

Article

Revamping Undergraduate Thesis in Safety Science and Engineering Through Integration of Advanced Lithium Ion Battery Safety Techniques

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Abstract: We address a thorough case study on how to include cutting-edge safety improvements for lithium-ion batteries into Safety Science and Engineering undergraduate thesis projects. The application of ethoxy (pentafluoro) cyclotriphosphazene (PFPN) as a flame retardant additive to enhance the thermal stability of lithium-ion batteries is the particular focus of the work. adiabatic acceleration calorimetry and differential scanning calorimetry were used to assess how well PFPN reduces the dangers of thermal runaway. Apart from the actual investigation, the paper suggests major changes to the undergraduate thesis program that include cutting-edge battery safety research to better suit the demands of the business. Among these changes are improved laboratory facilities, specialised research initiatives, and closer business partnerships. The results demonstrate that adding PFPN to the electrolyte greatly raises the temperature at which thermal runaway begins and lowers the peak temperatures during exothermic processes. To increase student preparedness for jobs in battery safety and engineering, the suggested curriculum changes seek to improve research productivity, provide students with specific technical skills, and foster industry relationships. In the end, this case study highlights the need of flexible and responsive educational initiatives that use state-of-the-art research to tackle the always changing issues related to lithium-ion battery safety.

Keywords: Ethoxy (pentafluoro) cyclotriphosphazene, Flame retardant additive, Thermal runaway, Industry relationships

1. Introduction

Many electronic products, such as electric cars and cellphones, rely on lithium-ion batteries, which use lithium as a main component. These batteries supply power to a broad variety of electronic gadgets, including electric cars and smartphones. However, the widespread use of these devices poses significant safety challenges, primarily due to the risks associated with thermal runaway. Thermal runaway occurs when an excessive quantity of heat triggers a chain of chemical reactions that perpetuate themselves, ultimately leading to a fire or explosion. Ensuring the safety of these batteries is crucial, not only to protect consumers but also to advance environmentally friendly energy technologies (Wang, 2024).

Improving the thermal stability of lithium-ion batteries has been a primary focus of recent scientific research. One promising approach involves incorporating flame-retardant chemicals into the battery material. A notable example is ethoxy (pentafluoro) cyclotriphosphazene (PFPN) (Wu, 2023). Adding these chemicals reduces the combustibility of battery electrolytes, subsequently lowering the risk of thermal runaway. This article presents the results of an experimental study conducted to investigate the efficacy of PFPN. Techniques such as Differential Scanning Calorimetry (DSC) and Adiabatic Acceleration Calorimetry (ARC) were used to assess the impact of PFPN on battery safety (Zhang, 2022).

Despite constant breakthroughs in safety technologies, there remains a significant lack of expertise in safety science and engineering, particularly in implementing these safety measures efficiently. Most undergraduate thesis programs in safety science and engineering do not provide comprehensive training on the latest safety technologies and procedures required for the secure management of next-generation energy storage systems. Addressing this educational gap is crucial to training engineers who can design and supervise the secure implementation of modern battery technologies.

The purpose of this article is to offer a case study focused on undergraduate thesis education reforms designed to address this gap (Sun, 2023). These reforms include integrating specialized safety research projects specifically geared toward battery technology into the thesis curriculum, enhancing laboratory sessions that replicate real-life scenarios, and collaborating with industry to provide students with hands-on experience in managing complex battery systems (Chang, 2023). These adjustments aim to give

students a comprehensive understanding of both theoretical and practical aspects of battery safety, enabling them to excel as pioneers in safety science and engineering.

This article has two main goals: firstly, to enhance knowledge about lithium-ion battery safety through the use of flame retardant chemicals like PFPN, and secondly, to establish a practical framework for improving undergraduate thesis education by incorporating safety-focused research. The following chapters will provide a comprehensive examination of the experimental research conducted on PFPN additives, outline the suggested educational reforms, and synthesize how these two essential areas can be combined into a unified safety and educational strategy.

2. Progress in Lithium Ion Battery Safety Technology

Lithium-ion batteries have quickly advanced and become a leading technology in energy storage. In this chapter, we explore the progress made in safety technology, specifically focusing on the creation of flame retardant chemicals and their impact on battery design and usage. Emphasis is placed on incorporating PFPN into the electrolytes of lithium-ion batteries to improve thermal stability and mitigate the hazards associated with thermal runaway (Yang, 2022). The synthesis of PFPN is shown in Fig. 1.

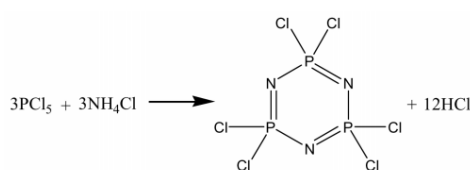


Fig. 1. The synthesis of PFPN.

2.1. Thermal Runaway Process and Flame-Retardant Additives

One serious safety concern with lithium-ion batteries is their extreme susceptibility to thermal runaway. A thermal runaway is the outcome of a temperature increase starting a self-perpetuating series of chemical reactions that raise the temperature even more and may cause flames or explosions (Yang, 2021). Thermal runaway is mostly caused by pressure buildup, which can break the battery shell, and electrolyte deterioration.

One effective method to address the dangers of thermal runaway is to incorporate flame retardant chemicals into the electrolytes, which has demonstrated encouraging outcomes. PFPN, a newly discovered substance, has been found to significantly improve the thermal stability of the electrolyte when used as an addition (Wu, 2021). The research shown in Table 1 compares the performance of PFPN with typical electrolyte formulations. The standard electrolyte used in this experiment is the commercial electrolyte LP30, which consists of a 1.0 mol solution of lithium hexafluorophosphate (LiPF₆) dissolved in a 1:1 mixture of dimethyl carbonate (DMC) and ethylene carbonate (EC). The results show that PFPN is better at preventing the initial temperature increase and delaying the occurrence of thermal runaway.

Table 1. Comparison of electrolyte formulations LP30 with and without PFPN.

Electrolyte Type	Initial Temperature Of Thermal Runaway	Peak Temperature
LP30	80 °C	250 °C
LP30 with PFPN	85 °C	230 °C

2.2. Empirical Verification and Prospects

The efficiency of PFPN as a flame retardant has been confirmed using experimental techniques such as DSC and ARC. These studies quantify the transfer of heat and the ability of a system to maintain a consistent temperature under-regulated thermal pressure. The results of these experiments provide empirical evidence that supports the theoretical advantages of including PFPN in battery electrolytes.

PFPN improves lithium-ion batteries' thermal stability and opens up new avenues for safer battery design. With the advancement of these technologies, there are chances to employ lithium-ion batteries more in more difficult applications like large-scale energy storage systems and electric cars. Validating these developments and making sure they are applied practically in contemporary battery safety engineering need empirical verification through undergraduate thesis research.

3. Current State and Reform Needs in Safety Science Education

Updating educational frameworks is critical to give engineers the abilities they need to handle lithium-ion battery systems as applications and technologies associated to them develop. The state of safety science and engineering undergraduate thesis curriculum is assessed in this part, which also points up shortcomings and makes necessary recommendations for bringing undergraduate thesis curriculum programs into compliance with industry standards and safety regulations. Even if many curricula include theoretical knowledge on battery safety, actual applications must be mirrored in real-world, hands-on experiences.

3.1. Present State of Undergraduate Thesis Curriculum

Programs teaching safety science and engineering seek to equip students with the knowledge and skills necessary to manage risks and carry out safety procedures in a variety of industries. Still, a look at current curricula exposes serious shortcomings in emerging technologies, especially in the areas of battery safety and energy storage. The present undergraduate thesis program does not give safety concerns associated with lithium-ion battery technologies enough weight. Even although theoretical battery technology topics are taught, students frequently do not have real-world experience with safety issues like thermal runaway. This gap prevents them from doing their thesis work on safety management matters as well as they could.

The progress in battery design and safety technology requires a reassessment of teaching approaches. Engineers must possess expertise in both traditional safety standards and modern diagnostic and preventative technologies because of the growing complexity of lithium-ion battery systems. These systems are known for their high energy densities and the potential for thermal incidents (Altbach, 2007). Advance methods like DSC and ARC aren't always available for students to use in real-life safety tests. Students can't properly assess and reduce the risks in lithium-ion batteries without having relevant practical experience (Ma, 2023).

3.2. Gap Between the Industry and Academia

The capacity of fresh graduates to successfully contribute to safety management and innovation is hampered by the gap between their theoretical education and the practical abilities needed by the lithium-ion battery sector. What the industry needs—especially with regard to contemporary lithium-ion battery technologies—and what students learn in safety science and engineering curricula differ by this “gap”. Graduates find it more difficult to apply what they have learned in class to practical settings, which is essential for battery technology innovation and safety management. The opinions of recent graduates and industry professionals on the suitability of educational programs are shown in Table 2 (Ma, 2023). Because these new modules feature real-world experimental setups, students will be able to apply theoretical principles in practical settings. Working together with business partners, the curriculum will be further enhanced and students will get firsthand experience with the problems facing modern battery technologies.

In general, the current program for safety science and engineering doesn't give students enough hands-on experience with lithium-ion battery thermal runaway problems. Students often lack practical experience with battery safety testing, especially using methods like DSC and ARC. While theoretical concepts of thermal runaway are taught in classes, students don't fully understand how different materials and additives change the onset and peak temperatures of thermal runaway. Additionally, flame-retardant additives like PFPN, which can significantly improve battery safety, are rarely covered in the curriculum. Most students are unfamiliar with their usage and benefits. To resolve these inconsistencies and incorporate practical safety measures into undergraduate thesis projects, several initiatives have been proposed. One such initiative involves implementing specialized modules focused on battery technology, covering topics such as thermal runaway, risk assessment, and the use of flame retardant additives like PFPN. Improving laboratory facilities is also essential. Incorporating advanced testing and diagnostic equipment like DSC and ARC will help provide students with a more comprehensive understanding of lithium-ion battery safety. Furthermore, forming partnerships with battery manufacturers and energy firms will facilitate hands-on training, internships, and thesis projects in authentic industrial environments (Li, 2023). These collaborations will ensure that students receive valuable practical knowledge while working on real-world projects, thereby enhancing their preparedness for careers in safety science and engineering.

Table 2. Survey on industry and graduate perceptions of educational preparedness.

Respondent Group	Belief in Adequate Preparation (%)	Identified Areas for Improvement
Industry professionals	35%	Advanced diagnostics, real-time safety management
Recent graduates	50%	Practical application, emergency response planning

4. Safety Science And Engineering Undergraduate Thesis Reform Proposals

Ensuring that educational innovations meet the desired goals requires a comprehensive evaluation strategy. This plan will evaluate the degree to which the modifications have matched curriculum with industry standards and prepared students. Graduate monitoring, industry comments, academic performance analysis, and student comments will all be part of the assessment. A system will be put in place to follow graduates for five years after graduation in order to track their work status and positions in the safety engineering field. Annual surveys of industry partners will offer information on the performance and readiness of graduates. This input will be used directly to guide curriculum modifications to meet industry demands. New evaluation tools will also measure how well students are understanding the new modules; they will include evaluations of both theoretical ideas and practical tasks. The curriculum will be kept current and interesting by gathering student feedback on changes through focus groups and end-of-course questionnaires.

The first stage in reorganizing the undergraduate thesis program is to include specialized modules that address contemporary battery technologies and the related safety concerns. Thermal runaway, high-energy system risk assessment, and the application of flame retardant technologies—including PFPN—will be the main topics of these modules. To guarantee students obtain practical skills in safety science and engineering, especially in battery systems, laboratory infrastructure will be improved in addition to the curriculum modifications. Modern testing and diagnostic tools include ARC and DSC will enable students to carry out flame retardant material experiments and thermal runaway simulations in real time.

The alignment of educational curricula with modern technology developments and safety regulations depends on cooperative connections with industry. Opportunities for internships and thesis projects in real industrial settings will be made possible by partnerships with battery manufacturers and energy companies, which will also allow guest lectures and workshops by industry professionals. The theoretical knowledge and actual implementation will be bridged by these experiences. The introduction of these changes calls for a well-thought-out plan that includes raising money for cutting-edge laboratory equipment, updating course materials, educating faculty members on the newest technologies, and establishing alliances with business. Table 3 gives a summary of the staged implementation plan together with the deadlines, accountable parties, and expected difficulties.

Table 3. Phased implementation plan for undergraduate thesis reforms.

Activities	Timeline	Responsible parties	Anticipated challenges
Thesis topic selection and training	Year 1–2	Faculty supervisors	Clear research objectives
Laboratory equipment upgrades	Year 2–3	Facilities management	Funding, equipment procurement
Industry partnerships for thesis projects	Year 3–4	Partnership office	Establishing mutually beneficial agreements

The proposed undergraduate thesis reforms in safety science and engineering aim to provide a strong and comprehensive structure that not only tackles current educational deficiencies but also equips students to address future challenges in battery safety and technology. By improving the curriculum, modernizing facilities, and establishing strong industry connections, graduates will not only be skilled in traditional safety measures but also highly capable of managing advanced technologies shaping the future of energy storage.

5. Experimental Analysis Of Lithium-Ion Battery Safety Enhancements Using PFPN

5.1. Experimental and Methodology

The experimental setup involves the utilization of DSC and ARC to quantify the thermal characteristics of lithium-ion batteries that have been improved using PFPN. DSC was employed to evaluate the performance of the LP30 and LP30+PFPN. The exothermic features of the innovative polymer composite flame-retardant electrolyte were combined with the thermal exciton model. To prevent moisture and oxygen from reaching them, enclose the two electrolyte solutions in aluminum DSC sample pans and seal them within an argon-filled glove box. The net electrolyte content in the sample pan is 6.5 ± 0.5 mg. The specimens were subjected to a temperature range of 30–350 °C, with heating rates of 1, 2, 4, 7, and 10 °C/min. The thermal stability properties (T_0 , T_p , and T_e) of conventional and flame-retardant electrolytes were compared to analyze their thermal behavior (Zhang, 2022).

To study LP30+PFPN electrolyte heat breakdown, we performed ARC studies in a controlled pseudo-adiabatic environment. Research suggests PFPN is flame retardant, although thermal qualities and parameters are unknown. ARC can measure the thermodynamic and reactive heat characteristics of PFPN in conventional and flame-retardant electrolytes under adiabatic circumstances. Testing comprised placing the electrolyte sample into a film-covered titanium alloy ball. Testing occurred in a glove

box. The experimental parameters for ARC used the hot waiting search mode and a net weight range of 3.0 ± 0.5 g. The sample is swiftly heated to 80.0°C from room temperature to start the experiment. After stabilizing the temperature for 30.0 minutes, heat release is seen. Self-heating below $0.02^\circ\text{C}/\text{min}$ suggests no exothermic process can occur at that temperature. Heat release is reevaluated after increasing temperature by 5.0°C at $10.0^\circ\text{C}/\text{min}$. If an exothermic reaction is detected, the system will adjust the external ambient temperature to match the reaction system temperature for a pseudo-adiabatic effect. The thermal waiting search mode terminates at 350.0°C , and the reaction system's adiabatic state controls temperature and pressure.

5.2. Thermal Characteristics and Discussion

The trials provide comprehensive results, demonstrating the impact of PFPN on the starting temperature of thermal runaway and its effectiveness in reducing the maximum temperatures reached during battery failure. The quantitative increases in thermal stability, comparing batteries with and without PFPN additions, are illustrated in Table 4.

Table 4. DSC characteristic parameters of LP30 and LP30+PFPN.

Heating rate ($^\circ\text{C}/\text{min}$)	Mass (mg)	LP30						LP30 + PFPN					
		T_{01} ($^\circ\text{C}$)	T_{p1} ($^\circ\text{C}$)	T_{e1} ($^\circ\text{C}$)	T_{02} ($^\circ\text{C}$)	T_{p2} ($^\circ\text{C}$)	T_{e2} ($^\circ\text{C}$)	T_{01} ($^\circ\text{C}$)	T_{p1} ($^\circ\text{C}$)	T_{e1} ($^\circ\text{C}$)	T_{02} ($^\circ\text{C}$)	T_{p2} ($^\circ\text{C}$)	T_{e2} ($^\circ\text{C}$)
1	6.5 ± 0.5	68.7	103.3	132.3	192.7	223.0	260.3	61.3	96.7	140.3	178.7	222.0	272.7
2		78.7	103.3	123.3	191.7	223.0	258.0	56.0	97.7	137.0	162.3	200.0	248.7
4		89.0	104.7	122.0	193.3	239.7	262.3	81.3	105.3	129.7	183.0	234.0	264.0
7		95.4	117.8	146.5	195.9	212.7	234.5	95.4	120.0	150.1	196.3	214.0	236.8
10		121.7	140.7	158.3	202.3	234.0	258.7	122.0	139.0	159.3	204.3	233.7	260.7

The specific parameters of this experiment are detailed in Table 5. Currently, the temperature of the reaction system starts to increase, and the pressure also increases. After a duration of around 1225 mins, the temperature of the reaction system rose to around 231°C , while the pressure reached approximately 70 bar. Currently, the heating rate and pressure raising rate have reached their maximum values, which are $0.51^\circ\text{C}/\text{min}$ and $1.2\text{ bar}/\text{min}$, respectively.

Table 5. ARC characteristic parameters of LP30 and LP30+PFPN

Tempe. ($^\circ\text{C}$)	Heating rate ($^\circ\text{C}/\text{min}$)	Heat release threshold ($^\circ\text{C}/\text{min}$)	Waiting time (min)	Tempe. increment ($^\circ\text{C}$)
80–350	10	0.02	30	5

As the value of the heating rate grows, the temperatures T_0 , T_p , and T_e also increase in the endothermic peaks of LP30 and LP30+PFPN. As the temperature rises, two peaks indicating endothermic reactions become evident in LP30 and LP30+PFPN. The LP30 compound exhibits two endothermic peaks, with temperature ranges of 68.7 – 158.3°C and 192.7 – 258.7°C . The LP30+PFPN compound exhibits two endothermic peaks, with temperature ranges of 61.3 – 159.3°C and 178.7 – 260.7°C . According to the literature, the initial endothermic peak is attributed to the dissolution of LiPF_6 , resulting in the formation of LiF in solid form and PF_5 in gaseous form in an environment devoid of reactivity. The second endothermic peak occurs due to the solvent evaporation in the electrolyte. The initial peak region has a lesser magnitude compared to the subsequent peak region, suggesting that the decomposition of LiPF_6 necessitates a lower amount of energy and is more readily reactive. When PFPN is added at the same heating rate, the areas of the two endothermic peaks increase, indicating a decrease in the reaction heat rate for both processes. Furthermore, the temperature range at which the endothermic peak occurs is widened, indicating that the endothermic reaction occurs at an earlier stage and the overall reaction system is safer compared to the original LP30. It may be deduced that PFPN can enhance the stability of the LP30 electrolyte.

6. Incorporating Battery Safety Into the Undergraduate Thesis Curriculum

This section reorients the attention towards the educational aspect of the article, specifically discussing how the curriculum for undergraduate thesis projects in safety science and engineering might be improved to incorporate advanced battery safety research, similar to the research examined in the preceding sections.

6.1. Proposals for Enhancing the Curriculum

One significant proposal is to modify the undergraduate thesis curriculum to provide students with more opportunities to participate in battery safety research. The revised curriculum would encourage students to engage in thesis projects involving experiments with lithium-ion batteries, with a specific emphasis on exploring the application of safety-enhancing additives like PFPN.

The new curriculum would provide a systematic framework for students to cultivate their thesis projects centered on the following fundamental domains. Students will be directed to choose ideas for their thesis that are in line with the current research on improving battery safety. Possible subjects could be “The impact of PFPN on the thermal durability of lithium ion batteries” or “Comparative evaluation of flame retardant additives in high-density energy storage applications.” Students will be provided with instruction in specialized research procedures that apply to battery safety, including DSC and ARC, as detailed in the experimental sections of this article. An oversight structure would be implemented, in which students are guided by faculty members who possess expertise in battery technology and safety. This would encompass frequent workshops and seminars conducted by industry experts as guest lecturers. Collaborating with battery makers and safety technology organizations would offer students valuable practical knowledge and the opportunity to work on real-life projects, so boosting the practical learning component of their thesis work (Wang, 2022).

6.2. Execution Plan

The strategic implementation of these curriculum changes will need securing administrative approval, setting aside funds for new laboratory equipment, and forging alliances with industry participants. The implementation strategy will designate particular dates and provide different academic institution stakeholders specific responsibilities.

6.3. Anticipated Results

Including cutting-edge battery safety methods into the undergraduate thesis program is supposed to give students specialized technical abilities suited to the particular needs and solutions in battery safety, so raising their attractiveness for jobs in the energy storage and safety industries. Moreover, raising the caliber and volume of research that undergraduate students generate will expand the body of knowledge already in this area. By taking this tack, the institution will also fortify its links with the safety technology and battery manufacturing sectors, promoting ongoing collaborations and increasing graduate job prospects.

6.4. Summary and Suggestions

The undergraduate thesis program will continue to lead in educational developments in safety science and engineering if battery safety is included in some of the undergraduate thesis program curricula. Through the provision of the skills required to handle complex safety concerns in the battery sector, this project will enable students to succeed in their future employment. Based on input from students and business partners, recommendations for additional curriculum improvements will guarantee that the program keeps developing and satisfies the requirements of contemporary engineering education.

7. Conclusion

The incorporation of cutting-edge safety improvements for lithium-ion batteries into undergraduate safety science and engineering thesis projects was thoroughly investigated in this paper. It concentrated especially on improving flame retardancy by adding PFPN. Utilizing careful experimental analysis, the work proved notable enhancements in the thermal stability of lithium-ion batteries, hence advancing safer battery technology. Apart from the scientific investigation, this effort suggested major changes to the safety science and engineering undergraduate thesis program to include cutting-edge battery safety research in thesis projects. By significantly raising the temperature at which thermal runaway occurs, PFPN enhances the safety buffer under typical operating conditions. Because the changed electrolytes show a lower maximum temperature during thermal events, there is a far lower chance of catastrophic failure. These results highlight the possibility of flame retardant substances to increase battery safety and establish a benchmark for the next studies on battery technology advancement.

With a special emphasis on enhancing the undergraduate thesis experience, the suggested undergraduate thesis changes seek to include battery safety concerns in safety science and engineering teaching. These changes, which emphasize the need for flexible and responsive engineering education programs, are predicted to improve student readiness for industrial demands, synchronize education with technological advancement, and foster cooperation between industry and academia. The first step in transforming educational programs is to include sophisticated lithium-ion battery safety techniques in the undergraduate thesis curriculum. The changes will grow as time goes on to include new battery safety laboratory courses, industry leader partnerships for practical training,

and the integration of safety science subjects into a wider spectrum of engineering disciplines. Ultimately, a thorough educational program that is in line with the changing demands of safety science and engineering has to be developed.

Furthermore crucial are the creation of policies and the standardization of business procedures. Safety laws and regulations must be updated to reflect the most recent scientific discoveries and technical developments as battery technology develops. Reaching this objective will need cooperation between regulatory agencies, industry stakeholders, and researchers. This work illustrates the use of PFPN as an efficient flame retardant addition, therefore adding to the scientific understanding of lithium-ion battery safety. Though novel mechanisms underlying thermal runaway were not found by this study, it offers insightful information on doable solutions to raise battery safety. We increased the thermal runaway starting temperature and lowered the peak temperatures during exothermic reactions by adding PFPN to the electrolyte. These results show a workable approach to reduce the possibility of thermal runaway and improve the general safety of lithium-ion battery.

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