BATTERY STORAGE FIRE SAFETY ROADMAP

EPRI's Immediate, Near, and Medium-Term Research Priorities to Minimize Fire Risks for Energy Storage Owners and Operators Around the World

July 2021

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EXECUTIVE SUMMARY

This roadmap provides necessary information to support owners, operators, and developers of energy storage in proactively designing, building, operating, and maintaining these systems to minimize fire risk and ensure the safety of the public, operators, and environment.

The investigations described will identify, assess, and address battery storage fire safety issues in order to help avoid safety incidents and loss of property, which have become major challenges to the widespread energy storage deployment. The research topics identified in this roadmap should be addressed to increase battery energy storage system (BESS) safety and reliability. The roadmap processes the findings and lessons learned from eight energy storage site evaluations and meetings with industry experts to build a comprehensive plan for safe BESS deployment.

BACKGROUND

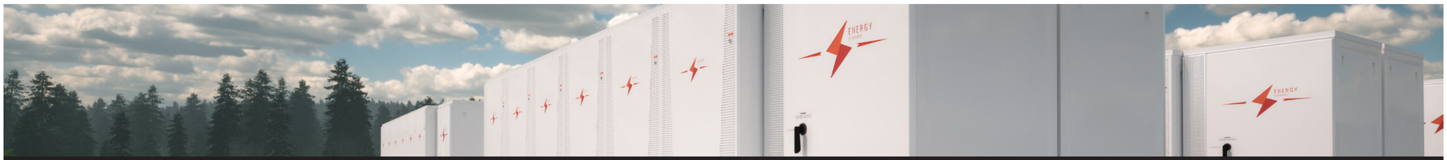
Owners of energy storage need to be sure that they can deploy systems safely. Over a recent 18-month period ending in early 2020, over two dozen large-scale battery energy storage sites around the world had experienced failures that resulted in destructive fires. In total, more than 180 MWh were involved in the fires. For context, Wood Mackenzie, which conducts power and renewable energy research, estimates 17.9 GWh of cumulative battery energy storage capacity was operating globally in that same period, implying that nearly 1 out of every 100 MWh had failed in this way.[1]

For up-to-date public data on energy storage failures, see the EPRI BESS Failure Event Database.[2] The *Energy Storage Integration Council (ESIC) Energy Storage Reference Fire Hazard Mitigation Analysis* (ESIC Reference HMA),[3] illustrates the complexity of achieving safe storage systems. It shows the large number of threats and failure pathways that may lead to the central hazard of thermal runaway as well as the large number of possible mitigations available in the pursuit of safe outcomes. To further compound the difficulty, codes and standards have provided new tools and procedures, but they are still trying to catch up with a fast-growing industry deploying multiple chemistries and exploring a multitude of configurations. How can operators of energy storage be certain that the systems they have deployed or will deploy are safe, considering today's best practices?

1 Wood McKenzie, Energy Storage Data Hub. https://www.woodmac.com/research/products/power-and-renewables/energy-storage-data-hub/

2 https://storagewiki.epri.com/index.php/BESS_Failure_Event_Database.

3 https://www.epri.com/research/products/000000003002017136.



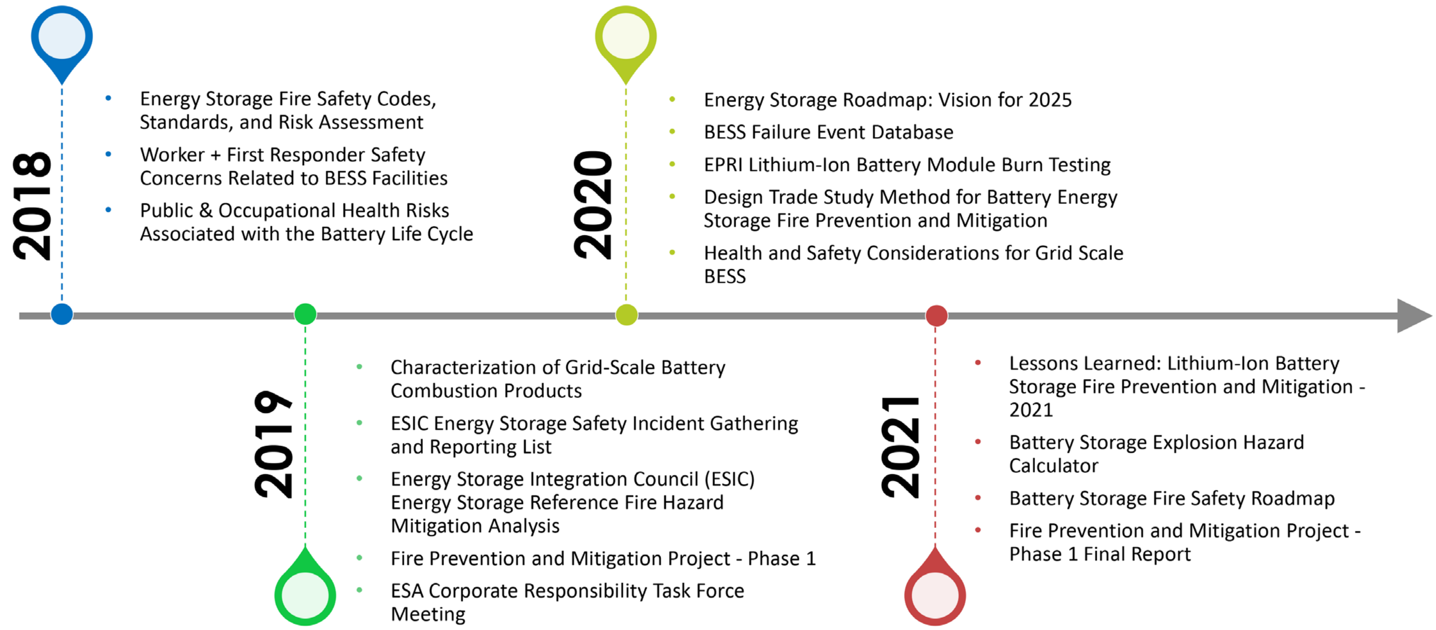


Figure 1 – EPRI energy storage safety research timeline

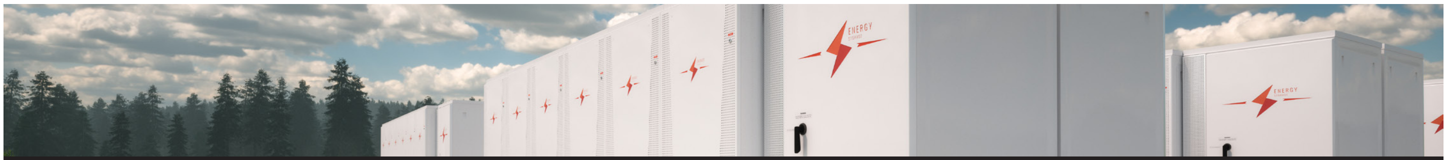
EPRI'S EXPERTISE IN ENERGY STORAGE SAFETY

For several years, EPRI has conducted a significant effort that addresses battery fire safety and related health, safety, and environmental issues. This work, conducted in collaboration with member utilities, battery solution providers, and other stakeholders, has facilitated the development of best practices and standards, with the aim of ensuring that needs for energy storage can be met in a safe and reliable way.

In 2019, EPRI began the Battery Energy Storage Fire Prevention and Mitigation – Phase I research project, convened a group of experts, and conducted a series of energy storage site surveys and industry workshops to identify critical research and development (R&D) needs regarding battery safety. Five utilities deploying the most energy storage in the world joined in the effort and gave EPRI access to their energy storage sites and design data as well as safety procedures and guides. In 2020 and 2021, eight BESS installations were evaluated for fire protection and hazard mitigation using the ESIC Reference HMA.

Each survey included a site review, workshop, and evaluation report comprising the following tasks:

- Site review:
  - Review specifications, design drawings, performance data, and operations and maintenance documentation provided by the site host participant.
  - Document important safety-relevant features (and lack thereof).
- Site workshop:
  - Discuss the Hazard Mitigation Analysis with the site engineering and operations personnel.
  - Document outcomes of the discussion, answering the following questions: Which threats, barriers, and consequences apply to this site? How do they apply? Why do they apply? What recommendations could improve the safety of system operations?
- Site evaluation report:
  - Draft the site evaluation report for member review.
  - Revise and finalize the evaluation report.



At the sites analyzed, system size ranges from 1–8 MWh, and both nickel manganese cobalt (NMC) and lithium iron phosphate (LFP) chemistries are represented. All systems except one are installed in a container or in a dedicated building that functions similarly and appears similar to a container. Six of the eight systems are either 1) installed in locations where all nearby areas have controlled access and are dedicated to the purpose of electrical power production and distribution, or 2) located in extremely remote areas.

For each site, EPRI analyzed safety measures using nine broad categories, as illustrated in Figure 2.

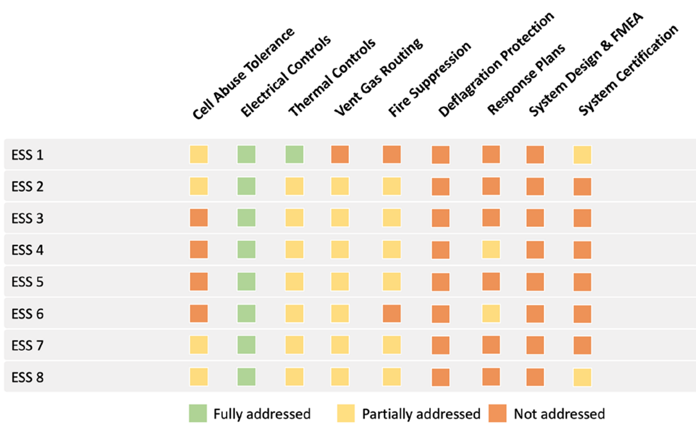


Figure 2 – Summary of system safety barriers at surveyed sites

Electrical controls were found to be the safety measure most commonly present across the eight surveyed sites. Cell abuse tolerance and thermal controls were present, but their level of effectiveness was hard to gauge from the available data. Similarly, it was not possible to assess the level to which system design efforts and failure modes and effects analysis (FMEA) addressed safety. Response plans were another area where there was minimal available data and an indication of insufficient levels of safety.

SAFETY ROADMAP: RESEARCH TOPICS

In order to develop and deploy energy storage safely, many tools and resources are needed. After compiling the results of the industry workshops and site surveys, 22 research topics were identified as industry needs. These have been categorized into four groups: 1) special topics, 2) response plans, 3) design tools, and 4) technology development, as shown in Table 1. A clickable link to the detailed description of each topic is provided in the right column.

Table 1 – Battery Storage Fire Safety Roadmap research topics

Category	Topic	Link
ST: Special Topics	ST1 Addressing the common explosion hazard	ST1
RP: Response Plans	RP1 Response plan guidelines for existing and future BESS	RP1
	RP2 Response plan standardization	RP2
	RP3 Hazard state identification and communication	RP3
	RP4 Contamination management	RP4
DT: Design Tools	DT1 Improving availability and application of 9540A testing	DT1
	DT2 Inclusion of gas prediction and deflagration protection tools in BESS design processes	DT2
	DT3 Expansion of 9540A testing to address statistical variation and multiple cell failures	DT3
	DT4 Guidelines for selection and design of suppression systems	DT4
	DT5 Standardized electrical controls reporting	DT5
	DT6 Failure modes and effects analysis (FMEA) guidance	DT6
	DT7 Integrated system design tools	DT7
	DT8 Adequacy and inclusion of thermal runaway propagation prediction tools in BESS design processes	DT8
TD: Technology Development	TD1 Robust electrical controls	TD1
	TD2 Detection of state of thermal reaction	TD2
	TD3 Detection of future thermal runaway events	TD3
	TD4 Detection of deflagration and toxicity risks	TD4
	TD5 Limitation of propagation using thermal controls	TD5
	TD6 Minimization of thermal runaway using thermal controls	TD6
	TD7 Safe cells with no thermal runaway potential	TD7
	TD8 Thermal runaway vent gas routing management during failure	TD8
	TD9 Ignition control	TD9

These research topics were then evaluated for their relative impact on safety, the effort required to address them, and the time horizon for the work. A graphical representation of the topics was developed for visualization and prioritization. To orient the reader to that overview chart, Figure 3 shows the methodology of representation with estimated potential improvement to safety of a single system (the size of the circle), estimated required effort to complete (Y-axis), and time frame of applicability (X-axis).

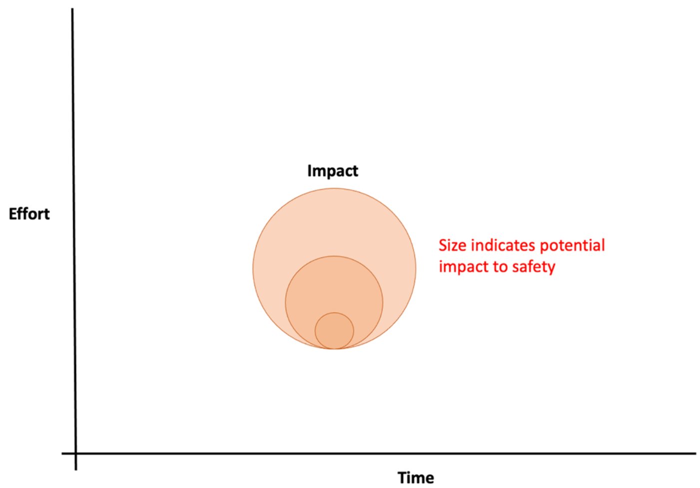


Figure 3 – Orientation guide for overview chart

All topics were plotted using the methodology in Figure 4. Note that the required effort to complete a task can vary largely, depending on who is tasked with the work. For example, select automotive companies that have invested many years in pursuing propagation-resistant lithium ion battery packs may more efficiently complete the task of preventing propagation in stationary systems than BESS integrators just entering the market. Large circles in the lower left corner of the plot represent the best return on investment, as this will significantly impact all existing and future systems for minimal investment.

These battery storage safety topics form the broad landscape of R&D efforts that need to be undertaken to address the safety concerns identified by EPRI's research. The type of effort and engagement required from stakeholders to address those challenges can further be used to determine the actors and organizations best positioned to advance the state of the art.

BATTERY STORAGE FIRE SAFETY ROADMAP: EPRI RESEARCH PRIORITIZATION

The selection and prioritization of these topics for EPRI's planned research have been evaluated based on EPRI's specific role and position within the industry. Some of the identified topics could be beneficially pursued by other organizations such as vendors, original equipment manufacturers (OEMs), Department of Energy (DOE) national laboratories, and other entities.

There are effectively two principal near-term recommendations that have arisen from EPRI's energy storage safety research and roadmapping effort:

- Address the common explosion hazard present in many existing systems.
- Develop the knowledge and tools necessary to conduct improved system-level safety analyses prior to system installation.

Both are attainable in the relatively near term and will provide significant improvements to the safety of present and future storage systems, which will enable continued rapid growth of the industry.

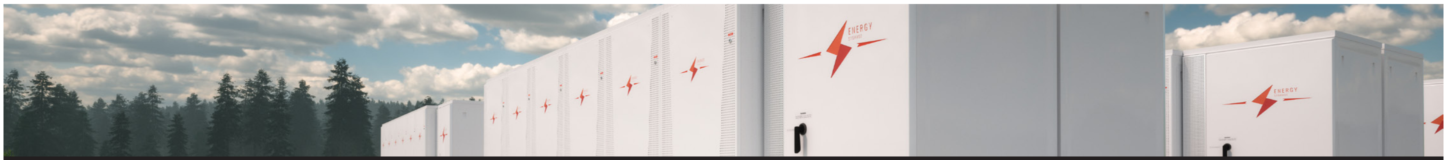
Of the 22 topics, 11 have been identified as priorities for future EPRI research, divided into three groups. The applicable and relevant stakeholders should also pursue further technology development efforts and long-term safety strategies. The EPRI-focused topics are outlined below.

Group 1, Immediate Actions: High-Impact, Low-Effort for Exisitng Systems

The most pressing needs identified in Table 2 in this effort are to address the common deflagration failure mode and poor response plans believed to be present in many energy storage systems operating today. These issues pose an immediate risk to life and property, particularly for first responders, and guidance for rectifying these issues can be developed with relatively little effort. Efforts here will benefit all future installations as well.installations.

Table 2 – Group 1 research topics

Category	Topic	Link
ST: Special Topics	ST1 Addressing the common explosion hazard	ST1
RP: Response Plans	RP1 Response plan guidelines for existing and future BESS	RP1
	RP2 Response plan standardization	RP2
DT: Design Tools	DT1 Improving availability and application of 9540A testing	DT1
	DT2 Inclusion of gas prediction and deflagration protection tools in BESS design processes	DT2



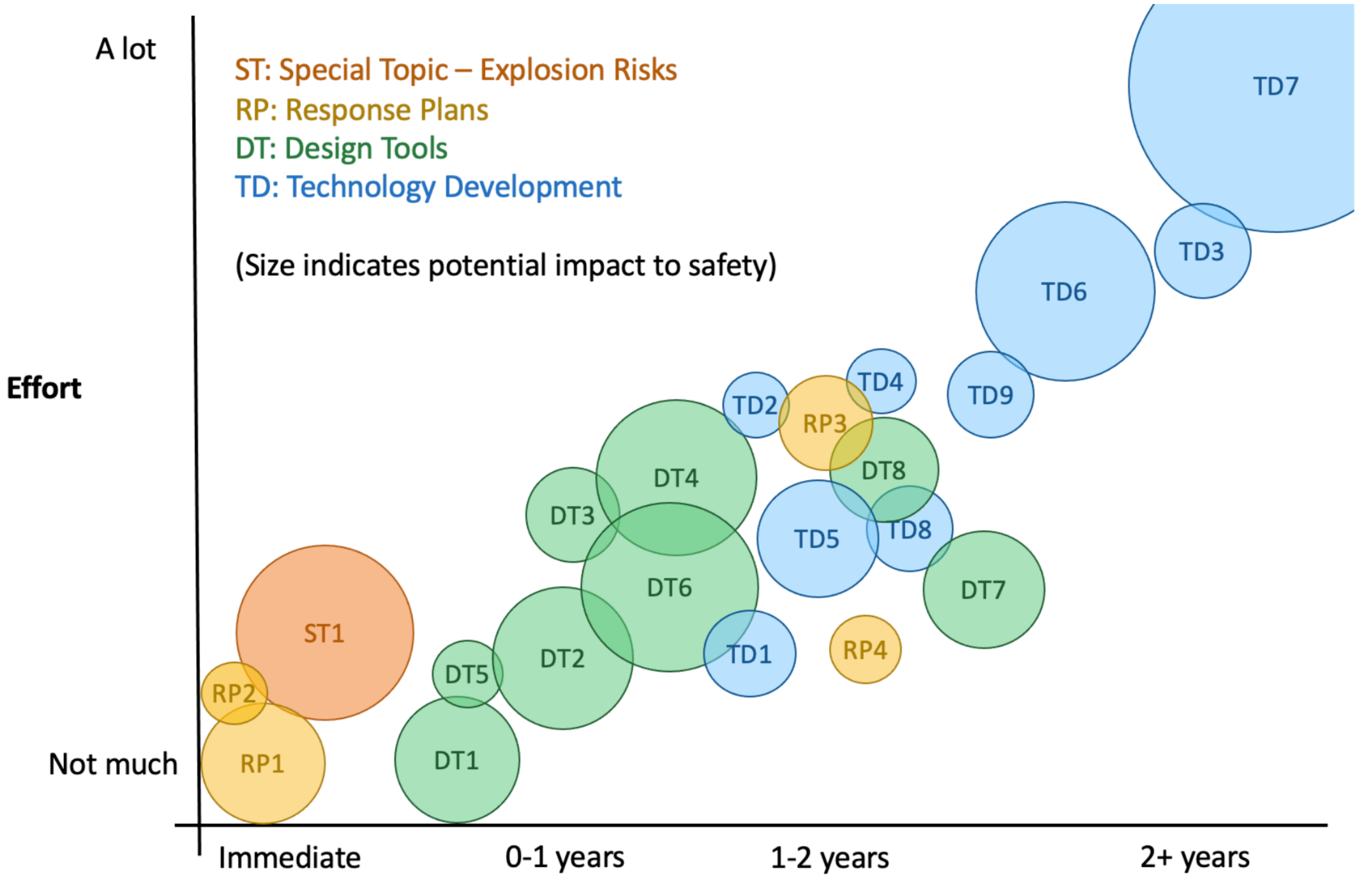


Figure 4 – Battery Storage Fire Safety Roadmap

Group 2, Near-Term Actions: High-Impact, Moderate Effort for Systems in Development

A large number of BESSs are anticipated to be installed in the near future. The medium-effort tasks in Group 2, shown in Table 3, can be completed relatively quickly. They address well-known industry concerns, and their results can be used to improve the safety of the many systems being installed in the near term.

Table 3 – Group 2 research topics

Category	Topic	Link
DT: Design Tools	DT3 Expansion of 9540A testing to address statistical variation and multiple cell failures	DT3
	DT4 Guidelines for selection and design of suppression systems	DT2
TD: Technology Development	TD1 Robust electrical controls	TD1

Group 3, Medium-Term Actions: System Design and Research Guidance for Future Systems

The last group addresses three topics, two of which (FMEA Guidance and Integrated System Design Tools) treat BESS safety from a wholistic systems-level vantage point. This work not only would create direct value by providing these tools to the industry but also could be used for identifying future safety research directions. For example, using the system design and FMEA tools together, research organizations can identify and encourage the safest system configurations, identify presently unknown failure methods, establish high-value barrier opportunities, and then develop targeted future R&D programs.

Table 4 – Group 3 research topics

Category	Topic	Link
DT: Design Tools	DT5 Standardized electrical controls reporting	DT5
	DT6 Failure modes and effects analysis (FMEA) guidance	DT6
	DT7 Integrated system design tools	DT7

Remaining Ungrouped Topics

As shown in Table 5, 11 remaining topics were not chosen for the near-term EPRI roadmap. As noted earlier, these topics are still relevant and could be pursued by vendors, integrators, OEMs, and other government and private entities.

For more information on the roadmap, research groupings, and specific topic details, the full, expanded Battery Storage Fire Safety Roadmap is below in the appendix.

Table 5 – Ungrouped research topics

Category	Topic	Link
RP: Response Plans	RP3 Hazard state identification and communication	RP3
	RP4 Contamination management	RP4
DT: Design Tools	DT8 Adequacy and inclusion of thermal runaway propagation prediction tools in BESS design processes	DT8
TD: Technology Development	TD2 Detection of state of thermal reaction	TD2
	TD3 Detection of future thermal runaway events	TD3
	TD4 Detection of deflagration and toxicity risks	TD4
	TD5 Limitation of propagation using thermal controls	TD5
	TD6 Minimization of thermal runaway using thermal controls	TD6
	TD7 Safe cells with no thermal runaway potential	TD7
	TD8 Thermal runaway vent gas routing management during failure.	TD8
	TD9 Ignition control	TD9

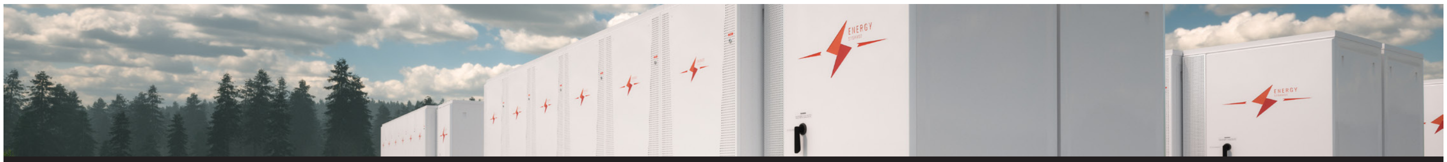
CONCLUSIONS

The research described in this report demonstrates that battery safety is a topic that touches all actors in the ecosystem and requires immediate and reinforced action. Cell suppliers, module and rack suppliers, suppression suppliers, systems integrators, operators, regulators, and first responders need to work together to build a cohesive responsibility for safety. Every stakeholder has a role to play in its respective purview.

- BESS suppliers need to address safety from the cell to the module, to the rack – all the way to the integrated systems. Identifying and addressing the true tolerance of a cell will require additional efforts from a variety of actors, including standards organizations.
- Integrators and battery suppliers should address the issues that emerge from the complex interactions between the different elements of a storage system and continue to innovate with safety technology. The significant coupling between design variables increases the complexity of this task. In addition, rigorous hazard analyses, such as the ESIC Reference HMA (EPRI report 3002017136) or FMEAs, appear to be effective strategies for identifying and improving system-level safety.
- BESS owners, maintenance, and operations staff need to be provided with the right tools to address safety hazards, assess potential environmental impact, and prepare effective, site-specific response plans for first responders to ensure the safety of the public, operators, and environment during a failure event.

If not correctly addressed, these hazards put the entire industry at risk. Technical safety staff, firefighters, and other professionals dealing with battery fires will be exposed to the greatest risk. However, if these near-term research topics are pursued, there is a future where energy storage can be deployed in a way that ensures the safety of the public, operators, and the environment. EPRI is committed to providing the research to enable tools and resources that support owners, operators, and developers of energy storage to ensure a safer future for energy storage.

Contact EPRI's Energy Storage and Distributed Generation Program to learn more about how to partner with EPRI's ongoing safety research.



APPENDIX: EPRI BATTERY STORAGE FIRE SAFETY ROADMAP – DETAILED TOPIC DESCRIPTIONS

In the subsequent sections, each research topic is explained in more detail. Each topic section includes the task name, applicability, impact, effort level, actors, and a detailed description as organized below.

TOPIC: ETD – EXAMPLE TASK DESCRIPTION

Applicability: The applicability of the task on given systems
Impact: High, medium, or low, as used in Figure 4
Effort: High, medium, or low, as used in Figure 4
Actors: Industry entities that are best suited to act on the task outlined
Description: A detailed description and explanation of the task intent and notes on the approach to execution 0

Special Topic – Explosion Risk

Six of the eight examined systems pose a possible explosion risk via the same failure mode. The behavior of these systems has four elements that contribute to this risk:

- They utilize a clean-agent suppression system that prevents ignition, thus encouraging the accumulation of hazardous gases.
- They have no ventilation, further encouraging the accumulation of hazardous gases.
- They have no deflagration protection to control a deflagration should one occur.
- They do not have a first-responder plan that addresses the possibility of explosion.

The explosion failure mode has not been addressed by the cell- and module-level UL listings. While UL 9540A does address explosion risk, most existing systems were installed prior to publication of 9540A, and the industry's experience with 9540A to date is still limited, meaning it may not always be implemented properly. Furthermore, there is statistical variability in thermal runaway events, and it may be necessary to conduct multiple tests per UL 9540A to confidently address this failure mode.

As shown in Figure 5, specific effort is recommended to advise on how to manage explosions due to the high suspected occurrence rate, potential loss of life should an explosion occur, and obvious industry benefits from a quick, coordinated response to this issue.

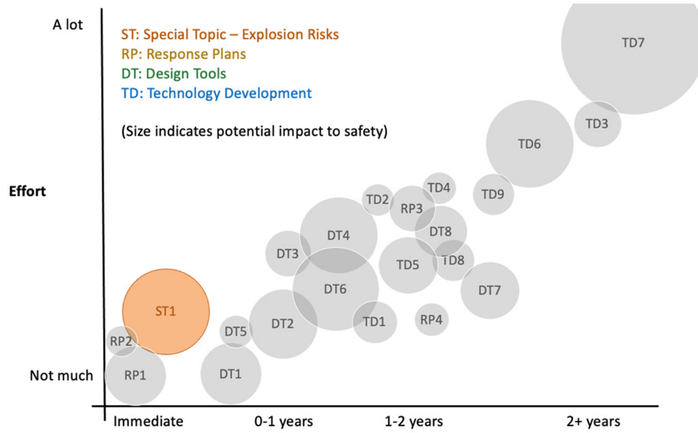


Figure 5 – Special topic – explosion risk

Topic: ST1 – Addressing the Common Explosion Hazard

Applicability: Existing and all future systems
Impact: High
Effort: Low to medium
Actors: BESS developers, BESS owners and operators, safety experts, first responders
Description: Immediate action is necessary on the many existing systems that include gaseous suppression systems without ventilation to eliminate deflagration risks, which threaten bystanders and first responders. At a minimum, a response plan must be made that specifically addresses how to deal with a system post-fault when it contains a dangerous amount of toxic and flammable gases that could explode if disturbed. The ability to retrofit deflagration panels and/or alternative suppression and ventilation systems should also be considered. One particular challenge to these efforts is that many of these older systems are no longer in production, and test-based design methods such as UL 9540A may not be applicable. An industry task force is recommended to create and distribute guidance to owners and operators as well as authorities having jurisdiction (AHJs) and first responders.

This information should also be applied to systems presently under development and to all future system builds. Ideally, recommendations to codes will be made that prevent this risk from occurring in the future

RESPONSE PLANS

Review of site surveys found that response plans were often lacking or missing entirely. Industry workshops raised additional challenges regarding response plan availability and content. As an improper response to a BESS fault can pose a potentially life-threatening risk to first responders and bystanders, response plan topics presented herein are generally high-impact, near-term tasks, as shown in Figure 6. In many cases, the effort needed to complete these tasks is relatively low.

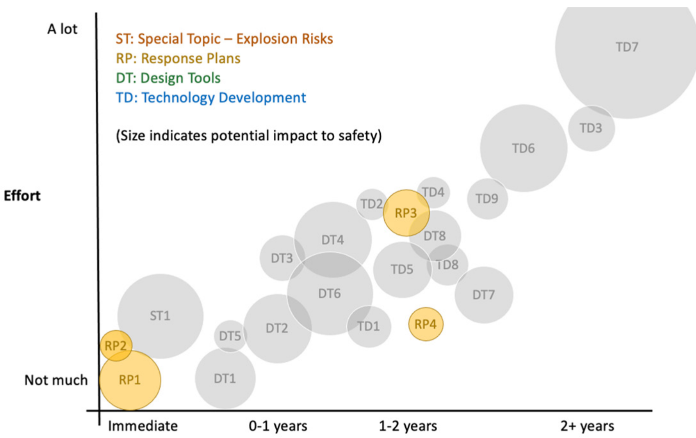


Figure 6 – Response plan tasks

Topic: RP1 – Response Plan Guidelines for Existing and Future BESS

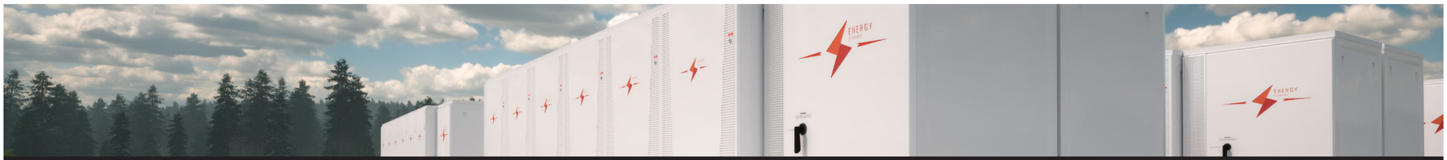
Applicability: Existing and all future systems
Impact: Medium-high
Effort: Low
Actors: First responders, BESS owners and operators, BESS developers, safety experts
Description: Many installed BESSs are believed to not have an adequate response plan in place that covers the known risks of such systems. Further, where response plans do exist, they may not be readily available to first responders. Finally, signage on many BESSs leaves significant room for improvement. An effort should be made to create informative guidelines for response plan writing and delivery as well as improved site signage. The goal is to limit risks to first responders and bystanders while also minimizing financial impact where possible.

Topic: RP2 – Response Plan Standardization

Applicability: Existing and all future systems
Impact: Low
Effort: Low
Actors: First responders, BESS owners and operators, BESS developers, safety experts
Description: The complexity and uniqueness of many operational BESSs have motivated a view in the industry that each BESS requires a unique response plan. This position is justified in that failure modes can vary broadly by BESS design. It is also true that first responders have a multitude of hazards to address and that many first responders are volunteers. Thus, a large diversity of BESS response plans could become counterproductive to enhanced safety. This task would address the question, "Can we create a minimal number of BESS hazard categories and response plans that would safely cover all systems?""

Topic: RP3 – Hazard State Identification and Communication

Applicability: Near-term future and subsequent systems
Impact: Medium
Effort: Medium
Actors: First responders, BESS owners and operators, BESS developers, research scientists, technology developers
Description: An optimal response to a system failure may entail first responders acting if, and only if, the failure event has overcome or threatens to overcome the installed barriers. Understanding the status of these barriers will likely require real-time system state knowledge to best minimize risks. Examples of this knowledge include whether more cells than planned have gone into thermal runaway, the concentration of gases accumulating in the system, and the temperature of different elements within the system. An optimal response requires 1) an understanding of failure modes and how to best assess their state based on real-time system properties, 2) the technology to reliably measure and report the appropriate indicators throughout the entirety of a failure event, and 3) a standardized means to communicate this information to first responders. This task must therefore address all three of these needs. Note that both new science and technology may be required; thus, this could become a long-term task. (Task RP3 requires completion of task TD2 and overlaps with tasks TD3 and TD4.)



Topic: RP4 – Contamination Management

Applicability: Near-term future and subsequent systems
Impact: Low
Effort: Low-medium
Actors: First responders, environment health and safety (EHS) experts, BESS owners and operators, BESS developers, research scientists, technology developers
Description: Where a system's installed fire suppression system is water-based, or when first responders are expected to inject water into a system, there is a risk of contaminating the surrounding environment. This task would seek to quantify the level of contamination possible, assess available strategies for mitigating such contamination, and recommend a best practice to minimize contamination risks.

DESIGN AND REVIEW TOOLS

Industry workshop discussions highlighted the need for improved design and review methodologies on several occasions. Site survey findings also suggested areas where enhanced ability of owners, operators, and AHJs to review designs could improve opportunities for catching and resolving safety problems prior to installation.

Eight design and review tool topics have been created from this data and are presented in Figure 7. They primarily address solutions that improve the industry's ability to predict system response to faults via either test- or model-based methods. There are needs here both in specific domains (such as thermal modeling and suppression system performance) and at the system level.

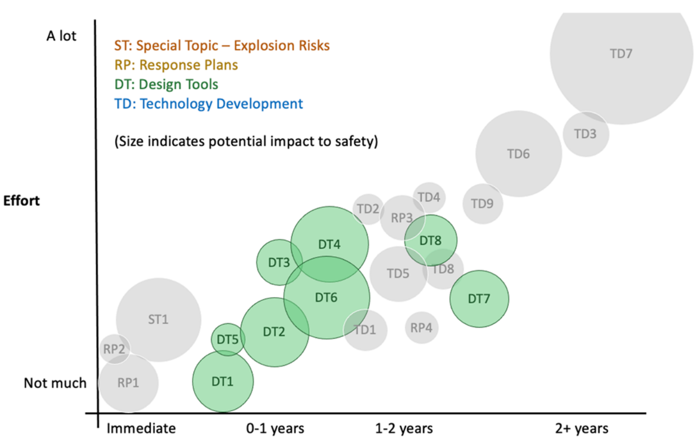


Figure 7 – Design and review tool tasks

Topic: DT1 – Improving Availability and Application of 9540A Testing

Applicability: Under-development and future systems
Impact: Medium-high
Effort: Low
Actors: First responders, BESS owners and operators, BESS developers, codes and standards organizations
Description: UL 9540A test procedures are a powerful tool that enables the design and construction of BESSs with significantly reduced safety risks relative to past systems. However, early findings suggest that developers are 1) not sharing test results from 9540A, 2) sharing inconsistent and/or questionable data from 9540A, and/or 3) applying 9540A data to their designs in unintended ways that do not create the intended levels of risk reduction. Reviewers of 9540A data are often not well informed as to what to look for – as they may not be energy storage experts – and/or the use of 9540A data is relatively new to the industry. In this task, guidelines and tools would be created and shared both for developers and reviewers to improve the consistency and quality of 9540A data usage..

Topic: DT2 – Inclusion of Gas Prediction and Deflagration Protection Tools in BESS Design Processes

Applicability: Near-term future and later systems
Impact: Medium-high
Effort: Low-medium
Actors: BESS developers, gas modeling experts, deflagration protection experts
Description: Deflagration risk caused by accumulation of excess vent gases is reasonably well understood today. The empirical, analytical, and simulation tools necessary to predict the concentration of gases due to a fault – as well as the design tools needed to size adequate deflagration protection systems given gas concentrations – are also well established and will soon be available to BESS developers. However, there is no widespread requirement that these calculations be performed or reviewed. This task would therefore focus on 1) providing widespread access to the necessary tools and knowledge for BESS developers to predict gas concentration and size deflagration protection systems, 2) ensuring understanding of these methods by BESS developers, AHJs, and other BESS reviewers, and optionally 3) standardizing review of the application of these methods to support the safe deployment of future BESSs.

Topic: DT3 – Expansion of 9540A Testing to Address Statistical Variation and Multiple Cell Failures

Applicability: Near-term future and later systems

Impact: Medium

Effort: Medium

Actors: UL, research scientists

Description: UL 9540A test procedures are a powerful tool that enables BESS design and construction with significantly reduced safety risks relative to past systems. However, two key improvement areas have been identified: 1) addressing statistical variation in cell response to fault events, and 2) properly specifying the level of thermal runaway propagation to be achieved in specific tests. The latter requires consideration of the failure modes to address in combination with the level of propagation resistance present in a specific storage device. The fourth edition of UL 9540A has made improvements in this regard, but the need for continued improvement is anticipated

Topic: DT4 – Guidelines for Selection and Design of Suppression Systems

Applicability: Near-term future and later systems

Impact: High

Effort: Medium

Actors: BESS developers, safety experts, suppression system suppliers

Description: The question, "Which suppression system should I choose for my BESS?" is far from answered. Gaseous and clean-agent systems do not address thermal propagation and pose a deflagration risk; in addition, post-event management is unclear. Water-based systems are often infeasible when an unlimited water supply is not available. These systems also might not suppress fires, generally result in a total loss of a system, and pose questions around hydrogen gas generation and environmental contamination. Other options have yet to be fully vetted for BESS applications. This task would focus on collecting available data from past suppression system testing, conducting new testing where necessary, and comparing the benefits and drawbacks of all extant suppression technologies. A design guide would result, enabling BESS developers to choose the right suppression system for their specific installation.

Topic: DT5 – Standardized Electrical Controls Reporting

Applicability: Under-development and future systems

Impact: Low-medium

Effort: Low

Actors: BESS developers, safety experts

Description: Electrical controls are often the first line of defense to failing and failed cells; they are also the most mature and most frequently implemented of all barriers. However, assessing the level of safety provided by a specific installation's electrical controls is difficult without detailed review of electrical schematics, software, and firmware. Many manufacturers are hesitant to disclose the information necessary for an informed assessment of system safety. This task seeks to develop a solution (for example, a standard questionnaire) that enables system developers to disclose adequate information needed for safety assessments without revealing sensitive intellectual property or requiring expert review of detailed design information.

Topic: DT6 – Failure Modes and Effects Analysis (FMEA) Guidance

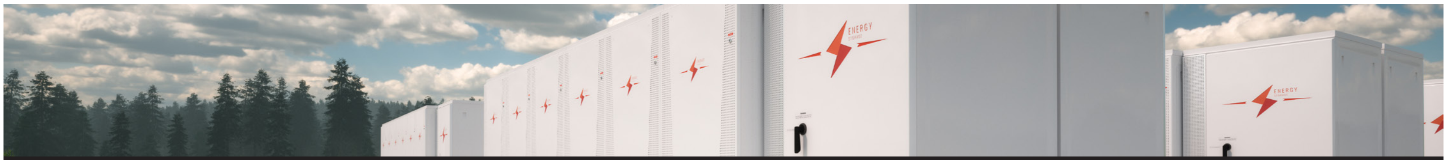
Applicability: Near-term future and later systems

Impact: High

Effort: Low-medium

Actors: BESS developers, safety experts, FMEA experts

Description: The quality of FMEAs conducted for BESS development is unclear, but the site surveys and continued failures of BESSs suggest there is considerable room for improvement, which could significantly reduce system risks. This task would focus on two main items to improve BESS FMEA effectiveness: 1) create and provide FMEA creation guidelines for BESS developers – as well as FMEA review guidelines for AHJs, owners, and operators – to ensure that the most common and hazardous failure modes are addressed, and 2) convene a task force of BESS safety and FMEA experts to perform a deep FMEA of a generalized BESS to identify presently unknown high-risk failure modes. While this guidance is predominantly intended for future systems where there is opportunity to affect the design process, it could also be applied to existing systems, identifying presently unrecognized failure modes and incentivizing modifications to operational procedures and/or response plans that can improve safety.



Topic: DT7 – Integrated System Design Tools

Applicability: Medium-term future and later systems
Impact: Medium-high
Effort: Low-medium
Actors: BESS developers, safety experts, model-based design experts
Description: BESS complexity and potential design variability are high, with significant coupling between many design variables. An integrated, systemwide design approach is therefore necessary to optimize safety while minimizing cost. However, it appears that today's industry design practices often leave optimal risk mitigation as a missed opportunity. Design tools that seek to capture this opportunity are needed. It is anticipated that fault block size will be a key variable in risk mitigation designs, impacting requirements for thermal protection and suppression, ventilation, and deflagration systems, with a strong overall impact on system cost. EPRI has developed the foundations of this work in *Design Trade Study Method for Battery Energy Storage Fire Prevention and Mitigation*.[4] In this task, that work would be extended to a higher level of fidelity, leveraging improved gas and thermal prediction tools as well as learnings from the suppression systems study. The result would be a design method/tools/guide for informing BESS subsystem choices that maximize safety and minimize lifetime costs.

Topic: DT8 – Adequacy and Inclusion of Thermal Runaway Propagation Prediction Tools in BESS Design Processes

Applicability: Near-term future and later systems
Impact: Medium-high
Effort: Low-medium
Actors: BESS developers, safety experts, thermal modeling experts
Description: It is suspected that properly sized deflagration protection will be challenging to install in many containerized systems due to limited availability of wall and ceiling space. Achieving adequate levels of safety may therefore require strict limitations on the amount of battery energy that is allowed to enter a thermal runaway state and generate gas. Increased usage of thermal analysis tools will be required to design to such limits. Use of simulation tools for thermal runaway prediction is not uncommon in other industries, and similar practices can be adopted. However, there may be a need to improve modeling methods to account for heat transfer from vented gases and flames in the specific setting of stationary storage systems. This task would therefore 1) assess the capability of existing thermal modeling tools and methods, 2) develop improved modeling methods where necessary, and 3) deploy these tools and methods to industry

4 https://www.epri.com/research/products/000000003002020573.

RESEARCH AND TECHNOLOGY DEVELOPMENT

Site surveys and industry workshops have highlighted many areas where improved technology and understanding of failure modes are needed to improve BESS safety, as shown in Figure 8. The emphasis here is on R&D of new and improved barriers to hazards, which could be further categorized by barrier type.

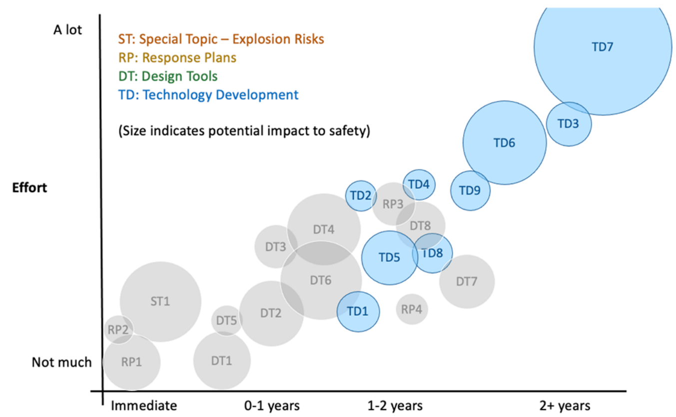


Figure 8 – Research and technology development tasks

The largest opportunity for guaranteeing a safe system response to a fault is, has been, and will continue to be the development of safer lithium ion cells. Such cells would have higher thermal runaway onset temperatures, release lower amounts of heat in thermal runaway, and release smaller amounts of less toxic, less flammable gas during such an event. Reaching this goal could remove much of the barrier complexity throughout the system. However, this goal has long been pursued by the lithium ion battery industry and is a challenging long-term task.

Compared to the mobile applications that have historically driven cell-level safety improvements (such as consumer and automotive), stationary storage applications present unique opportunities for ensuring system-level safety (such as access to water supplies for fire suppression and lower risks of significant mechanical deformation). Therefore, it is recommended that investments to improve BESS safety focus on these areas.

Topic: TD1 – Robust Electrical Controls

Applicability: Near-term future and later systems
Impact: Medium
Effort: Low-medium
Actors: Technology developers, safety experts
Description: While it is believed that most BESSs include effective electrical controls, the robustness of these systems is unclear. For example, what is the likelihood that a single measurement will fail, and what would be the effect of failure on system safety? What is the likelihood that a contactor will fail to isolate a battery exposed to a short circuit? This task would seek to 1) evaluate multiple systems in detail to determine the level of robustness of battery management system and other electrical controls, 2) identify the circuits, devices, and failure modes where redundancy and robustness are most valuable, and 3) publish findings and issue guidance to both BESS developers and AHJs/reviewers.

Topic: TD2 – Detection of State of Thermal Reaction

Applicability: Near-term future and later systems
Impact: Low-medium
Effort: Medium
Actors: Technology developers, cell developers, research scientists, BESS developers
Description: Understanding the state of a thermal runaway reaction may be critical for activation of suppression systems and actions of first responders. This task would pursue the development of technologies that can predict future propagation, heat release, and gas release after a thermal runaway event has begun and would include sensor efficacy testing, which is required for task RP3.

Topic: TD3 – Detection of Future Thermal Runaway Events

Applicability: Far-term future and later systems
Impact: Medium
Effort: High
Actors: Technology developers, cell developers, research scientists
Description: The ability to predict some future runaway events presents the opportunity to limit incurred damage and safety risks, though such an ability will not eliminate the need for other safety systems as some failure modes will not be predictable. This task would pursue the development of technologies that can predict future thermal runaway events based on measurements of system response during nominal operation (such as voltage, current, and temperature). (This task overlaps with task RP3.)

Topic: TD4 – Detection of Deflagration and Toxicity Risks

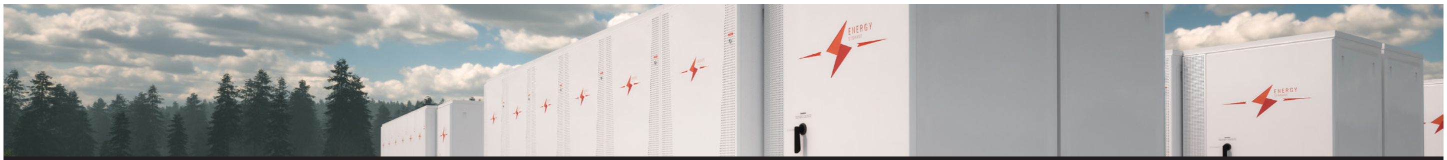
Applicability: Near-term future and later systems
Impact: Low-medium
Effort: Medium
Actors: Technology developers, safety experts, deflagration protection experts
Description: Detection of deflagration and toxicity risks, most readily via gas concentrations, is critical in certain systems for venting and suppression system activation as well as supporting first-responder actions. Technical challenges include maintaining function throughout the entirety of a safety event, addressing heterogeneity of gas concentrations throughout a system, and minimizing response time. (This task overlaps with task RP3.)

Topic: TD5 – Limitation of Propagation Using Thermal Controls

Applicability: Medium-term future and later systems
Impact: Medium-high
Effort: Medium
Actors: Technology developers, thermal modeling and system design experts
Description: As discussed previously, it is anticipated that the ability to control the propagation of thermal runaway to a limited number of cells will be critical to ensuring desired safety levels are achieved. This task would explore different methods of limiting propagation in stationary systems, drawing on past work in other applications. The result of this task would be data on the ability of various methods to limit propagation and recommendations on when to use which approaches.

Topic: TD6 – Minimization of Thermal Runaway Using Thermal Controls

Applicability: Far-term future systems and later
Impact: High
Effort: High
Actors: Technology developers, cell developers, research scientists, thermal modeling and system design experts
Description: If the heat and/or gas released by a single cell during thermal runaway could be minimized and propagation to neighboring cells prevented entirely, then safety risks could be decreased dramatically as could the requirements for additional safety systems. This task would pursue the development of such thermal control technologies and report on their viability.



Topic: TD7 – Safe Cells with No Thermal Runaway Potential

Applicability: Far-term and later systems
Impact: Very high
Effort: Very high
Actors: Cell developers, research scientists, safety experts
Description: The battery industry has long pursued the development of safer cells, which could eliminate the need for all of the other safety systems and precautions associated with BESSs. This task is a large one, however, and it carries considerable technological risk. It is included in this discussion primarily for completeness, and it is not recommended that EPRI and its members directly invest in this effort.

Topic: TD8 – Thermal Runaway Vent Gas Routing Management During Failure

Applicability: Medium-term future and later systems
Impact: Medium
Effort: Medium
Actors: Technology developers, gas prediction experts, safety experts
Description: The effectiveness and practicality of gas routing for the prevention of ignition and propagation have not been extensively explored in stationary systems. However, gas routing is considered in other industries, and its implementation may be well suited to stationary systems. This task would complete a feasibility study on the use of gas routing for stationary systems.

Topic: TD9 – Ignition Control

Applicability: Medium-term future and later systems
Impact: Medium
Effort: Medium
Actors: Technology developers, safety experts
Description: To date, the industry has favored the prevention of vent gas ignition on the premise that fire will lead to increased propagation and heat release. However, the realization that common fire suppression methods can lead to increased risk of deflagration brings this premise into question. Allowing gases to burn can reduce the risk that sufficient quantities of flammable gases will accumulate to present a deflagration risk. This task would answer the question of when gas ignition should be suppressed and when it should be encouraged.

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