The Science of Thermal Runaway:
Engineering Safe Solutions – Battery Enclosure

Teacher Overview – Battery Enclosure
Engineering Design Process

Welcome to the Science of Thermal Runaway's engineering design process: Engineering Safe Solutions for a Battery Enclosure. This teacher overview will help you support your students through the process. We want to begin by reassuring you that you do not need to be an expert in engineering to use this engineering design process with your students. Every time you create something, from a new recipe to a lesson revision, you are engaging in the design process. Like other methods of design, the engineering design process is a method for conceiving, designing, testing, and refining a product or idea. The engineering design process focuses on measurable design requirements and data-driven design decisions. You can read more about engineering design on the NGSS website (link).

At a Glance: Engineering Safe Solutions – Battery Enclosure

Define the Problem

Throughout the Science of Thermal Runaway pathway, students will define the criteria and constraints of a safe battery enclosure.

(1) Define Materials for Success

Students identify thermal properties of materials then determine which materials meet the criteria for thermal performance.

(2) Develop Solutions

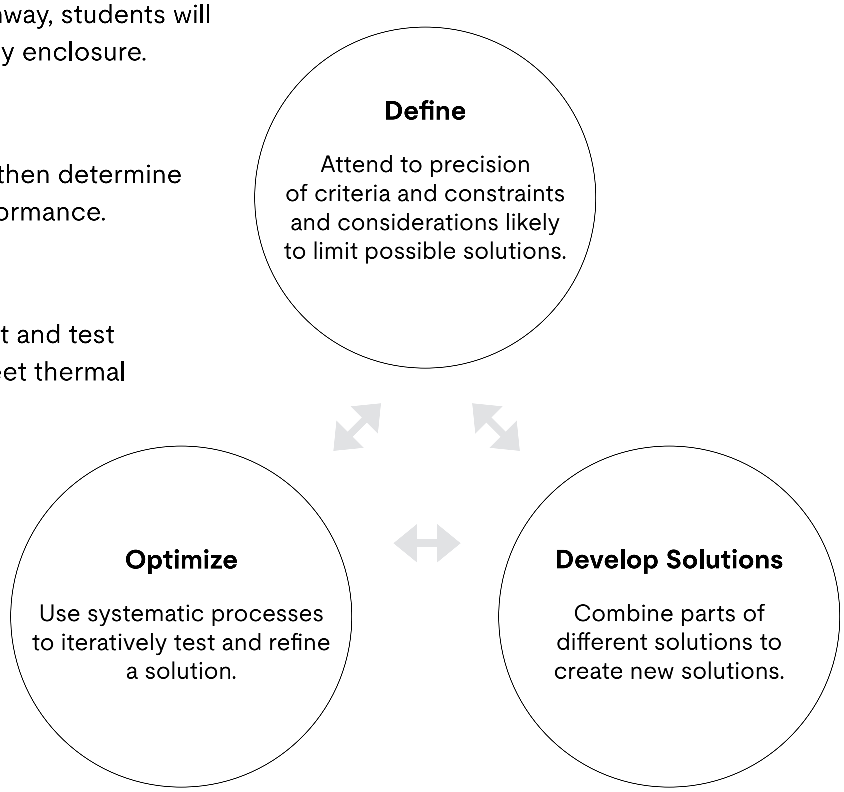
Utilizing their own data, students design, construct and test a portable electric power device enclosure to meet thermal performance standards.

(3) Optimize Designs

Students modify and improve their enclosure design based on repeated test resulted and analyze each design against thermal performance standards.

(4) Communicating Ideas

Students construct arguements about the best enclosure design using empirical evidence from the challenge and scientific reasoning.



This extension offers a complete engineering design cycle situated in the problem of thermal runaway in lithium-ion battery-powered devices. You are invited to choose the activities that make the best sense for you and your students. They can be completed in the order described or as stand-alone, one-at-a-time activities, based on your needs. Shown in the visual, and described below, is what we consider an ideal instructional sequence; though we again emphasize that it is not one size fits all option.

We think it is important to note that Define the Problem has been situated primarily in the online module; and therefore, is not numbered. However, we did think it important to provide some guidance for how we envisioned its execution. Guidance and suggestions for it and each subsequent part of the engineering design cycle are outlined in the following pages.

Background to the Problem of Thermal Runaway

What's the problem? Rechargeable lithium-ion batteries can experience a phenomenon called thermal runaway. Thermal runaway is a rapid, uncontrolled increase in temperature leading to additional increases in temperature. This can result in fire ignition within the device, which could burn the user, or risk other cells in the battery pack.

Thermal runaway can occur because of immediate or latent damage to the battery, in particular damage that causes an internal short circuit. Throughout the Science of Thermal Runaway pathway, students identified hazards facing lithium-ion batteries used in portable electrical-powered devices, and then through this engineering design extension identify significant criteria for a safe battery enclosure. Students will continually return to the theme that battery enclosures for portable electrical-powered devices need to manage the heat from a battery, both during normal operation and in the event of thermal runaway.

The challenge. In this engineering design process, students select, test, and choose a material(s) to use in a battery enclosure to safely manage thermal energy. Students will test their design for thermal performance criteria like UL safety engineers test portable electric devices to meet Standard UL 2272. Students will follow a four-part engineering design process to (1) define thermal properties of materials that are desirable for the design, (2) develop solutions using these materials in a prototype, and (3) optimize their designs based on data, repeated tests, and scientific understanding of thermal properties. Finally, students will (4) communicate their results about what materials and design are best for mitigating the risk of thermal runaway.

Defining the Problem of a Safe Battery Enclosure (MS-ETS1-1)

The first step in the engineering design process is defining the problem to be engineered. As mentioned earlier, this portion of the engineering design cycle is primarily situated in the online module. It includes opportunity for students to understand **design requirements** such as **criteria** (goals of your design) and **constraints** (mandatory elements in the design, or clear restrictions on the product or process). In this portion of the engineering design extension, you will guide students as they refine their problem definition to focus on the excess heat from batteries that can lead to thermal runaway.

Materials:

- Student Guide from the Science of Thermal Runaway pathway
- Resource cards scaffold, if needed

Teaching Guide: Define the Problem

<u>Facilitate Discussion of **Criteria**</u>

After students read the first page of the student guide, "The Science of Thermal Runaway: Engineering Safe Solutions," facilitate discussion about the design's criteria, or goals.

Teacher Notes/Guiding Questions:

- Criteria are measurable indicators of a design's success and often comparatives (words ending in "-er"). Examples: go faster, cost less, or even save money
  - *What criteria could be measured to indicate the success of your design? (temperature)*
  - *Where do these criteria originate? (UL Standard)*
- Data about a design's form and/or function should be gathered and analyzed to determine how successfully a design meets the criteria.
  - *What data could be collected and analyzed to determine if your design is successful? (internal and external temperature over a certain period of time)*
- Since criteria are goals that can be completed to varying degrees, the design could successfully achieve a criterion to a higher or lower degree. For instance, a design criterion could be, "The hoverboard should be as lightweight as possible." For this criterion, it would be better if the hoverboard was very lightweight, but the hoverboard design could still be successful if it was a little heavier (MS-ETS1.A).

<u>Facilitate Discussion of **Constraints**</u>

Transition discussion to support students in delineating the constraints, or measurable "musts," for their designs.

Teacher Notes:

- If these constraints are not met, then the design cannot succeed. Some constraints for thermal performance are provided in the student guide for The Science of Thermal Runaway: Engineering Safe Solutions.
  - *What constraints have already been identified for us in this engineering problem? (no more than 5F increase outside and no more than 7F increase inside)*
  - *Why can't we accept an internal temperature change of 5.2 degrees? (Any temperature outside the UL Standard runs the risk of leading to thermal runaway.)*
  - *What other constraints do we have in this engineering challenge? (Materials that can be used to test ideas based on classroom experience versus professional lab.)*
- Depending on the device students choose to engineer an enclosure for, they may identify additional constraints. Be sure to review the constraints to see if they are mandatory requirements or limitations on the design.

<u>Support Formalized Sense-Making of **Problem Statement**</u>

After a whole-group discussion of criteria and constraints, students individually write a refined problem statement in their student guide. Support students in formalizing their ideas by encouraging them to narrow down their statement to the more important criteria and constraints.

Teacher Notes:

- As you walk around to read what students are writing, you may find that students have an excess of variables (e.g., flammability of the encasement, location of different parts in the circuit). When you come across these descriptions, commend students for their thinking, but also remind them that our current focus is based on what we use to enclose the battery.
- Encourage students to share their finalized, or refined problem statements (MS-ETS1-1).

Summarize this portion of the engineering extension by making explicit to students that they've completed an important part of engineering design: problem definition. Whether you plan to continue with the next part of the engineering design challenge or you are stopping here, it will benefit students for you to ask questions like:

- *What might next steps for this engineering challenge be like?*
- *How has your understanding of engineering changed (or remained the same) as we have worked through this?*

Define the Problem

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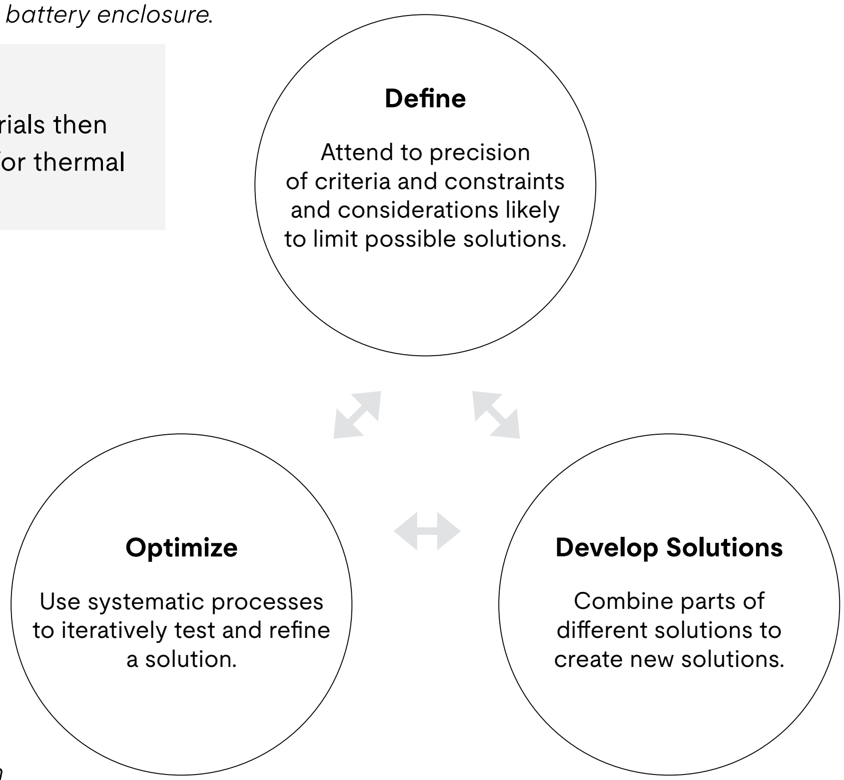


Define Materials for Success

In this portion of the engineering extension, students investigate the thermal properties of various materials to identify what materials will be most successful at meeting the design constraints for their enclosure's thermal performance. The choices for materials will be a natural constraint of the engineering challenge and a scientific core idea we want students to consider in each of the subsequent parts of the engineering design process. This constraint applies relevant scientific principles of thermal properties of matter (e.g., Is this a conductor or insulator? What is the ignition temperature of this matter? What is the specific heat of this matter?).

As students investigate these core ideas of thermal properties of various materials you may find it useful to provide separate lessons on thermal conductivity and/or specific heat. We encourage you to create these separate opportunities as you see appropriate for meeting your students' needs. Our teaching guide is written with this background knowledge already in place.

Materials:

- Engineering Design Challenge Student Notebook
- Materials for testing
- Prototype for enclosure
- Temperature probe
- Infrared thermometer

Teaching Guide (1): Define Materials for Success

Introduce Focus: Identify Materials for Success

Explicitly establish the learning goal as understanding specific properties of matter and their interactions with thermal energy.

Teacher Notes/Guiding Questions:

- Consider assigning students the role of a materials engineer that needs to evaluate a material's thermal performance.
- Elicit student thinking about why testing materials is important before testing in/around the battery enclosure. Guiding questions could be like:
  - *Why does it make sense to first investigate the thermal properties of the different materials? (To make evidence based, informed decisions about a potential solution for a safe battery enclosure.)*

Facilitate Ideation: Individual and Teams

Ideation, or brainstorming, should activate student prior knowledge for thermal properties. During the ideation process, encourage students to recall and apply specific language like conductor and insulator as they brainstorm a list of options for different materials to use in their investigation.

Teacher Notes/Guiding Questions:

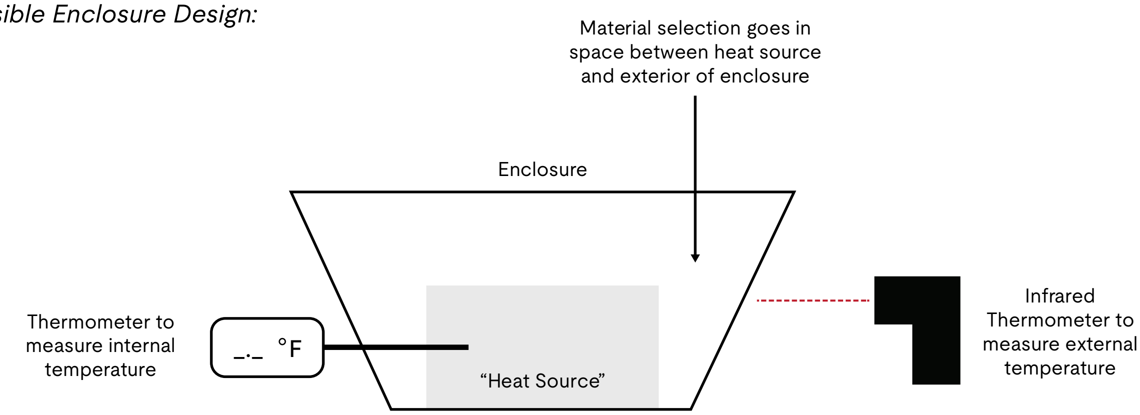
- Support students in their ideation and individual development of a model to show their current thinking about what might work and why. Possible supports are outlined in the student handout (page 2).
- Once individual ideation is winding down, transition students to share ideas as a team. It is important that discussion in the team encourages all ideas to be voiced. Supports for team ideation are outline in the student handout (page 3).
- As you walk around to monitor student active engagement, look for opportunity to ask questions of the small groups that focuses attention on what thermal properties will help them meet the thermal performance standards (constraints) of the design challenge.
  - *Why is the team starting to think that _____ might be the best material?*
  - *What properties does it (they) have?*
  - *Did someone suggest something similar? … different?*
  - *Have you considered ______________? (see ideas in suggested materials for testing)*
- Students close their conversations by choosing a material to test for success. This decision and their rationale should be recorded in the student guide and shared with you to guarantee materials are available for testing.
- If the students' decision includes materials, you do not have access to, then you may need to suggest they bring the material for testing purposes.
- Suggested Material for Testing
  - *Dough, Wood chips, Soil, Sand, Cardboard*
  - *Various types of plastic such as Styrofoam*
  - *Plastic from disposable containers*

Prepare the Enclosure and Material(s) to Test

Initial measurable observations about the thermal properties of matter need to be tested before given full consideration as a solution. Therefore, students now need to test their thinking about the decisions they have made as a team. Teams need to test their material for its effectiveness and therefore preparations for conducting this investigation need to occur. The guidance described below uses an enclosure, like a small rectangular plastic container, as a simplified model of portable electric-powered device. The purpose of this model is to simulate the exterior of a lithium-ion battery-powered device, like a hoverboard, and thus has inherent advantages if built as suggested.

Suggested Preparations for Enclosure:

- Ensure that the enclosure you use includes space between the heat source (battery/handwarmers) and exterior. This space allows you to test materials between the heat source (battery/handwarmers) and its outside.
    - *Possible Enclosure Design:*



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    - *If you prefer not to construct an enclosure, then <u>purchase a container with a void in it.</u>*
    - *When preparing the enclosure, ensure that there is a hole to access the inside of the enclosure. This will be needed during testing to determine any temperature changes.*

Suggested Preparations for Materials to Test

- Open and activate the handwarmers prior to material testing.
- It takes about 20 minutes for handwarmers to reach the optimal temperature of 120°F.
    - *You want the temperature to be relatively stable and consistent among your groups, so that data collection is not impacted by the handwarmers' chemical reaction.*
- Since students will need to measure internal temperature with a probe and external temperature with an infrared thermometer, then you will want to check that students know how to read the temperature data on both types of tools. (Model how to read temperature as needed.)

Prepare for Testing

Before testing, students need to prepare in two ways. First, students need to identify how measurements will be recorded in their data table. (MS-ETS1.B) Second, students need to familiarize themselves with the materials and tools being utilized. (MS-PS3-3) Much of this is supported on pages 3 and 4 of the student guide.

Teacher Notes/Guiding Questions:

- The student guide includes a sample data table that purposefully omits some considerations like recording data from multiple trials.
    - *How could you modify the suggested table to better fit our needs for collecting multiple data points?*
- Consider formatively checking on students understanding of the independent and dependent variables to be measured and recorded.
    - *Which variable is being manipulated by you? Would this be labeled the dependent or independent variable?*
- When checking that students know how to use and read the infrared thermometer and temperature probe, this is a good time to decide which unit of measurement (Celsius or Fahrenheit) should be recorded. We encourage use of Celsius.
    - *We all need to agree on which unit of measurement for temperature we will record. What do you all think?*
    - *Should we record Celsius or Fahrenheit? Why do you think this?*
    - *Why is it important for us to agree on this before we start testing our different materials?*

- An important note about infrared thermometers: The temperature reading fluctuates quickly. Students may decide that the "average temperature" reading is most useful. This process for data collection will also need to be decided prior to material testing so that all data is collected in the same way.
    - *What are you noticing about the temperature reading from the infrared thermometer?*
    - *How can we create a reliable data set if the reading changes so quickly?*
    - *Again, why is it important for us to agree on this data collection process before we start testing our different materials?*

Test Materials

Allow students to test their material for its thermal properties.

Teacher Notes/Guiding Questions:

- You may want to assign or encourage groups to test different materials. This will guarantee your class data is representative of all the materials options (MS-ETS1.C).
- As you walk around to support and monitor students, encourage active participation by all group members, commend accurate data collection, and challenge students to collect data for more than one material if time allows.

Make Sense of Outcomes: Teams and Class

Once data for material(s) has been recorded, students need to first analyze and interpret their team data (page 4 of student guide), and then share this analysis with the class. The focus for data analysis is on whether their selected material met the constraint (safety standard) and how these results compare to scientific understandings of thermal properties. It is important to provide students an opportunity to share team data and then analyze these multiple sources of evidence from their classmates (MS-ETS1-2). This is an opportunity for collective sensemaking about thermal properties.

Teacher Notes/Guiding Questions:

- *How do the materials between our teams compare?*
- *What does the 'best' data look like?*
- *How does this data compare to what we understand about insulators and conductors?*
- *What might this data mean in terms of the specific heat for _________ material?*

Summarize this portion of the engineering extension by making it explicit to students that they've completed an important part of engineering design: defining materials for success. Whether you plan to continue with the next part of the engineering design challenge or you are stopping here, it will benefit students for you to ask questions like:

- *What might next steps for this engineering challenge be like?*
- *Why would it be important to take these next steps?*
- *How has your understanding of engineering changed (or remained the same) as we have worked through this?*

Define the Problem

Throughout the Science of Thermal Runaway pathway, students will define the criteria and constraints of a safe battery enclosure.

(1) Define Materials for Success

Students identify thermal properties of materials then determine which materials meet the criteria for thermal performance.

(2) Develop Solutions

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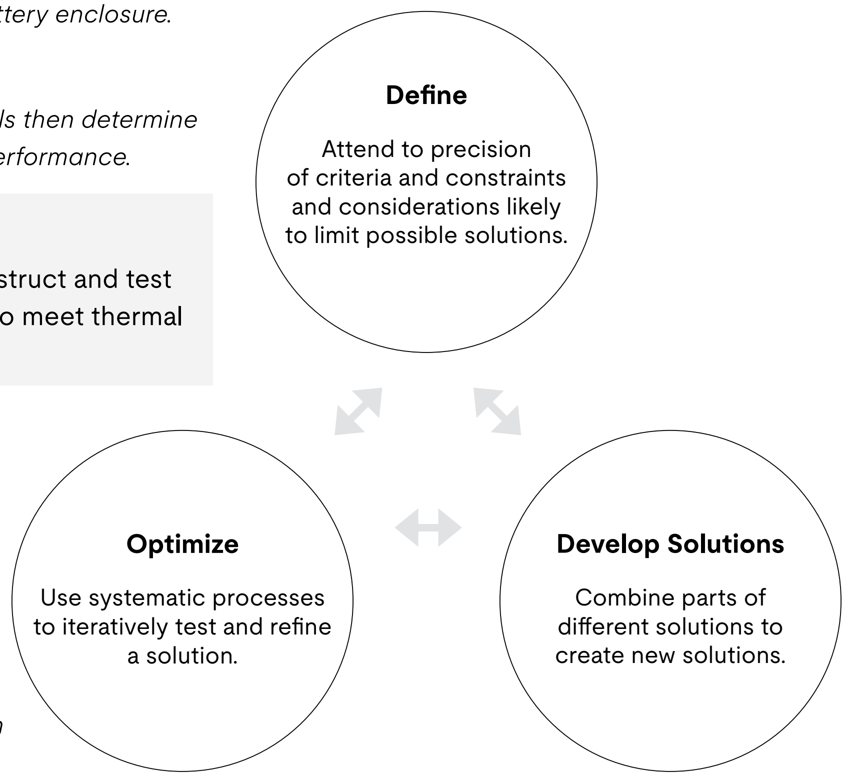
Students construct arguements about the best enclosure design using empirical evidence from the challenge and scientific reasoning.



(2) Develop Solutions

Students apply what they have come to understand from defining material of success to develop solutions. This includes designing and testing their battery enclosure for the most effective material(s) at reducing risk of thermal runaway. Students test their design against the provided thermal performance constraints, just like product designs are measured based on the constraints of UL Safety Standards.

Materials:

- Engineering Design Challenge Student Notebook
- Class data on thermal performance of materials or teacher-provided data for students to reference when making decisions

Teaching Guide (2): Develop Solutions

<u>Establish Goals of Engineering Design Process Phase: Developing Solutions (MS-ETS1.B)</u>

Explicitly establish the learning goal is to engage in the engineering design process of developing solutions in a more informed way. It is important to note that the focus for this portion of the engineering design process is in the informed decision making for a refined design, not testing (see pages 5 and 6 of the student guide).

Teacher Notes/Guiding Questions:

- If you did not choose for students to define materials for success through an investigation, then you can provide some appropriate data for students to use when making decisions. Relevant data could include identification of materials as insulators or conductors, specific heat, thermal conductivity. For example: (insert data table)

Specific Heat Data of Some Common Substances

Material	Specific Heat Capacity (J/g °C)
Water	4.179
Air	1.01
Glass	0.753
Paper	1.336
#6 plastics (polystyrene) *Packing peanuts, cafeteria trays, egg cartons*	13-15
#5 plastics (polystyrene) *Tupperware, dairy containers*	1.920
Soil *Depends on whether soil is dry (lower) or wet (higher)*	0.8-1.48
Wood Birchi, commonly used in popsicle sticks	1.9
Clay	0.92
Cork	2.0
Copper	0.385
Steel	0.490

Thermal Conductivity of Common Substances

Material	Thermal Conductivity (k) (W/mK)
Water	0.60[1]
Air	0.026[1]
Glass	0.81[3]
Paper	0.5
#6 plastics (polystyrene) *Packing peanuts, cafeteria trays, egg cartons*	0.3
#5 plastics (polystyrene) *Tupperware, dairy containers*	0.1-0.22
Soil *Depends on whether soil is dry (lower) or wet (higher)*	0.5-1
Wood Birchi, commonly used in popsicle sticks	~0.15[1]-0.19[1]
Clay	0.6
Cork	0.43
Copper	401.0[1]
Steel	60.5[1]

- If you are using the data table, rather than direct observations from (1) Defining Materials for Success, then you will want to guide sense making with these types of questions:
    - *What does the specific heat value mean to you?*
    - *If you think about walking on sand versus walking on _____, then which value do you think is more closely aligned to the specific heat of sand?*

<u>Develop a Model of Redesign</u>

Students will consider the thermal performance of the tested materials, the thermal performance criteria (standard), and scientific principles to design a solution for a safe battery enclosure. Students will develop a model of the redesign and then caption this model with statements about data and scientific principles that support their decisions (MS-ETS1-3). (see pages 5 and 6 of student guide)

<u>Predict and Justify</u>

As students prepare for a new round of testing, we encourage to build student confidence in sense-making of the criteria and materials for success as they make predictions about the outcomes in the (upcoming) iterative testing (see page 6 of the student guide). As students make predictions and justify their decisions, consider asking these types of questions:

- *What do you think makes your design the best at meeting the thermal performance standards?*
- *What data did you collect earlier in our process that makes you think this?*
- *What other materials were you considering? How did you eventually decide on this one?*
- *What are you anticipating will occur when we run these next tests?*
- *Based on what you have heard others share, which material do you think will be your biggest competitor?*

Summarize this portion of the engineering extension by making explicit to students that they've completed an important part of engineering design: developing solutions. Whether you plan to continue with the next part of the engineering design challenge or you are stopping here, it will benefit students for you to ask questions like:

- *Why would it be important to take the next steps of testing our design solutions?*
- *How did learning about the outcomes from other teams impact your decision making?*
- *How has your understanding of engineering changed (or remained the same) as we have worked through this?*

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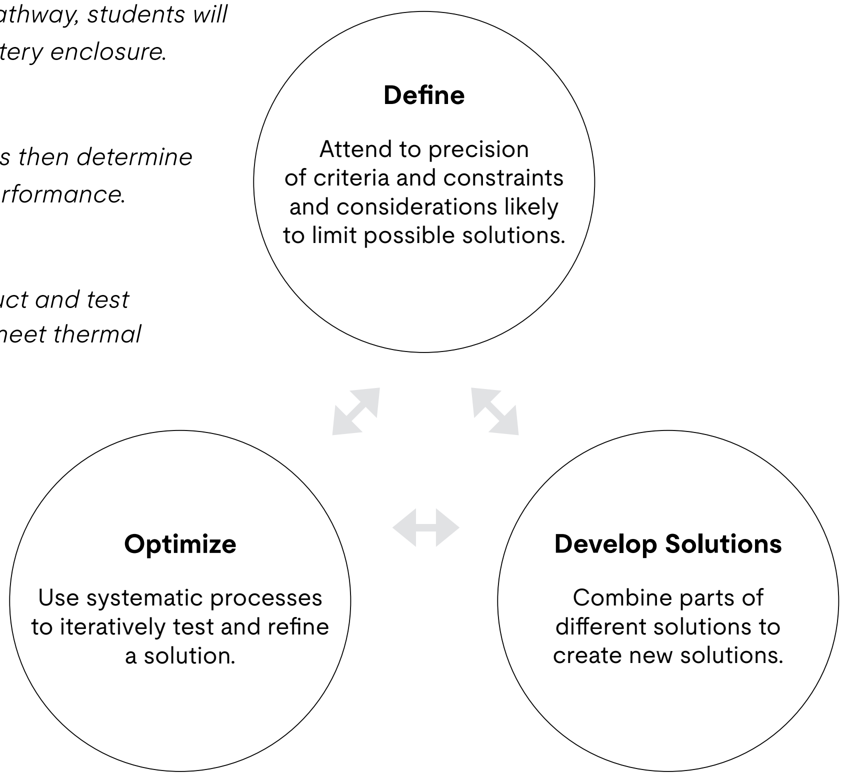


(3) Optimize Design and Iterative Testing

In this portion of the engineering design process, students test revised ideas and designs for their effectiveness at minimizing the risk of thermal runaway. Lithium-ion battery enclosures must maintain an internal and external temperature balance for safety. UL safety engineers test products against thermal performance standards like UL2272 to certify that products are safe. This iterative testing process ensures customers can expect safe products.

Materials:

- Engineering Design Challenge Student Notebook
- Student enclosure design
- Materials for testing
- Prototype for enclosure
- Temperature probe
- Infrared thermometer

Teaching Guide (3): Optimize Designs

Establish Goals of Engineering Design Process Phase: Optimizing the Design Solution (MS-ETS1.C)

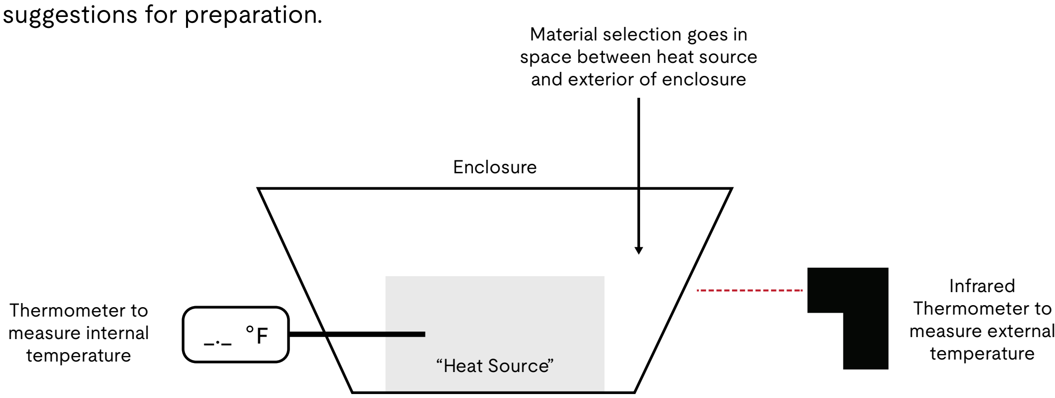
Explicitly establish that the learning goal is to engage in the engineering design process of iterative testing and optimizing design solutions. Depending on how you chose for students to arrive at this part of the engineering design process, they have had opportunity to evaluate multiple designs, both their own as well as classmates'. In this phase of the engineering design process, students incorporate the most effective outcomes to test a final design.

Prepare Design

With your support students prepare their revised enclosure for testing. These revisions are based on their evaluation of previous solutions from both their own group and their classmates. As a reminder, students may choose to combine parts of these solutions in their new design (MS-ETS1-3). (see procedure 1 and 2 on page 6 of the student guide)

Teacher Notes/Guiding Questions:

- If you did not choose for students to use the prototype enclosure in previous experiences, then you will want to prepare the enclosure and materials for testing. See Teacher Notes/Guiding Questions in (1) Define Materials for Success for more specific suggestions for preparation.



Iterative Testing

Students should carefully construct their plan for collecting and recording data. This record of data could involve creating their own data table (MS-PS3-4) or using one you provide. Students should collect data from multiple trials of their designed test to continue to refine their design.

Teacher Notes/Guiding Questions:

- The student guide includes a sample data table from (1) Define Materials for Success that purposefully omits some considerations like recording data from multiple trials; but encourages students to consider what data collection should be like. If your students had this experience, then the student guide will serve as an appropriate scaffold to support students in recording data from their iterative testing. If your students did not have this experience, then you may need to provide a scaffold like the one described in (1) Define Materials for Success.

Iterative Testing

Once iterative testing data has been recorded, students need to make sense of the outcomes. Students need to consider whether their design decisions included measurable outcomes that met the constraint (safety standard) by first calculating the mean change in temperature. Then, students need an opportunity to analyze their own, and other team data, for similarities and differences between design performance.

Teacher Notes/Guiding Questions:

- Consider guiding class discussion from prompts similar to those in the student guide (see page 7):
  - *Did your revised material pass the criteria for thermal performance?*
  - *What characteristics of your team solution worked well?*
  - *What characteristics of other team solutions worked well?*

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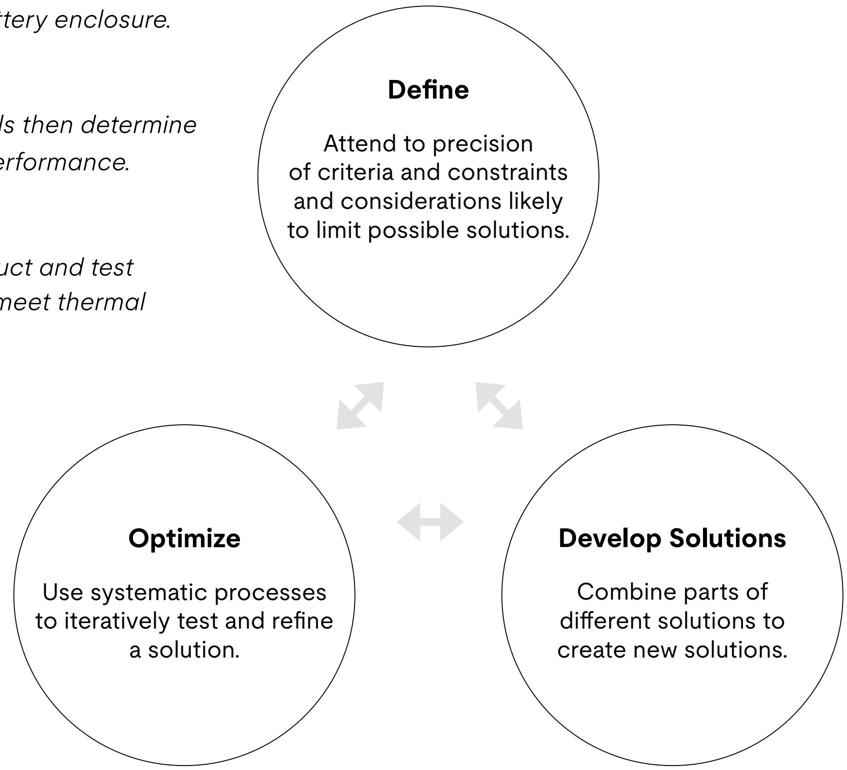

(4) Evaluate and Communicate Ideas

In this portion of the engineering design process, students make recommendations for the most effective design at minimizing the risk of thermal runaway. Engaging in argument based on evidence is the root of science and engineering practices. Creating an opportunity for students to support or refute claims for their own solutions that solve problems in our designed world is our trademark for a quality engineering challenge. (MS-ETS1-2)

Teaching Guide (3): Optimize Designs

<u>Establish Goals of Engineering Design Process Phase: Evaluate Designs and Communicate Findings (MS-ETS1.C)</u>

Explicitly establish that the learning goal is to engage in the engineering design process of engaging in argument from evidence to make a recommendation for the most effective material to enclose the battery found in a lithium-ion powered device. For students this includes a model of their proposed design that has been revised several times and may reflect parts of different solutions from previous designs (both their own and their classmates').

Support Development of Argument/Recommendation

Your students' previous experiences with constructing an argument will likely determine how you support their development of an argument and recommendation about how the battery enclosure for a lithium-ion powered device should be designed.

Teacher Notes/Guiding Questions:

- **Claim:** Students should consider the thermal performance standard, your stakeholders, and the criteria and constraints facing a lithium-ion battery powered device when making a decision that represents their claim, or recommendations, for the design of the battery enclosure.
  - *Before students begin to consider their claim/recommendation, consider a way to compile all class data into a table or scatterplot. This would also provide an exemplar model for students to later reference when providing the evidence that supports their claim/recommendation.*
  - *It is intentional that students do not have to construct their final design. This allows for some creativity in the final recommendation and allows students to represent features that may not be able to complete in the classroom.*
- **Evidence:** Students use empirical evidence from data tables to develop a visual representation, like a scatterplot, to support their claim/recommendations. Students are prompted in the student guide (see page 8) to show the relationships between their proposed material(s) (independent variable) and the thermal performance (dependent variable).
  - *Consider referring students back to the compiled class data table or scatterplot as an exemplar model for students to use.*
- **Reasoning:** The students' justification (reasoning) to support their proposed design (claim) should relate back to scientific knowledge.
  - *A word bank is provided in the student guide (see page 8) for students to reference when working to apply scientific language in their justifications.*
  - *You may also find sentence starters can help students articulate their thoughts. An example might be:*

    I chose ________ because it is a ______________, you can see in the data that the ____________ is _____________.
    material — thermal property — type of energy — what happens

Communicate/Share Out Recommendations

In summary of this engineering design process, you may find it helpful for students to engage in a final share-out of recommendations. There are myriad ways to consider how this could look and sound: from a Gallery Walk to TQE (Thoughts-Questioning-Epiphanies) Method to a Mock Meeting with the UL Research Institute. Whatever your choice, this opportunity to formalize and reflect on what was learned throughout this process is important to consider.

References:

NGSS Lead States. 2013. Next Generation Science Standards: For States, By States. Washington, DC: The National Academies Press.