Reciprocating Engines

Session Time: Five, 50-minute sessions

DESIRED RESULTS

ESSENTIAL UNDERSTANDINGS

The intended purpose and use of an aircraft drives aircraft design considerations and construction techniques, materials, and components. (EU1)

A deep understanding of how an aircraft operates, which enables a pilot to fly an aircraft to its maximum capabilities in both normal and abnormal situations. (EU5)

ESSENTIAL QUESTIONS

1. How does a reciprocating engine work?
2. What kind of reciprocating engines are used in aircraft?

LEARNING GOALS

Students Will Know

- What a reciprocating engine is and be able to describe its main components
- The four strokes that define how an engine produces power
- The differences between gasoline and diesel engines

Students Will Be Able To

- *Differentiate* among various engines according to their features. (DOK-L3)
- *Explain* how a spark ignition four-stroke engine works using models and appropriate terms. (DOK-L3)
- *Construct* a Stirling engine and compare its properties to those of a four-stroke internal combustion engine that utilizes spark ignition. (DOK-L3, 4)

ASSESSMENT EVIDENCE

Warm-up
Students watch and describe, in their own words, an animation showing a typical four-stroke combustion cycle and brainstorm the animation's relevance to airplane engines.

Formative Assessment
Using illustrations, students identify and describe each stage of the four-stroke combustion cycle, including the name of each stroke, its function, the position of key engine components, and the order in which it takes place.

Summative Assessment

Students build a working Stirling engine, then use what they've learned to assess the similarities and differences between Stirling engines and internal combustion engines.

LESSON PREPARATION

MATERIALS/RESOURCES

- Reciprocating Engines Presentation
- Reciprocating Engines Student Notes
- Reciprocating Engines Student Activity 1
- Reciprocating Engines Student Activity 2
- Reciprocating Engines Student Activity 3/Teacher Notes 3
- Reciprocating Engines Student Activity 4
- Reciprocating Engines Teacher Notes 1
- Reciprocating Engines Teacher Notes 2
- Reciprocating Engines Teacher Notes 4

Build a Stirling Engine (per class)

- 1 - Glass test tube, preferably 20 x 200mm (20 x 150mm may be substituted, if needed)
- 1 - Rubber test tube stopper with a hole in it
- 6 - Glass marbles to fit in the test tube
- Two-sided tape
- 1 - Glass Syringe, 5ml (Note: Using glass is essential.)
- 1 - Wood pencil with graphite lead
- 1 - Sterno (Note: A tea candle may be substituted, but may not provide enough heat.)
- 1 - Block of wood, approximately 6" x 3"
- 1 - Piece of clear acrylic tubing, 3" in length and measuring 9/32" OD x 5/32" ID
- 1 - Wire pant hanger, approximately 12" long (Note: Dry cleaner hangers work perfectly.)
- Pliers
- Ruler

LESSON SUMMARY

Lesson 1 - Reciprocating Engines
Lesson 2 - Propellers
Lesson 3 - The Power Cycle: Intake Systems
Lesson 4 - The Power Cycle: Combustion and Exhaust
Lesson 5 - Turbochargers and Superchargers

The lesson begins with a warm-up exercise in which students watch a video animation showing a typical four-stroke combustion cycle and brainstorm its relevance to airplane engines. The video should be watched with the sound off so that students can form their own ideas about what they're seeing, rather than listening to the narrated explanation.

Next, students are introduced to essential terms, including *internal combustion engine* and *reciprocating engine.* Students get a brief overview of the combustion cycle before examining each of the four strokes in depth. Students will learn the process and purpose of the intake, compression, power or combustion, and exhaust strokes. For each stroke, students will learn the location and direction of travel of the piston, the position of valves, and what is happening inside the cylinder.

In the formative assessment, students will use what they've learned to identify and explain each of the four strokes.

Next, students will take a closer look at the parts of a reciprocating engine and the key processes that enable the engine to function, such as lubrication. Students will then consider the different ways in which engines can be classified, including ignition type, cylinder arrangement, and cooling method. Students will examine each of these areas in depth, learning the differences among engine types. They will use this information to complete an activity in which they identify the cylinder arrangement of different engines and provide information about key characteristics of each arrangement.

Students will also briefly consider the differences between gasoline and diesel powered engines, including the advantages and disadvantages of each.

Finally, the students will work in small groups to build functioning Stirling engines. They will compare these models to what they've learned about reciprocating engines, identifying similarities and differences and presenting their findings to the class.

BACKGROUND

Most light aircraft are powered by internal combustion engines that burn chemical fuel (typically gasoline or diesel) to produce mechanical work (such as turning a propeller). The name "internal combustion engine" refers to the fact that these engines are powered by combustion (the rapid, controlled burning of a mixture of fuel and air) which takes place entirely within the engine. In order for combustion to take place, fuel, air, and an ignition source must be present.

A reciprocating engine is a type of internal combustion engine that translates the up-and-down (reciprocal) motion of pistons into rotational motion through a connecting rod that links each piston to the crankshaft. Each piston is contained within a cylinder. It is here, inside the individual cylinders where the four-stroke combustion cycle takes place.

Each time a piston moves up or down within its cylinder is considered a "stroke." The four strokes that make up the combustion cycle are:

1. Intake, where a mixture of fuel and air are pulled into the cylinder;
2. compression, where the mixture is squeezed to increase its density and flammability;
3. combustion or power, where the fuel-air mixture is ignited and burned;
4. and exhaust, where the spent gases are pushed out of the cylinder and into the exhaust system.

There are many variations in reciprocating engines, but they all function in essentially the same way.

In aircraft, these variations may be based on cylinder arrangements (in-line, radial, V-type, horizontally opposed), ignition source (spark ignition or compression ignition), cooling system (air cooled or liquid cooled), and number of strokes in the combustion cycle (two or four, although two-stroke aviation engines are rare).

DIFFERENTIATION

To support student comprehension in the **EXPLORE** section, encourage students to take notes using a graphic organizer, such as a T-Chart or Tree Chart in order to understand and structure new information when comparing an internal combustion engine and a reciprocating engine and when classifying reciprocating engines.

To support student engagement and comprehension in the **EXPLORE** and **EXPLAIN** sections, create learning centers for students to rotate to in small groups to explore the lesson concepts. Create task cards for each center to focus student learning and give opportunities for reflection.

To support student engagement and motivation in the **EVALUATION** section, allow for student choice in how they demonstrate the concept. For example, you may allow students to create an animated video with text and/or voiceover to demonstrate a stirling engine. This strategy increases student motivation by personalizing the learning experience.

LEARNING PLAN

ENGAGE

Teacher Material: Reciprocating Engines Presentation

Slides 1-3: Introduce the topic and learning objectives of the lesson.

Slide 4: Conduct the **Warm-Up**.

Warm-Up

To begin the lesson, tell students they will watch a video animation that shows a critical process used in the type of engine that powers a typical small airplane. Also tell them that the bluish substance at the start of the video is a mixture of fuel and air.

Begin playing the video with the sound turned off. Be prepared to play only the first minute of the video, pausing at several points to ask students what they believe is happening.

- "4 Stroke Engine Animation" (Length 1:19)
  http://video.link/w/9fWf

- Pause at 0:12 and ask students what they observed in the first few seconds of the video.

Students should note that the chamber in the engine is filling with the mixture of fuel and air. As the chamber fills, the piston (students will likely not yet know this term) moves down.

- Pause at 0:28 and ask students what they observed in the second segment.

The valve that lets fuel and air into the chamber closes and the piston begins to move back up. Again, students will likely not know these terms, but they should note that as the piston moves up, the fuel-air mixture is compressed. Ask students what happens to gases as they are compressed. (Pressure and temperature both increase.) This is represented by the color change in the animation: the "cool" blue of the mixture changes to a "hotter" purple.

- Pause at 0:44 and ask students the same question.

At the beginning of this segment, a spark at the top of the chamber (from the spark plug) causes the fuel-air mixture to burn. The expanding gases force the piston back down.

- Pause at 0:58

At the beginning of this segment, another valve opens at the top of the chamber and the piston begins to move back up. As the piston moves up, the substance in the chamber (which has now turned a smoky color) is forced out of the chamber through the valve that has opened. Students should be able to infer that the smoky substance is exhaust produced by the burning fuel.

After students have described each segment, watch the video again, without pausing. Then, ask students if they can hypothesize how the processes they have just seen in the animation relate to airplane engines—that is, how might these processes generate power that can be used to move an airplane?

EXPLORE

Teacher Materials: Reciprocating Engines Presentation, Reciprocating Engines Teacher Notes 1
Student Materials: Reciprocating Engines Student Activity 1, Reciprocating Engine Student Notes

Slide 5: An engine is a device that produces useful work by converting energy from one form to another. Most commonly, engines convert chemical energy from a fuel into mechanical energy.

In an internal combustion engine, a mixture of fuel and air is burned. This is called combustion. The process of combustion happens entirely within the engine. Virtually all motor vehicles, including automobiles and light aircraft, use this type of engine, making internal combustion engines engines the most popular engines currently in use.

Slide 6: A common type of internal combustion engine is the reciprocating engine. In a reciprocating engine, the linear (forward-and-backward or up-and-down) motion of pistons is converted into the rotary motion of a crankshaft, which generates the useful power of the engine. Each forward and backward (reciprocating) motion of the pistons is called a stroke. Reciprocating engines are very common in small general aviation airplanes.

Ask students: What types of machines use reciprocating engines? Possible responses include ships, tractors, motorcycles, cars and household machines like lawn mowers and generators.

Slide 7: Reciprocating engines come in different designs, but all have similar parts. Provide students with **Reciprocating Engines Student Notes** to review the basic parts of a reciprocating engine. (The following numbers correspond to the diagram in this part of the presentation.)

1. Intake port: The fuel-air mixture is channeled into the cylinder through this port.
2. Intake valve: This connects directly to the intake port and is a barrier between the intake port and the cylinder. It opens to let the fuel-air mixture flow into the cylinder and closes to prevent further flow of the mixture into the cylinder. Due to the thermal stresses it undergoes, the intake valve is typically constructed out of highly resilient material such as silicon and chrome alloys.
3. Spark plug: The spark plug is the source of ignition in most reciprocating engines. It is connected to an electrical system and provides sufficient electrical spark at the right time to ignite and burn the fuel-air mixture. In compression ignition engines, the heat generated by compressing the air serves as the source of ignition. In these engines, fuel is sprayed into the hot, highly compressed air and it ignites.
4. Exhaust valve: This connects directly to the exhaust port of the cylinder. It opens and closes intermittently between the strokes of the piston to allow the gases that result from burning the fuel-air mixture to escape into the exhaust system. Both the intake and exhaust valves are subjected to very high stresses from varying temperatures due to combustion. Thus, they are constructed out of high-strength alloys that can withstand such high temperatures and pressures.
5. Exhaust port: This port connects the exhaust system to the cylinder. After combustion in the cylinder, the waste gases are expelled from the cylinder through this port.
6. Cylinder head: The head is the topmost part of the cylinder, where all the cylinder accessories are located, including the intake and exhaust valves and the spark plug.
7. Piston rings: The piston rings, located on top of the piston, serve different purposes. They aid in sealing the chamber within which combustion occurs. This ensures gases do not escape during the process, allowing the engine to produce maximum power. The rings also provide lubrication, allowing the piston to slide freely up and down inside the cylinder.
8. Piston: The piston is used to compress the fuel-air mixture supplied to the combustion chamber to a peak pressure point that is sufficient for effective combustion. It also connects to the crankcase and crankshaft and drives the crankshaft to produce the useful work of the engine.
9. Connecting rod: The connecting rod links the piston to the crankshaft. It is the medium through which the linear motion of the piston is converted to the rotary motion of the crankshaft.

10. Rod bearing: This vital part of the engineering design is what enables the rotary motion of the crank pin within the connecting rod.
11. Crankshaft: The crankshaft is located within the engine block and is used to convert linear motion from the piston to rotational energy.
12. Crankcase: This is the main housing that supports all the activities of an operational engine. It houses the crankshaft, connecting rods, and rod bearings.

Slide 8: In order for combustion to happen, an internal combustion engine requires a source of fuel (chemical energy), sufficient oxygen (from air), and an ignition source. Different engines use different fuels and ignition sources, depending on their purpose and design. Fuels may include gasoline, aviation gasoline (avgas), and jet A1 diesel.

In a typical reciprocating engine, once the fuel and air are mixed (in a predetermined ratio), a source of ignition is activated. This starts the process of burning the mixture in a controlled manner within the cylinder. As this mixture burns, gases are released into the surrounding environment. These gases are called exhaust. The release of gases from the combustion process also creates sufficient pressure to push the pistons within the cylinder. The movement of the pistons (and any attached components, such as crankshafts) is what generates the mechanical energy that moves the machine.

Slide 9: In a reciprocating engine, pistons move up and down within cylinders. Each movement, either up or down, is called a stroke. The pistons are attached to a crankshaft by a connecting rod. As the pistons move, they move the connecting rod, which forces the crankshaft to rotate. This process changes linear motion to rotational motion. Two strokes of the piston result in one complete rotation of the crankshaft. Four strokes of the piston, or two revolutions of the crankshaft, form a complete cycle. This cycle repeats continuously to drive the engine. Each stroke in a four-stroke engine serves a specific purpose. The will be explained in the next four slides.

Slide 10: The first stroke in the combustion cycle is the intake stroke. During the intake stroke, the intake valve opens and the piston moves down from the top of the cylinder, or top dead center (TDC). This movement creates a low-pressure area above the cylinder that sucks the fuel-air mixture into the cylinder. As the piston reaches the bottom of the cylinder, the intake valve closes. The exhaust valve is closed throughout this stroke.

Slide 11: The second stroke in the cycle is the compression stroke. During the compression stroke, both intake and exhaust valves are closed, and the fuel-air mixture is trapped within the cylinder. The piston moves back up toward the top of the cylinder. As it moves upward, it compresses the fuel-air mixture within the cylinder. The amount of compression that the cylinder can achieve is based on the manufacturer's design. This value is known as the compression ratio and is directly proportional to the amount of power that the engine can produce.

Teaching Tips

Compression ratio refers to the ratio of the maximum volume a cylinder can hold when the piston is at its lowest point in the cylinder (bottom dead center) to the minimum volume it can hold when it is at its highest point (top dead center). The higher the compression ratio, the more power the engine is able to produce. Diesel engines typically have compression ratios of 16:1, compared to 8:1 for gasoline engines.

Slide 12: The third stroke in the cycle is called the power stroke or combustion stroke. In this stroke, the intake and exhaust valves remain closed. With the piston at the top of the cylinder, the highly compressed fuel-air mixture is ignited (often by a spark from a spark plug). This causes the fuel-air mixture to burn, releasing gases which rapidly expand, forcing the piston down toward the bottom of the cylinder. This downward stroke is what powers the engine.

Slide 13: The final stroke within the four-stroke cycle is the exhaust stroke. The momentum from the crankshaft forces the piston back up toward the top of the cylinder. The exhaust valve is opened; as the piston travels upward, it forces the gases released during the power stroke out of the combustion chamber and into the exhaust system of the engine. This concludes one complete cycle of a four-stroke engine, and the process is repeated many times over.

Slide 14: This illustration shows the complete four-stroke cycle. To put it all together, have students watch the video, which uses an animation to summarize each stroke in the cycle.

- "4 Stroke Engine Working Animation" (Length 3:01)
  http://video.link/w/9F0f

Slide 15: Complete the **Formative Assessment**.

> **Formative Assessment**
>
> Students look at pictures of each stage of the four-stroke cycle. Students name the stroke and give its order in the cycle. Students give a complete description of what is happening during each of the four strokes. Provide students with **Reciprocating Engines Student Activity 1** worksheet. Correct answers are found in **Reciprocating Engines Teacher Notes 1**.
>
> [DOK-L2; *categorize*, DOK-L3; *explain*]

EXPLAIN

Teacher Material: **Reciprocating Engine Presentation**
Student Material: **Reciprocating Engine Student Notes**

Slide 16: Reciprocating engines must be lubricated to function, making the oil system a crucial part of any engine. Oil is typically used for lubrication, cooling, and cleaning of many engines. The pistons are constantly moving up and down within the cylinder at very high speeds. To ensure smooth operation, oil is needed to lubricate the portions of the piston that are in touch with the cylinder. Since these areas, such as the piston head, are subject to high temperatures, the temperature of the oil also rises; a system of circulation is therefore necessary to regulate the temperature of the oil while still providing lubrication to the piston and cylinders. Without adequate oil, a reciprocating engine will seize.

Slide 17: Reciprocating engines can be classified by different aspects of their design. Each of these will be covered in greater detail in upcoming slides.

- Ignition System: A reciprocating engine may utilize spark ignition or compression ignition.
- Cylinder Arrangement: The engine's cylinders may utilize a radial, in-line, v-type, or horizontally-opposed arrangement.
- Method of Cooling: Liquid or air may be utilized to cool the engine.
- Number of Strokes: The engine's pistons may utilize a two-stroke or four-stroke cycle. Note that two-stroke engines are rare in aviation applications and will not be discussed in depth here.

Slides 18-19: Reciprocating engines typically use one of two systems to ignite the fuel-air mixture: spark ignition or compression ignition.

- Spark Ignition: In this system, a spark plug is located near the top of a cylinder. The spark plug is connected to an electrical power source. Electrical current run through the spark plug generates a spark. (Typically, energy in excess of 20,000 volts is necessary to ignite and smoothly burn the fuel-air mixture.) The spark ignites the fuel-air mixture inside the cylinder. Spark ignition systems are widely used due to their lightweight components. Most aircraft engines have two spark plugs per cylinder for redundancy. Spark ignition systems typically use avgas (aviation gasoline) or mogas (motor gasoline) as fuel for combustion. Spark ignition systems are not as efficient as compressed air systems because the peak pressure of the fuel-air mixture is lower; consequently, spark ignition systems produce less power. Spark ignition engines are also more prone to detonation. Detonation occurs when one or more pockets of the fuel-air mixture are ignited outside the normal ignition envelope, causing an uneven combustion of the mixture and reducing the efficiency of the engine. And spark plugs are subject to carbon buildup, called fouling, over time, which can prevent them from firing properly.

- Compression Ignition: In this system, air is compressed within the combustion chamber of the cylinder until it reaches a temperature high enough to ignite as soon as fuel is injected into the cylinder. These systems are less complex in design as they do not need an electrical system to provide ignition. They are more efficient producers of power because they are able to compress the mixture to a much higher peak pressure. Compression ignition systems are generally heavier, as tougher materials are needed to withstand such high temperatures and pressures. However, the overall operating cost of compression ignition systems may be lower; the parts are subject to less wear and tear, and the typical fuels (such as diesel and jet fuel) are readily available.

Slides 20-21: Most reciprocating engines have more than one cylinder connected to the crankshaft. The arrangement of the cylinders in relation to the crankshaft can be used to classify the engine. There are four common arrangements:

- Radial Engines: In this arrangement, the cylinders form a circular pattern around the crankcase. The number of cylinders used is only limited by design. Radial engines have a good power-to-weight ratio and can be cooled easily, since all cylinders are equally exposed to the oncoming air flow. These engines were widely used during World War II and the design remains common today.
- In-line Engines: As the name implies, in-line engines have all cylinders connected to the crankshaft in a straight line. This configuration makes it easier to create a more aerodynamic cowl, as the line of cylinders is narrow, requiring little frontal area. In-line engines generally have a low power-to-weight ratio compared to most other engine designs. Although the design is simple, in-line engines may also require heavier crankcases, making them unfavorable to aviation purposes. They also have inefficient and uneven air cooling systems. Cylinders in front are more exposed to the oncoming air flow, which may cool them sufficiently, while the rearmost cylinders receive very little cooling.
- V-Type Engines: V-Type engines are engines that are arranged in a V-shape in relation to the crankcase. They require a more complex design, since the banks on either side of the case have to be even. The frontal area of a V-type engine is relatively small and this design is more compact than in an in-line engine. V-type engines are also more powerful than in-line engines.
- Horizontally-Opposed Engines: Horizontally-opposed engines are the most common engine designs used in general aviation airplanes. Cylinders are arranged on opposite sides of a crankcase. Each cylinder on one side of the crankcase opposes a cylinder on the other side. This arrangement allows for a lighter crankcase and, consequently, an excellent power-to-weight ratio. The smaller frontal area of the engine make it possible to have a more streamlined cowl that reduces the effect of drag on the airplane.

Slides 22-23: Every engine needs a method of cooling to be able to operate efficiently and prolong the engine life. Reciprocating engines are commonly cooled using one of two methods: air or liquid. Each of these systems will be covered in greater detail in an upcoming lesson.

- Air-Cooled Engines: These engines use a combination of fins on the body of the cylinder and both rigid and flexible baffles around the cowling of the airplane to dissipate heat from the engine. They also trap oncoming air around the cylinders and provide cooling. This design is lightweight and relatively simple. Although it can be used in any arrangement of cylinders, it is more effective when there is more exposure of the cylinders to oncoming air flow. When air is used as the cooling mechanism, the temperature of the engine can vary widely, which causes additional wear and tear on the engine and reduces the life cycle.
- Liquid-Cooled Engines: Liquid-cooled engines can be cooled using either water or oil. They require a more complex system: a circulatory mechanism must be designed to contain the liquid and efficiently dissipate the heat from the engine. In addition, these engines are typically heavier due to the added liquid. However, the cooling mechanism

ensures a more stable range of operating temperature, thus reducing the stress on the engine and prolonging its life.

Slide 24: Engines may also be classified by the type of fuel they burn. In general aviation airplanes, gasoline engines are more common than diesel engines, although diesel aircraft are available. The chart on this slide summarizes differences between a gasoline engine and a diesel engine:

Ignition Type: Gasoline engines typically use spark ignition, while diesel engines typically use compression ignition (though there are exceptions). Compression ignition engines do not require an electricity source for ignition.

Compression Ratio: Gasoline engines have much lower compression ratios—and thus a lot less power—than diesel engines.

Weight: Diesel engines weigh a lot more because they have to be built to withstand the high pressures and temperatures needed to support compression ignition and combustion.

Power Output: Diesel engines have relatively more power output for a given RPM. The compression ratio can also indicate this.

Fuel Tolerance: Diesel engines can tolerate a greater diversity of fuel types, while gasoline engines are very sensitive to the nature of fuel used for operation. Gasoline engines typically require avgas, also known as 100LL. 100 is the octane rating of the fuel, while the LL indicates the presence of lead in the fuel.

Teaching Tips

A fuel's octane rating measures the resistance of the fuel to detonation or knocking during combustion. A higher octane rating implies the fuel is more resistant to knocking. Thus an octane rating of 87 (as in regular gasoline for automobiles) means the fuel is less resistant to detonation than a fuel with an octane rating of 100 (as in avgas).

EXTEND

Teacher Materials: Reciprocating Engine Presentation, Reciprocating Engines Teacher Notes 2
Student Material: Reciprocating Engines Student Activity 2

Slide 25: Provide students with **Reciprocating Engines Student Activity 2** worksheet. Students will review what they have learned by identifying the different engines on this worksheet and describing their features. Correct answers are provided in **Reciprocating Engines Teacher Notes 2**.

EVALUATE

Teacher Materials: Reciprocating Engines Presentation, Reciprocating Engines Teacher Notes 3, Reciprocating Engines Teacher Notes 4
Student Materials: Reciprocating Engines Student Activity 3, Reciprocating Engines Student Activity 4

Slide 26: Conduct the **Summative Assessment**.

Summative Assessment

As a summative assessment students will build a working Stirling engine and compare and contrast its design and operation to that of a reciprocating internal combustion engine.

Though Stirling engines are not used in airplanes, they are closely related to the operation of reciprocating engines. Building a model reciprocating engine is not feasible, but building a model Stirling engine can be completed in class using common household supplies.

Watch the video on how to make a Stirling engine: https://video.link/w/LwMp (Length 3:16). Students will then build a model Stirling engine using **Reciprocating Engines Student Activity 3**, which provides the materials list, safety procedures, along with a step-by-step procedure for students to follow. Have students work in small groups to complete the activity.

Once the models have been built, distribute copies of **Reciprocating Engines Student Activity 4** to students to complete.

[DOK-L4; *create*]

Summative Assessment Scoring Rubric

- Contributions show evidence of one or more of the following:
  - Ability to follows instructions and procedures as outlined in the activity sheet
  - Knowledge of the principles governing the operation of internal combustion engines and Stirling engines
- Contributions show understanding of course of the concepts covered in the lesson
- Contributions show in-depth thinking including analysis or synthesis of lesson objectives

Points **Performance Levels**

9-10 The group successfully built a fully functional model Stirling engine using the materials provided. The group followed the procedure in a very organized fashion. The group thoroughly compared and contrasted reciprocating engines with Stirling engines showing several examples in each column of **Reciprocating Engines Student Activity 4**.

7-8 The group built a model Stirling engine using the materials provided. The engine has minor flaws preventing it from functioning properly. The group followed the procedure to the best of their ability. The group sufficiently compared and contrasted reciprocating engines with Stirling engines showing examples in each column of **Reciprocating Engines Student Activity 4**.

5-6 The group built a model Stirling engine but did not use all of the provided materials as outlined in the procedure. The model engine has many flaws preventing it from functioning properly. The group did not closely follow the procedure. The group insufficiently compared and contrasted reciprocating engines with Stirling engines showing gaps in understanding.

0-4 The group was not able to build a model Stirling engine and did not use all of the materials provided. The model engine is not functional. The group did not closely follow the procedure. The group was not able to compare and contrast reciprocating engines with Stirling engines showing many gaps in understanding.

GOING FURTHER

As environmental concerns and new technologies have made electric cars more desireable and practical, some people are looking to electricity as the future power source for aircraft. Watch this video about some of the most promising electric aircraft around today. Would you want to fly one? Write three to four paragraphs explaining the advantages and limitations of electric aircraft as they exist today, and explain why you or would not choose to fly one.

- "10 Amazing Electric Aircraft—The Future of Aviation" (Length 9:29)
  http://video.link/w/Ckjg

For more information about how Stirling engines work, have students watch this video, https://video.link/w/44cl (Length 3:24) moderated by Bill Nye.

STANDARDS ALIGNMENT

NGSS STANDARDS

Three-dimensional Learning

- **HS-PS1-4** - Develop a model to illustrate that the release or absorption of energy from a chemical reaction system depends upon the changes in total bond energy.
    - Science and Engineering Practices
        - Developing and Using Models
- Disciplinary Core Ideas
    - PS1.B Chemical Reactions
- Crosscutting Concepts
    - Energy and Matter
- **HS-PS3-2** - Develop and use models to illustrate that energy at the microscopic scale can be accounted for as a combination of energy associated with the motion of particles (objects) and energy associated with the relative positions of particles (objects).
    - Science and Engineering Practices
        - Developing and Using Models
    - Disciplinary Core Ideas
        - PS3.A Definitions of Energy
    - Crosscutting Concepts
        - Energy and Matter
- **HS-PS3-3** - Design, build, and refine a device that works within given constraints to convert one form of energy into another form of energy.
    - Science and Engineering Practices
        - Developing and Using Models

- Constructing Explanations and Designing Solutions
- Disciplinary Core Ideas
    - PS3.A Definitions of Energy
    - PS3.B Conservation of Energy and Energy Transfer
- Crosscutting Concepts
    - Cause and Effect
    - System and System Models
    - Energy and Matter

COMMON CORE STATE STANDARDS

- **RST.9-10.2** - Determine the central ideas or conclusions of a text; trace the text's explanation or depiction of a complex process, phenomenon, or concept; provide an accurate summary of the text.
- **RST.9-10.4** - Determine the meaning of symbols, key terms, and other domain-specific words and phrases as they are used in a specific scientific or technical context relevant to grades 9-10 texts and topics.
- **WHST.9-10.6** - Use technology, including the Internet, to produce, publish, and update individual or shared writing products, taking advantage of technology's capacity to link to other information and to display information flexibly and dynamically.
- **WHST.9-10.8** - Gather relevant information from multiple authoritative print and digital sources, using advanced searches effectively; assess the usefulness of each source in answering the research question; integrate information into the text selectively to maintain the flow of ideas, avoiding plagiarism and following a standard format for citation.
- **HSN.Q.A.1** - Use units as a way to understand problems and to guide the solution of multi-step problems; choose and interpret units consistently in formulas; choose and interpret the scale and the origin in graphs and data displays.

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