is difficult to know how this affects the downstream solar supply chain.

Qinghai Gaojing Solar Energy Technology Company (青海高景太阳能科技有限公司) is a newcomer to the wafer production sector. As the company is currently still under construction, and they are located outside the Uyghur Region, they had the opportunity to operate with low risk of exposure to forced labour in the Uyghur Region. However, in March 2021, Gaojing signed two contracts that put it in the direct XUAR supply chain, one with Xinte and the other with Daqo.[292] It is unclear who Gaojing's customers are at this time.

Canadian Solar (阿特斯阳光电力集团) is a vertically-integrated manufacturer that produces ingots, wafers, cells, and modules in its manufacturing facilities across Asia and the Americas and develops solar farms around the world.[293] Canadian Solar owns U.S. energy developer Recurrent.[294] While the company is a registered Canadian business, with headquarters in Guelph, Canadian Solar modules are largely manufactured in the PRC, including in the company's original and largest plant in Suzhou.[295] Canadian Solar's primary exposure to forced labour in the Uyghur Region is through supplier GCL-Poly. Canadian Solar has a joint venture with GCL-Poly on a solar cell production facility in Jiangsu, which may be affected if that facility is importing polysilicon from the GCL subsidiary in Xinjiang.[296] Canadian Solar operates a solar power generation facility in the XPCC 3rd Division city of Tumxuk (Chinese: Tumushuke 图木舒克), Xinjiang, and likely benefits from that relationship with the XPCC. In December of 2013, the XPCC approved a plan to fix high prices for electricity provided by 29 new photovoltaic plants, and Canadian Solar may have benefited from the plan.[297] U.S. Customs records indicate that Canadian Solar mainly ships directly to their own distributor/subsidiary in the United States. They also ship to a Puerto Rican company, Power Solar LLC, as well as a Texas company, FC Felhaber.[298]

Risen Energy Company (东方日升新能源股份有限公司) primarily produces photovoltaic cells and modules. Risen also develops and builds solar energy generation facilities worldwide, including in the United States, European Union, India, Latin America, Australia, and Asia.[299] In 2020, Risen purchased a polysilicon manufacturing plant in Inner Mongolia, initiating the company's entry into the polysilicon production business.[300] Risen has no known direct investments in Xinjiang, nor is there any evidence of employing forced labour in its manufacturing. Nonetheless, Risen Energy's supply chain is potentially affected by their relationship with Wuxi Shangji Automation Co. Risen Energy has a three-year contract to purchase silicon wafers from Wuxi Shangji,[301] who purchases polysilicon from Daqo, Xinte, and GCL-Poly. Risen struck a deal to provide modules to Tokai Engineering M Sdn Bhd. of Malaysia in Spring 2020 and to Asia Pacific renewables company UPC-AC Energy SA in fall 2020.[302] They reported a shipment of modules to Malaysia-based Armani Energy Sdn Bhd in early 2021.[303]

Astronergy/Chint Solar (正泰新能源) Astronergy is supplied by GCL-Poly[304] and LONGi,[305] both of whom represent high risk of forced labour in their supply chains. There is no discernable evidence that Chint Solar itself participates in any labour transfer programmes.

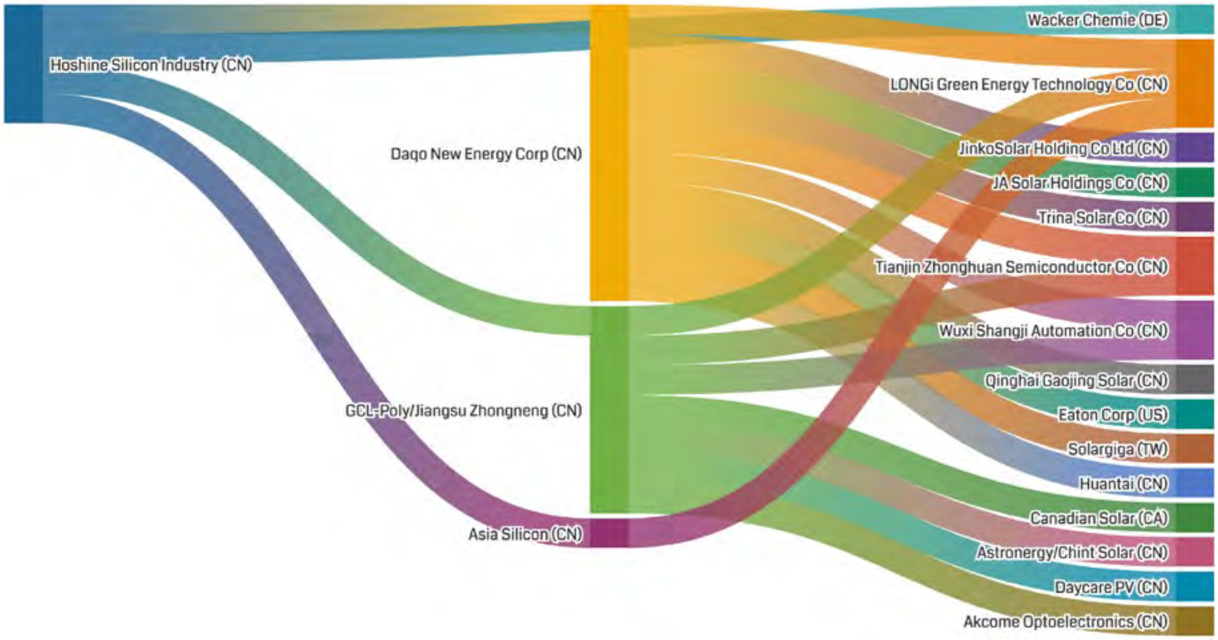
Wuxi Suntech Power Company (无锡尚德太阳能电力有限公司) was an early leader in Chinese photovoltaic module manufacturing. It has not been a significant exporter in recent years, but it is still in operation. Suntech manufactures solar cells and modules. The company has built solar power generation farms in the United States, United Kingdom, Europe, India, Yemen, Brazil, Thailand, and Kazakhstan.[306] In 2008, Suntech established a subsidiary in Xinjiang, Xinjiang Suntech Energy Engineering Co., Ltd.[307] It is focused on power generation plants and engineering. The company does not manufacture solar modules for domestic or export use in its Xinjiang subsidiary. We have located no evidence that Suntech is engaged in forced labour in any direct way, including in its power plants in Xinjiang. It is possible that these plants receive subsidies from the government, but there is little record of Suntech's finances nor is there much in the way of corporate filings that would allow a sound determination. Given this lack of information, no clear determination can be made.

Implications

The pervasive impact of Xinjiang labour transfers on the solar supply chain is made evident when examining Chinese module manufacturers. Nearly every major Chinese end product manufacturer in the industry has a stake in Xinjiang, whether through their investments in solar energy power plants or through their suppliers. With two major international manufacturers – JinkoSolar and Trina Solar – operating potentially compromised bases within Xinjiang and with the significant evidence of forced labour transfers throughout the supply chain, the vast majority of the PRC solar supply chain is at very high risk of being tainted by forced labour in the Uyghur Region.

The final section of this report suggests some alternatives available and on the horizon.

5. CONCLUSIONS & FUTURES

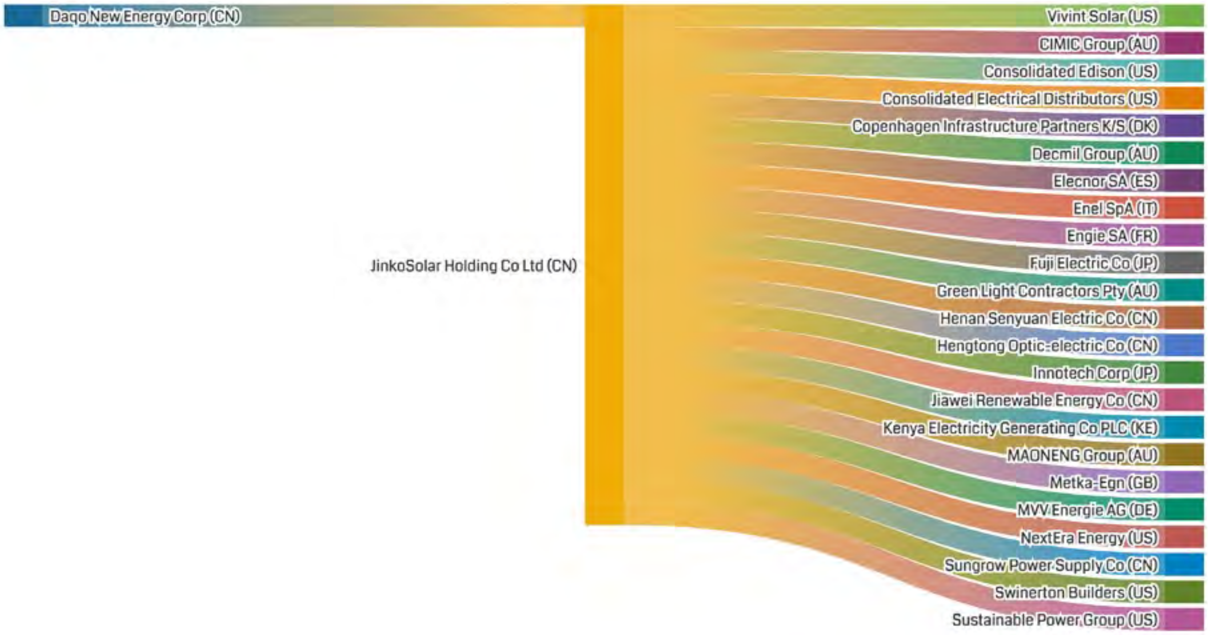


Hoshine Silicon Industry's downstream customers

A mapping of Hoshine's confirmed downstream supply chain alone begins to give us a sense of how significant the effects of Xinjiang forced labour are on the international solar market. Hoshine has indicated in its own corporate filings that it supplies polysilicon manufacturers Daqo, Jiangsu Zhongneng (a subsidiary of GCL-Poly), Asia Silicon, and Wacker. Daqo alone supplies all four of the solar module manufacturers with the largest market share in 2019 – LONGi, JinkoSolar, JA Solar, and Trina Solar.[308] The fifth, seventh, and eighth ranked module manufacturers – Canadian Solar, Risen, and Astronergy/Chint – all also have a risk of labour transfers in their supply chains.

The downstream companies that are potentially affected by forced labour span the globe (see the Supply Chain Exposures table at the end of this report). JinkoSolar's connection to Daqo alone and its own engagement in labour transfer programmes affect end users globally. A review of JinkoSolar's confirmed recent contracts is indicative of the potential global exposure to Xinjiang forced labour.

With the recent call to action and due diligence protocol released by the Solar Energy Industries Association designed to "ensure the solar supply chain does not include abhorrent forced labour practices,"[309] this issue has garnered significant attention within the industry. The call to action has been signed by 245 solar industry companies as of the end of March 2021,[310] which suggests a nearly industry-wide commitment to addressing the problems reported in this study.[311] Signatories include JinkoSolar, LONGi, JA Solar, and Trina Solar, all of whom would have to make significant



Daqo New Energy > JinkoSolar downstream customers

changes to adhere to their commitment to ensure that they are not purchasing raw materials made with Xinjiang forced labour or participating in labour transfers themselves. In addition to the companies that have publicly announced contracts with the suppliers employing forced labour programmes in Xinjiang, there are scores more that have signed on to the SEIA pledge and may yet be exposed through relationships with suppliers that we have not identified here. The work to identify all affected companies in the solar supply chain will be an arduous task, but it is not at all impossible. This report is intended to assist in that process.

While Xinjiang-made raw materials and polysilicon dominate the market, there are alternatives. Polysilicon market analyst Johannes Bernreuter reminds us that while Xinjiang accounts for 45% of the world's solar-grade polysilicon supply, 35% more of it comes from other regions of China, and 20% from outside of China. [312] Experts agree that this is enough to supply the United States and Europe's needs for solar modules.[313] However, this does not account for the companies in the interior of China and internationally whose supply chains are likely affected by manufacturing in the Uyghur Region, especially those whose supply chains reach back to Hoshine. The extent to which Xinjiang metallurgical-grade silicon and polysilicon pervades the market means that module manufacturers that want to avoid producing goods that are potentially tainted by forced labour in Xinjiang will have to scrutinise their supply chains thoroughly, all the way to the raw quartz materials, to determine if they are produced with forced labour or blended with affected materials. They will have to demand that the polysilicon that goes into the manufacture of their wafers is not sourced from companies engaged in forced labour transfers. This effectively leaves only a few Chinese alternatives with no confirmed exposure to forced labour in the Uyghur Region.

As the United States ponders the Uyghur Forced Labour Prevention Act, locating alternatives to Xinjiang-sourced solar energy products becomes increasingly critical – not only for U.S. manufacturers and retailers but also for those other global markets where U.S. sanctions could mean Xinjiang-made goods head their way. Bernreuter predicted in March that "what will likely happen is this: Wafer manufacturers, who usually blend polysilicon volumes from different suppliers, will exclude feedstock from Xinjiang from the mix for part of their production in order to offer ‘Xinjiang-free’ wafers. Those can then be used for solar cells and modules destined for export to the U.S.; European customers will probably demand products untainted by forced labour as well.”[314]

Indeed, in February 2021, JinkoSolar announced that the company had “already undertaken necessary steps to ensure” that their products sold in the United States would not be made of products produced in whole or in part in Xinjiang. However, S&P Global reported that in JinkoSolar’s SEC filings the company noted that “some products it sells into the U.S. could contain material from Xinjiang, adding that it ‘may’ reconfigure its supply chains if Washington enacts tight trade restrictions on the region.”[315] JinkoSolar did not indicate how this shift in shipments would affect its other international customers. Presumably, the Xinjiang-originated products would go to markets other than the United States if the legislature enacted a law prohibiting those products and JinkoSolar complied.

The alternatives to Xinjiang-sourced metallurgical-grade silicon and solar-grade polysilicon seem to be contracting in some places and expanding in others in recent months, but the industry could see a significant expansion if there is increased demand from consumers, manufacturers, or governments.

Expansion of Chinese Production Beyond Xinjiang

Perhaps pre-empting legislative mandates, in November of 2020, JinkoSolar signed a contract with Tongwei to purchase 93,000 metric tons of polysilicon, which is not produced in Xinjiang and has a decreased risk of including metallurgical-grade silicon from Xinjiang, though blending is always a possibility.[316] If Tongwei expands as expected, it will be in a position to meet significant demand for non-Xinjiang polysilicon,[317] but Tongwei’s relationships with LONGi and others will require some scrutiny to ensure that its cells are not produced with polysilicon that is blended with the materials coming from Xinjiang.

Chinese manufacturers seem to be turning toward Inner Mongolia for expansion of their raw materials mining and processing and for polysilicon production. JA Solar is investing significantly in the expansion of its Baotou, Inner Mongolia wafer-production subsidiary.[318] In February 2021, TBEA announced plans for Xinte to create one of the world’s largest polysilicon plants in Baotou as well.[319] This could potentially represent an alternative to TBEA’s Xinjiang polysilicon.[320] However, the Baotou site is unlikely to be completed soon enough to meet short-term demand spurred by shifting supply chains out of the Uyghur Region, so this is not currently a viable alternative to TBEA’s Xinjiang operations. Furthermore, it would be important to monitor rights abuses in Inner Mongolia, as recent reports have pointed to government policies aimed at ethnic assimilation in the region and experts are concerned about the potential for increased repression, given the precedents in Xinjiang and Tibet.[321]

Global Alternatives

Hanwha Q CELLS is a manufacturer of solar cells and modules for the international market whose affiliate, Hanwha Solutions [formerly Hanwha Chemical], previously manufactured polysilicon as well. Hanwha closed its polysilicon manufacturing base in 2020, due to non-competitive electricity costs. Hanwha has no known facilities or direct ties to Xinjiang or to the XPCC. It is unclear who is currently supplying Hanwha; we were unable to find any listing of its suppliers. Hanwha has not released details on its plans in response to the Solar Energy Industries Association’s call to action, though it is a signatory. Given the anxieties about forced labour in the Xinjiang-based polysilicon manufacturing sector and Korea’s stringent carbon emissions policies for green energy, Korean manufacturer Hanwha may be looking outside China for its supply.

OCI is a chemical company that manufactures polysilicon and operates in Korea, China, Malaysia, the Philippines, Vietnam, and the United States. After the closure of its polysilicon manufacturing base in Gunsan, Korea, OCI manufactures all of its solar-grade polysilicon in its Malaysia plant.[322] The company owns and operates Mission Solar in San Antonio, Texas, where it manufactures solar panels as well.[323] OCI has no confirmed exposure to forced labour in the Uyghur Region through its subsidiaries. However, Hoshine's response to a query on an online investor forum named OCI as a customer; [324] if that is in fact the case (though we have located no other evidence that it is), then OCI has exposure to forced labour through that supplier. In December 2020, OCI announced a US $55 million debottlenecking of production capacity in its Malaysia polysilicon facility.[325] Malaysia remains an important alternative for low-priced hydropower electricity for the production of polysilicon. In February 2021, LONGi Green Energy recommitted to buying polysilicon from OCI,[326] and while it did have a previous three-year contract with OCI, and thus this is not necessarily a new development, this contract does at least represent an alternative to polysilicon sources in Xinjiang.

American and European manufacturers may present additional options, as they currently account for approximately 15% of polysilicon production globally. Germany's **Wacker Chemie** currently retains the third highest polysilicon manufacturing capacity in the world (though it is on track to lose that placement in the course of the coming year with Daqo's and Xinte's planned expansions); however, if Wacker is indeed purchasing raw materials from Hoshine, that presents a significant forced labour risk. **Hemlock Semiconductor** continues to produce polysilicon, though the company has also reduced its production capacity by half.[327] **REC Silicon** has a closed polysilicon factory that might be brought back online.[328]

Another option might be an alternative to polysilicon-based modules altogether. U.S.-based **First Solar** is ranked ninth among module manufacturers and is not exposed to Xinjiang polysilicon because the company uses thin film technology which does not require polysilicon at all. First Solar has expanded capacity recently and announced that it is considering developing yet another facility, but at this time, solar analyst Chase has reminded the industry that First Solar will not be able to supply the world alone.[329]

If the Uyghur Forced Labour Act is passed or if similar forced labour legislation is passed in other countries, this will put the onus on companies to shift suppliers. Chase suggests consumers "will pay an almost unnoticeable amount more for modules" if module manufacturers refuse Xinjiang polysilicon.[330] Other Chinese suppliers as well as the above listed non-Chinese companies could make up for the loss of the Xinjiang supply. Still, the cost of energy in Korea, the United States, and the European Union is rarely if ever as low as can be supported by the government-subsidised coal industry in Xinjiang. This is what has made Chinese competitors so strong in recent years. Shifting the green energy supply chain out of Xinjiang to avoid human rights abuses could be encouraged by subsidized energy costs for the production of green energy, investments in polysilicon and wafer production facilities outside of China, and acceptance of slightly higher prices for new energy solutions.

Moving away from forced-labour-tainted polysilicon may spur innovation as well. Such a shift in the supply chain may even provide an impetus for further work on more efficient processes, which has already advanced significantly in recent years. It might also encourage the development of alternatives to polysilicon in the manufacture of modules.[331] An emphasis on lower carbon impact may also work hand-in-hand with calls to excise forced labour from the supply chain, as the two are intertwined in the Xinjiang region.[332]

Extracting forced labour from the solar supply chain may seem complicated and may come at a cost to manufacturers and customers. However, as this report indicates, the solar supply chain is relatively easy to map, and identifying forced labour exposure in Xinjiang is less of a challenge than in industries such as textiles or agriculture. And doing so is critical, as it would not only address the forced labour issue in Xinjiang but would also substantially reduce the carbon emissions of the solar industry. From a human rights and climate perspective, the alternative of basing our green energy future on coal's high carbon emissions and on the forced labour of oppressed communities is a higher and longer-term price to pay.

APPENDIX A: FORCED LABOUR EXPOSURES

Corporate responses to requests for comment will be included in an appendix available on the website for this report.

Raw Materials

COMPANY	XINJIANG MANUFACTURING LOCATION	FORCED LABOR EXPOSURE	CAMP CO-LOCATION	XPCC RELATIONSHIP	CURRENT OR RECENT DOWNSTREAM CONTRACTS*
Xinjiang Hoshine Silicon Industry Co./ Hesheng 新疆合盛硅业有限公司	Raw materials facility	Labour transfers	Within 6 miles, where likely suppliers are co-located	Significant subsidies, located in XPCC industrial park	Daqo, Asia Silicon, GCL-Poly/ Jiangsu Zhongneng, Wacker Chemie
Xinjiang Sokesi New Material Co. 新疆索科斯新材料有限公司	Raw materials facility	Labour transfers	Unknown	None known	Daqo
Changji Jisheng New Building Materials Co. 昌吉吉盛新型建材有限公司	Raw materials facility	Labour transfers	Unknown	None known	
Xinjiang China Silicon Technology Co./ Xinjiang Zhonggui 新疆中硅科技有限公司	Raw materials facility	Labour transfers to industrial park, job fair	Unknown	Yes, direct beneficiary, located in XPCC industrial park	Unknown
Xinjiang Jingweike New Energy Development Co. 新疆晶维克新能源发展有限公司	Raw materials facility in XPCC park	Labour transfers (job fair)	Unknown	Has joint venture with XPCC	Unknown
Xinjiang Jingxin Silicon Industry Co. 新疆晶鑫硅业有限公司	Raw materials facility	Labour transfers	Unknown	Has joint venture with XPCC	Unknown
Xinjiang Yusi Technology Co./Yu Silicon 新疆宇硅科技有限公司	Raw materials facility in XPCC park	Labour transfers to industrial park	Unknown	Yes, direct beneficiary, located in XPCC industrial park	Unknown
Xinjiang Jiagesen New Energy Materials Co., Ltd. 新疆嘉格森新能源材料股份有限公司	Raw materials facility	Labour transfers to industrial park	Unknown	Yes, direct beneficiary, located in XPCC industrial park	Unknown

COMPANY	XINJIANG MANUFACTURING LOCATION	FORCED LABOR EXPOSURE	CAMP CO-LOCATION	XPCC RELATIONSHIP	CURRENT OR RECENT DOWNSTREAM CONTRACTS*
Xinjiang Guopeng Technology Co. 新疆国鹏科技有限公司	Raw materials facility	Labour transfers to industrial park	Unknown	Yes, direct beneficiary, located in XPCC industrial park	Asia Silicon
Xinjiang Xintao Silicon Industry Co. 新疆鑫涛硅业有限公司	Raw materials facility	Likely labour transfers	Unknown	XPCC was a shareholder until 2019	Xinte, Beijing Zelin, Qinghai Baitong, Xuzhou Zhengxu Silicon Material, Shanghai Chaojin
Beijing Dadi Zelin Silicon Industry Co. 北京大地泽林硅业有限公司	Raw materials facility	Labour transfers to industrial park	In park adjacent to possibly not-yet-finished camp, prison, and detention centre	Unknown	Asia Silicon Daqo (until 2020)

Polysilicon

COMPANY	XINJIANG MANUFACTURING LOCATION	FORCED LABOR EXPOSURE	CAMP CO-LOCATION	XPCC RELATIONSHIP	CURRENT OR RECENT DOWNSTREAM CONTRACTS*
Daqo New Energy Corp 大全新能源股份有限公司	Polysilicon facility	Labour transfers, in immediate supply chain	None	Direct beneficiary	LONGi, JinkoSolar, JA Solar, Trina Solar, Tianjin Zhonghuan, Wuxi Shangji, Qinghai Gaojing, Eaton Corp, Sunshine/Solargiga, Huantai
GCL-Poly 保利协鑫能源控股有限公司	Polysilicon facility	Labour transfers, in immediate supply chain	None	Direct beneficiary	LONGi, Wuxi Shangji, Tianjin Zhonghuan, Canadian Solar, Astronergy/Chint Solar, Daycare PV, Akcome Optoelectronics
TBEA/Xinte 特变电工/ 新特能源公司	Polysilicon facility	Labour transfers, corporate participation in rural “poverty alleviation,” possible in supply chain	None	Strategic cooperative agreement	LONGi, JA Solar, Qinghai Gaojing, Beijing Jingyuntong, Wuxi Shangji
East Hope Group 东方希望	Polysilicon facility	Labour transfers	None	Unknown	Unknown
Tongwei Solar Company 通威股份	None	Possible in supply chain	None	None known	JinkoSolar Holding, Trina Solar, Tianjin Zhonghuan, Jiangsu/Baotou Mieke, LONGi
Asia Silicon (Qinghai) Company 亚洲硅（青海）有限公司	None	In immediate supply chain	Unknown	Unknown	LONGi

Ingots Wafers, Cells & Modules

COMPANY	XINJIANG MANUFACTURING LOCATION	FORCED LABOR EXPOSURE	CAMP CO-LOCATION	XPCC RELATIONSHIP	CURRENT OR RECENT DOWNSTREAM CONTRACTS*
JinkoSolar Holdings Company 晶科能源控股有限公司	Ingots and wafers	Co-located in park with detention centre and prison, labour transfers, in supply chain	Internment camp and prison in industrial park	None known	Vivint Solar, CIMIC Group; Consolidated Edison, Consolidated Electrical, Copenhagen Infrastructure, Decmil Group, Elecnor SA, Enel SpA, Engie SA, Fuji Electronics, Green Light Contractors, Henan Senyuan, Hengton Optic-Electric, Innotech, Jiawei Renewable, Kenya Electricity Generating Co, MAONENG Group, Metka-Egn, MVV Energie, NextEra, Sungrow, Swinerton Builders, Sustainable Power Group
LONGi Green Energy 隆基绿能科技股份有限公司	None	In supply chain	None	Power generation plants supported by XPCC	Amass Int'l, FC Felhaber, Vina Cell, Shanghai EZ New Energy, Taizhou Zhonglai, Jiangsu Runergy, Sunnova, Tongwei, Astronergy
Trina Solar Energy Company 天合光能股份有限公司	Modules (facility may be closed)	Possible labour transfers in plant, in supply chain	None	Power generation plants may be supported by XPCC	UK Ministry of Defense, Xinjiang TBEA, NextEra, Sungrow, Enel Green Power, Enviromena Power, JGC Corporation, X-ELIO Energy, Ortiz Energia, Greenko Group, TOYO Engineering, Hero Future Energies, WEG S.A. Greening Components, BayWa r.e Renewable Energy, Aldo Componentes Eletronico, Marubeni Corp, Sol Distribution, Changzhou Shengping, Sonepar Group, IBC SOLAR, China DaTang, Changjiang Huasheng, Saving Service Co., Scatec Solar, Solar City, Downer Utilities Australia, Cypress Creek, Zhejiang Energy, Hero Solar Energy, Niagara Renewable Energy, COBRA Infraestructuras, Matrix Renewables
JA Solar Holdings 上海晶澳	None	In supply chain	None	Power generation plants supported by XPCC	Escala Solar Energias Renovables, Cypress Creek, Acciona SA, Acciona Chile, Exel Solar SAPI, Iberdrola SA, Sungrow
Tianjin Zhonghuan Semiconductor 天津中环半导体股份有限公司	27% equity in Xinjiang GCL	Shareholder in Xinjiang GCL, in supply chain	None	None known	SunPower, Maxeon Technologies

COMPANY	XINJIANG MANUFACTURING LOCATION	FORCED LABOR EXPOSURE	CAMP CO-LOCATION	XPCC RELATIONSHIP	CURRENT OR RECENT DOWNSTREAM CONTRACTS*
Qinghai Gaojing Solar Energy Company 青海高景太阳能科技有限公司	None	In supply chain	None	None known	Unknown
Canadian Solar 阿特斯阳光电力集团	None	In supply chain	None	None known	Power Solar LLC, FC Felhaber
Risen Solar 东方日升新能源股份有限公司	None	In supply chain	None	None known	Tokai Engineering M Sdn Bhd., UPC-AC Energy, Armani Energy Sdn Bhd
Astronergy/Chint Solar 正泰新能源	None	In supply chain	None	None known	Unknown
Wuxi Suntech Power Company 无锡尚德太阳能电力有限公	None	Unknown	None	None known	Unknown

* Downstream contracts are not an exhaustive lists of all customers.

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