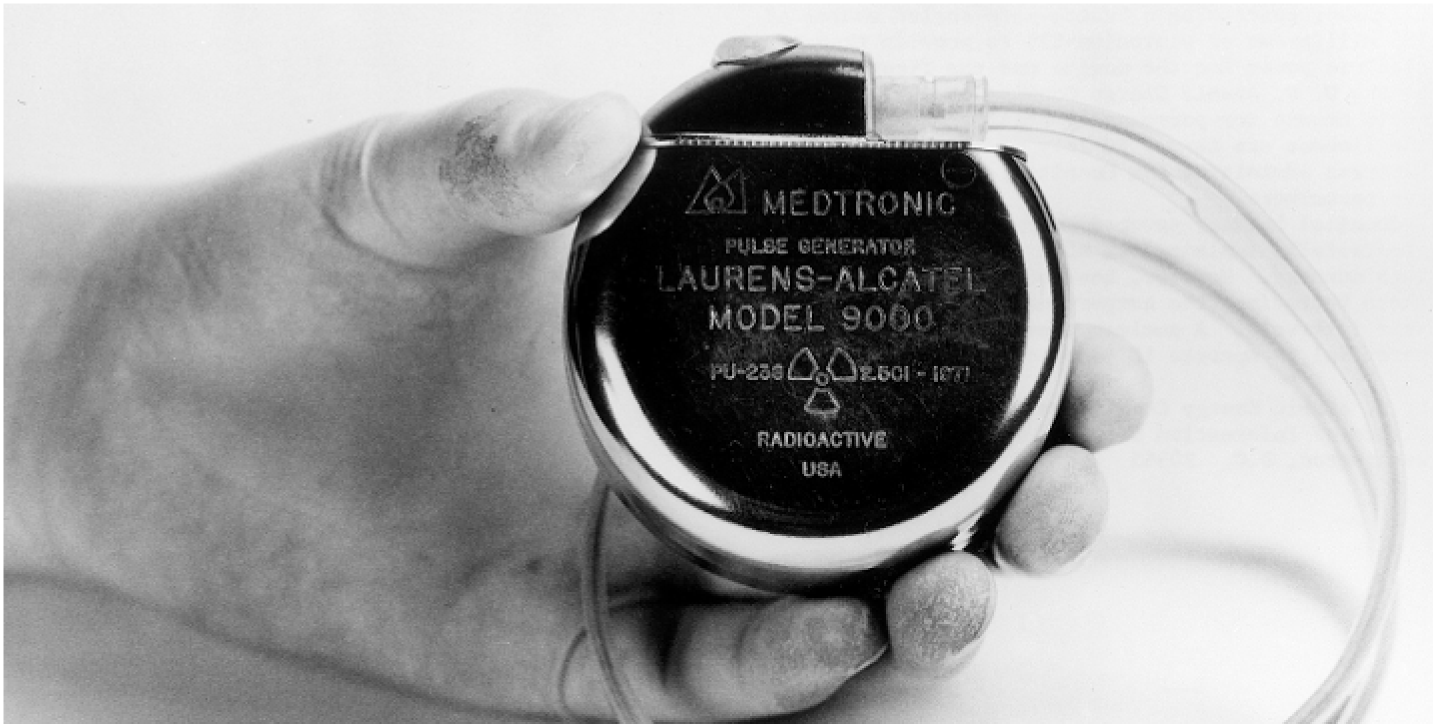
How Thermoelectric Generators Work

October 24, 2018 Alfred

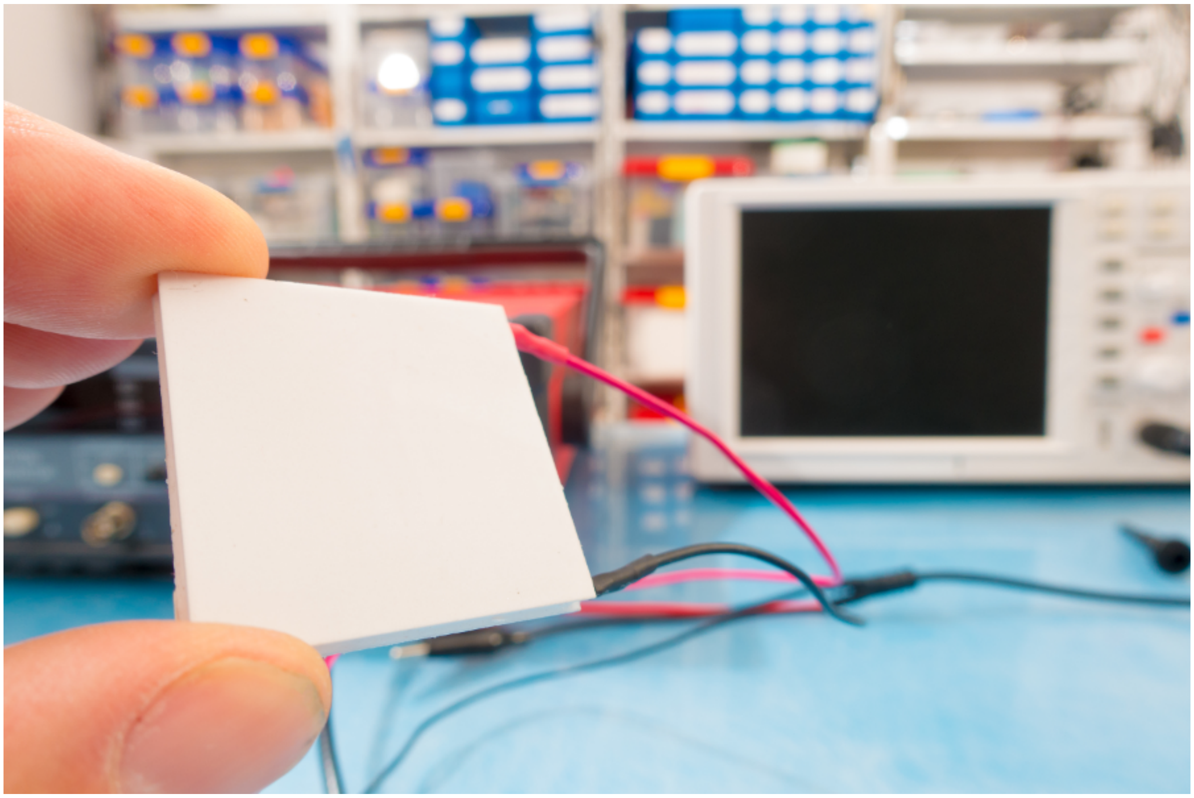
2 comments (https://thermoelectricsolutions.com/how-thermoelectric-generators-work/#comments)



(https://thermoelectricsolutions.com/how-thermoelectric-generators-work/)

How Thermoelectric Generators Work

Thermoelectric generators (TEG) are solid-state semiconductor devices that convert a temperature difference and heat flow into a useful DC power source. Thermoelectric generator semiconductor devices utilize the Seebeck effect to generate voltage. This generated voltage drives electrical current and produces useful power at a load.



Thermoelectric Generator Module

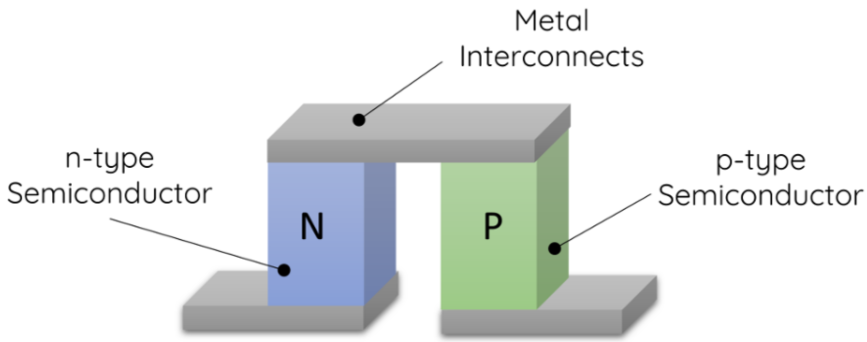
A thermoelectric generator is not the same as a thermoelectric cooler. A thermoelectric cooler works in reverse of a thermoelectric generator. When a voltage is applied to thermoelectric cooler, an electrical current is produced. This current induces the Peltier effect. With this effect, heat is moved from the cold side to the hot side (https://thermoelectricsolutions.com/how-is-heat-transported-peltier-module/). A thermoelectric cooler is also a solid-state semiconductor device. The components are the same as a thermoelectric generator but the design of the components in most cases differ.

While thermoelectric generators are used to produce power, thermoelectric coolers (Peltier coolers) are used for removing or adding heat. Thermoelectric cooling has many applications in cooling, heating, refrigeration, temperature control and thermal management.

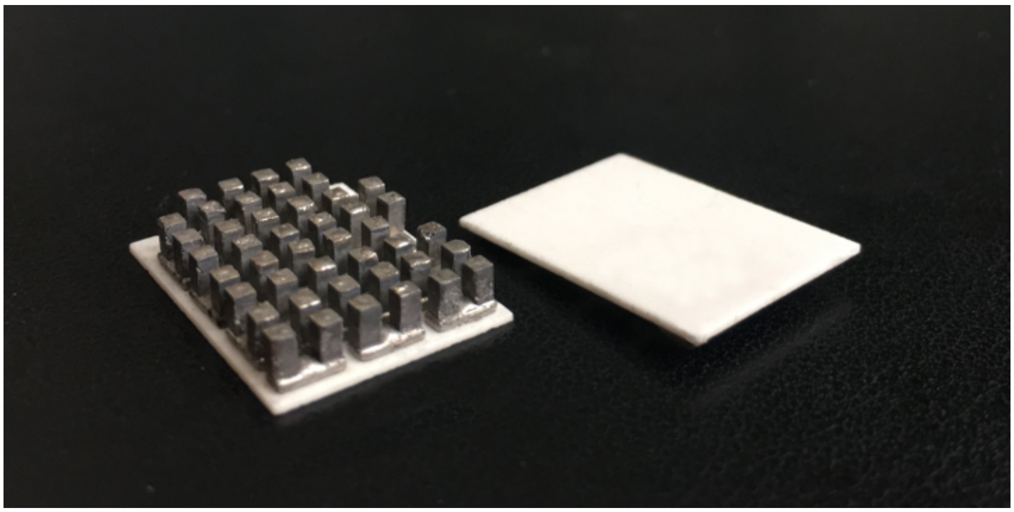
The focus of the rest this post is thermoelectric generators.

How does a Thermoelectric Generator utilize the Seebeck Effect?

The basic building block of a thermoelectric generator is a thermocouple. A thermocouple is made up of one p-type semiconductor and one n-type semiconductor. The semiconductors are connected by a metal strip that connects them electrically in series. The semiconductors are also known as thermoelements, dice or pellets.

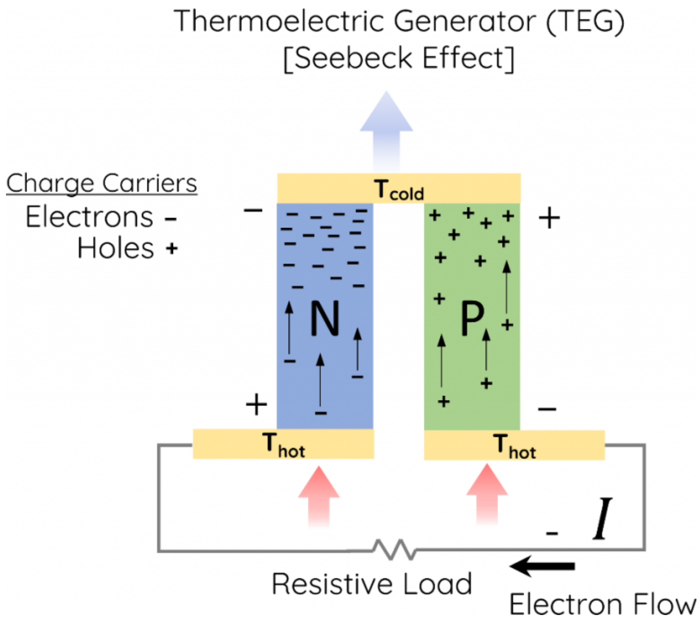


Thermoelectric Generator Couple



Thermoelectric Generator (Pellets, Dice, Semiconductors, Thermoelements)

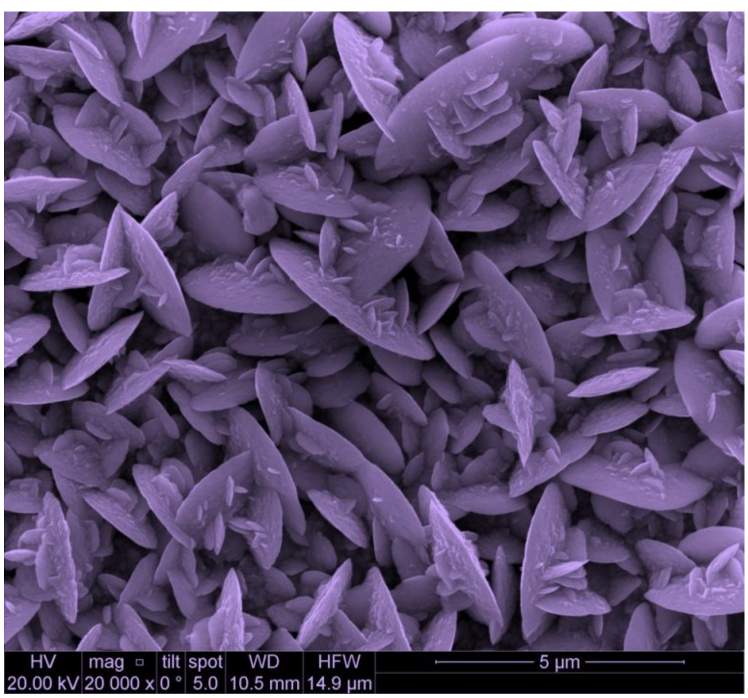
The Seebeck effect is a direct energy conversion of heat into a voltage potential. The Seebeck effect occurs due to the movement of charge carriers within the semiconductors. In doped n-type semiconductors, charge carriers are electrons and in doped p-type semiconductors, charge carriers are holes. Charge carriers diffuse away from the hot side of the semiconductor. This diffusion leads to a buildup of charge carriers at one end. This buildup of charge creates a voltage potential that is directly proportional to the temperature difference across the semiconductor.



Thermoelectric Generator Charge Carriers

What Semiconductor Materials are used for Thermoelectric Generators?

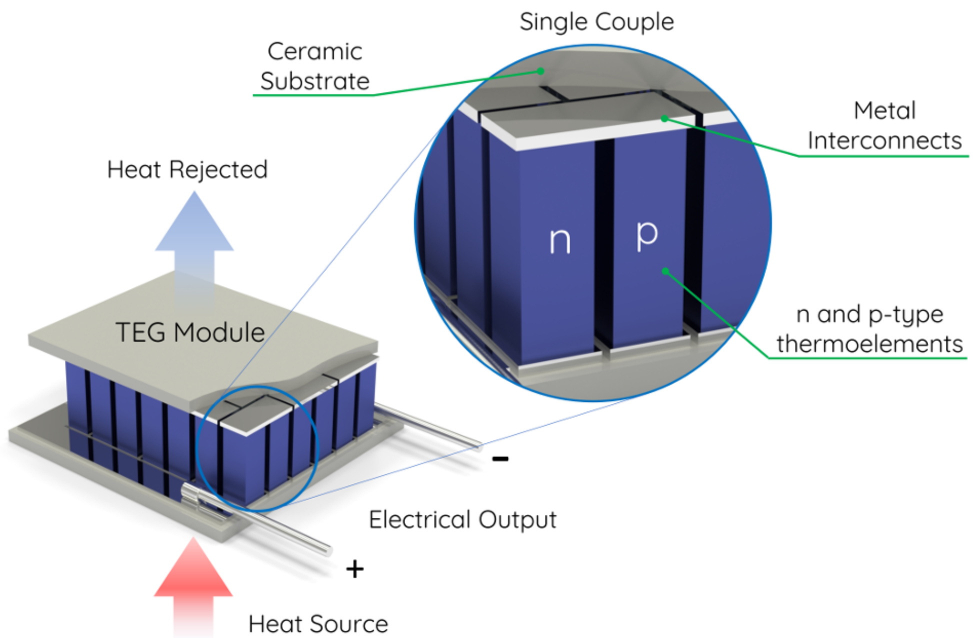
Three materials are commonly used for thermoelectric generators. These materials are bismuth (Bi2Te3) telluride, lead telluride (PbTe) and Silicon germanium (SiGe). Which material is used depends on the characteristics of the heat source, cold sink and the design of the thermoelectric generator. Many thermoelectric generator materials are currently undergoing research but have not been commercialized.



Antimony Bismuth Telluride (BiSbTe)

What is a Thermoelectric Generator Module?

To create a thermoelectric generator module, many p-type and n-type couples are connected electrically in series and / or parallel to create the desired electrical current and voltage. The couples are placed between two parallel ceramic plates. The plates provide structural rigidity, a flat surface for mounting and a dielectric layer to prevent electrical short circuits.



Thermoelectric Generator Module

Who discovered the Seebeck Effect? When was the Seebeck Effect Discovered?

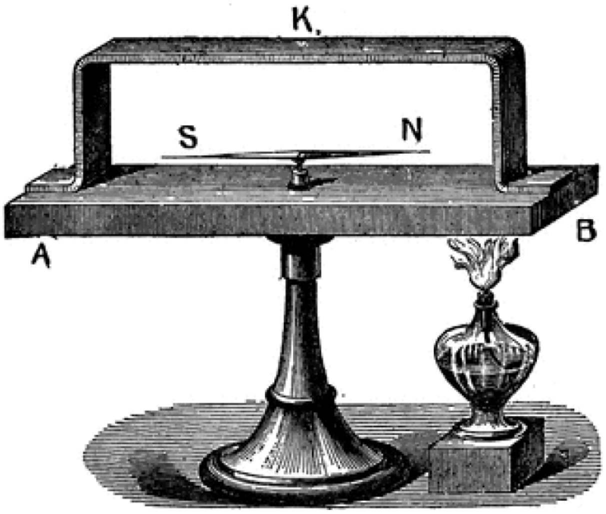
Until recently it was thought that Thomas Seebeck discovered what is known today as the Seebeck effect. It is now believed that ~~Alessandro Volta discovered the Seebeck effect (http://dspace.nbuv.gov.ua/xmlui/bitstream/handle/123456789/27907/01-Pastorino-ENG.pdf?sequence=1)~~ 27 years prior to Thomas Seebeck. The discovery happened 224 years prior to this writing.

In 1794, Alessandro Volta did experiments where he formed an iron rod into a u-shape. One end of the rod was heated by dipping it in boiling water. When the unevenly heated rod was electrically connected to a no longer living frog leg, a current was passed through the frog leg and the muscles contracted. This is believed to be the first demonstration of the Seebeck effect.

Alessandro Volta

In 1821, Thomas Seebeck discovered when one of the junctions of two connected dissimilar metals was heated, a close proximity compass needle would rotate. Initially this was called the thermomagnetic effect. Later it was found that a voltage and thus a current was induced by the junction heating. The current produced a magnetic field by Amperes law. This induced voltage due to junction heating became known as the Seebeck effect.

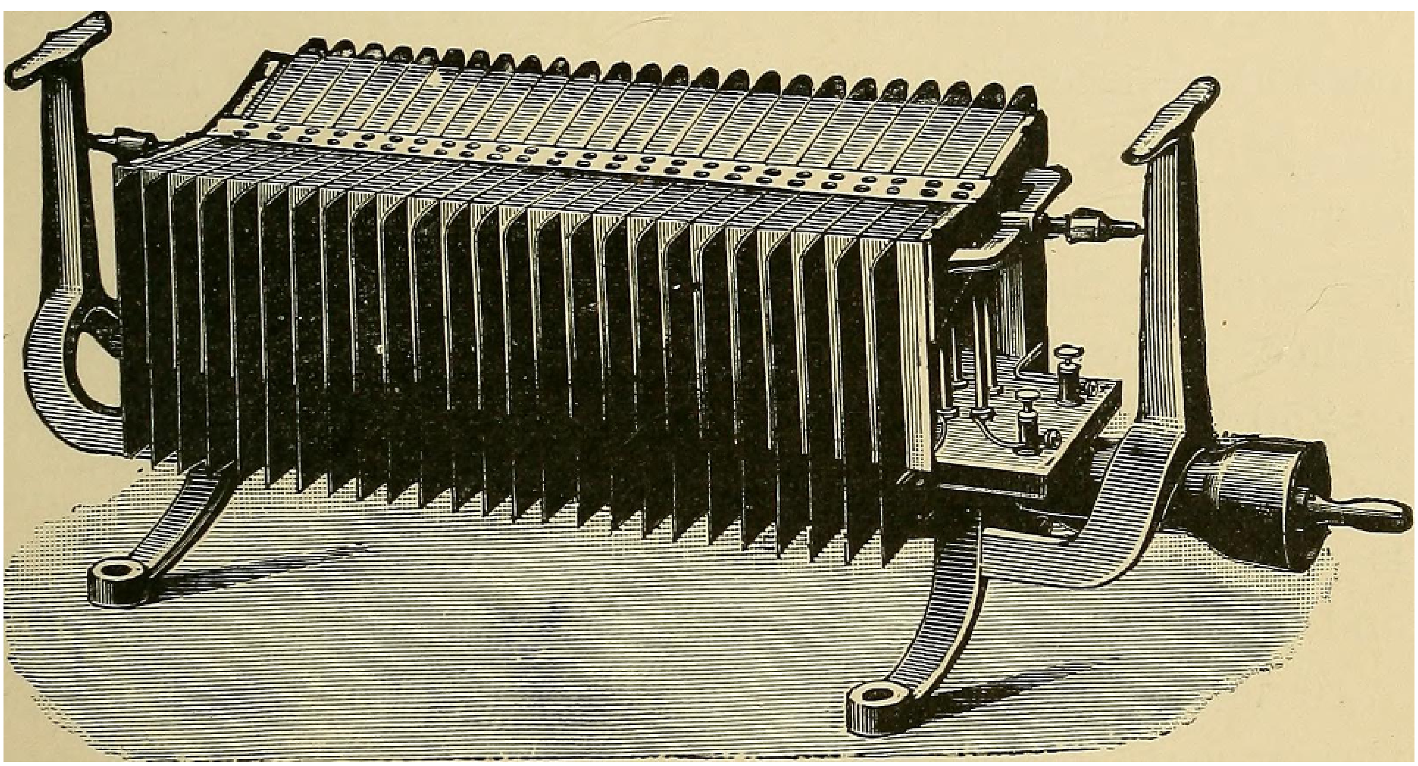
Thomas Seebeck

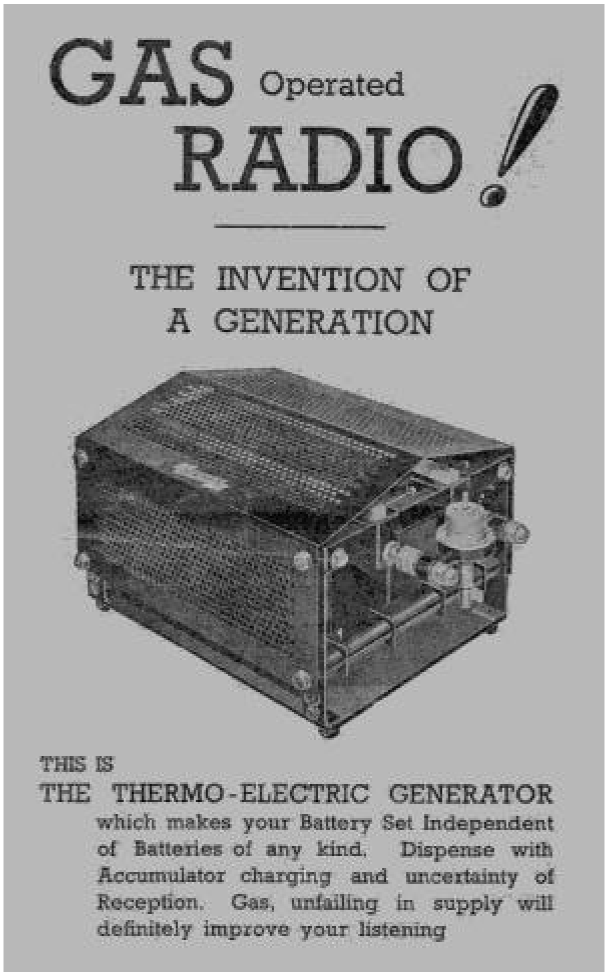


Seebeck's demonstration of the Seebeck effect

When was the First Thermoelectric Generator Developed?

Thermoelectric generators date back to the early 1800's (http://www.douglas-self.com/MUSEUM/POWER/thermoelectric/thermoelectric.htm). Many different designs have been developed since.


Thermoelectric Generator from 1901



Thermoelectric Generator 1930's

What are the Advantages of Thermoelectric Generators

1. **Reliability** - Thermoelectric generators are solid-state devices. Having no moving parts to break or wear out makes them very reliable. Thermoelectric generators can last a very long time. The Voyager 1 (https://voyager.jpl.nasa.gov/mission/status/) spacecraft thermoelectric generator, as of this writing has been operational for 41 years. It has traveled over 13 billion miles without any maintenance or repairs.

2. **Quiet** - Thermoelectric generators can be designed to be completely silent.

3. **No Greenhouse Gases** - Thermoelectric generators do not require any greenhouse gases to operate. Some energy conversion technologies do.

4. **Wide Range of Fuel Sources** - Thermoelectric generators do not have restrictions on fuels that can be used to generate the needed heat. Many other energy conversion technologies do.

5. **Scalability** - Thermoelectric generators can be designed to output power levels smaller than microwatts and larger than kilowatts.

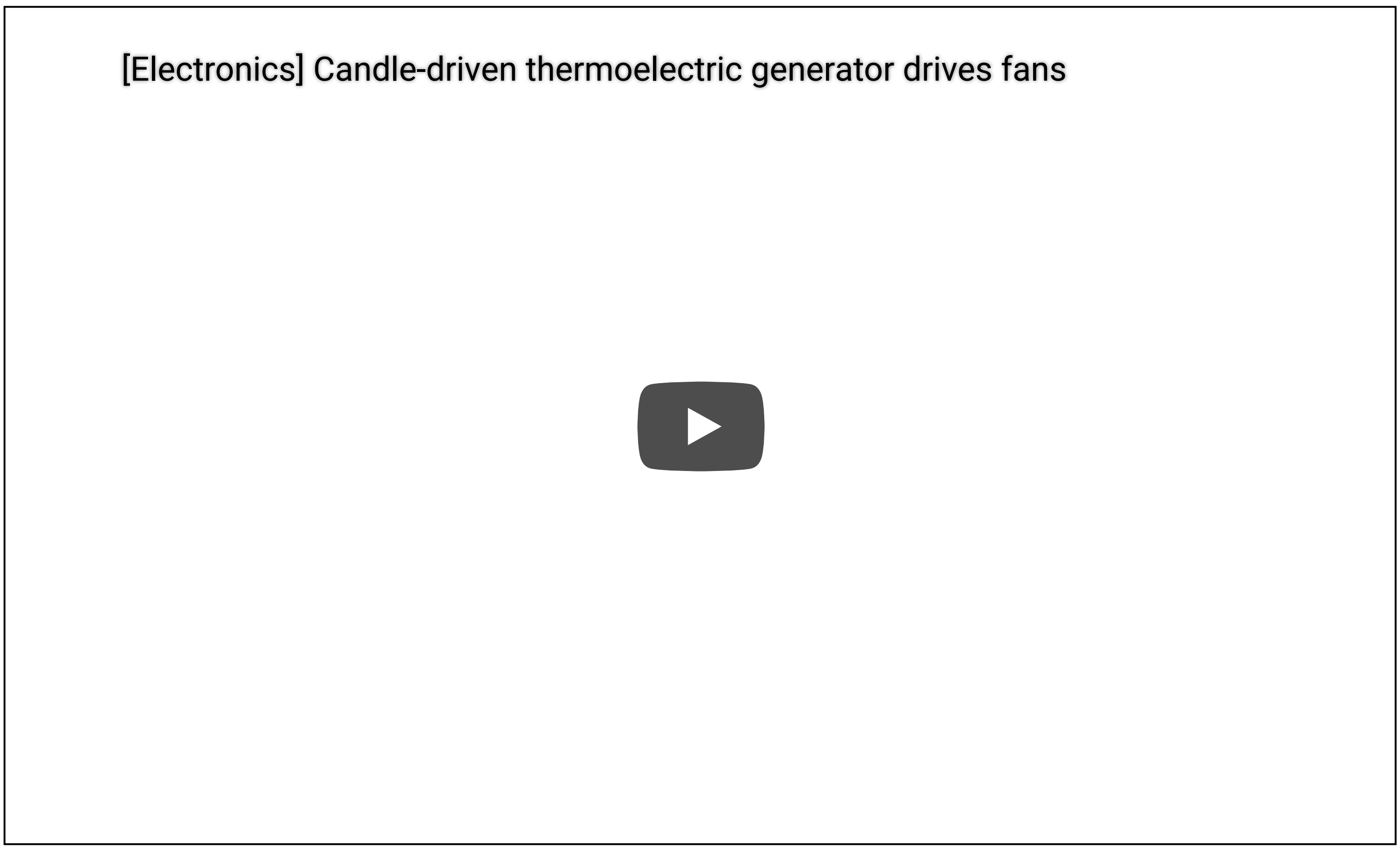
6. **Mountable in Any Orientation** - Thermoelectric generators operate in any orientation. Some energy conversion technologies are sensitive to their orientation relative to gravity.

7. **Operation Under high and Zero G-forces** - Thermoelectric generators can operate under zero-G or high-G conditions. Some other energy conversion technologies cannot.

8. **Direct Energy Conversion** - Thermoelectric generators convert heat directly into electricity. Many energy conversion technologies require intermediate steps when converting heat to electricity. For example, heat energy from fuel is converted in a turbine to mechanical energy, then mechanical energy is converted to electricity in a generator. Each energy conversion step adds losses in the form or waste heat. This makes thermoelectric generators less mechanically complex than some other energy conversion technologies.

9. **Compact Size** - Thermoelectric generators can be designed to be very compact. This leads to greater design flexibility.

Video Demonstration of a Candle Powered Thermoelectric Generator



What are the Disadvantages of Thermoelectric Generators?

Thermoelectric generators are less efficient than some of the other energy conversion technologies. This means that for the same amount of thermal energy (heat) input to the generator, less of that heat is converted to electricity. For applications like waste heat recovery where the heat is free, this becomes less of a concern.

Thermoelectric generators can have a higher initial cost per watt of electrical power output than some energy conversion technologies for some applications. However, the lifetime cost per watt can be lower. Initial cost of a thermoelectric generator amortized over the long life of a thermoelectric generator can make the lifetime cost lower than other technologies, depending on the application. No maintenance cost is another factor that lowers the lifetime cost of a thermoelectric generator.

There is a fair amount of thermoelectric generator module manufacturing knowledge. However, a disadvantage is, the design and engineering expertise required to effectively apply thermoelectric generators to an applications is rare. This Inhibits wider adoption due to applications that result in lower efficiency and high cost.

Despite the disadvantages, thermoelectric generators are still widely used because they have many advantages that other energy conversion technologies do not have.

What are the Applications of Thermoelectric Generators?

A wide range of thermoelectric generator applications exist. Thermoelectric generator applications can be categorized by the heat source that is utilized to generate electrical power.

Common Heat Sources for Thermoelectric Generators:

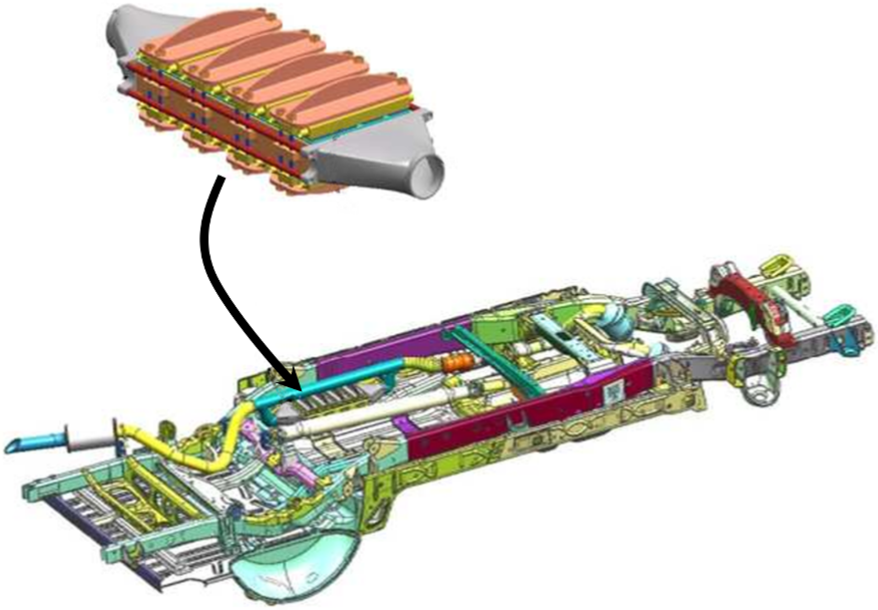
1. Radioactive Decay
    - Plutonium-238

2. Waste Heat
    - Automotive exhaust (https://www.energy.gov/sites/prod/files/2014/03/f13/ace00e_fairbanks_2013_o.pdf)
    - Steel Foundries
    - Wood Stoves
    - Gas Flares
    - Candles
    - Hot Water Pipes
    - Solar Photovoltaic Panels
    - Electronics

3. Body Heat

4. Renewable Sources
    - Geothermal
    - Solar Thermal

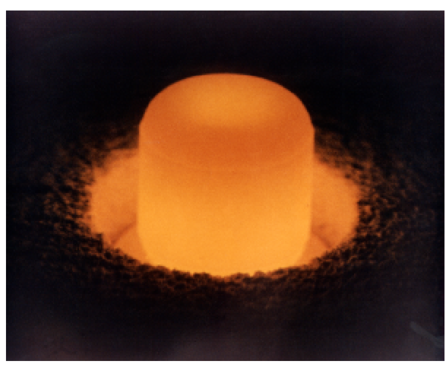
5. Combustion
    - Any Fuel Source, Internal or External Combustion



Categories of Thermoelectric Generator Applications

Extreme Environment

Thermoelectric generators are often used for applications where power is needed in an extreme environment. Because thermoelectric generators have no moving parts, they are very reliable. This reliability makes thermoelectric generators a great application for places where it is too far, too expensive or too dangerous for a repair person to travel. Sometimes these extreme applications utilize heat that is generated from a radiological source like Plutonium-238.



Plutonium Pellet

Some of these types of applications include spacecraft, mars rovers, Lunar power stations, power generation in Antarctica, (https://e-reports-ext.llnl.gov/pdf/797345.pdf) flashing light buoy's, lighthouses and nuclear pacemakers.

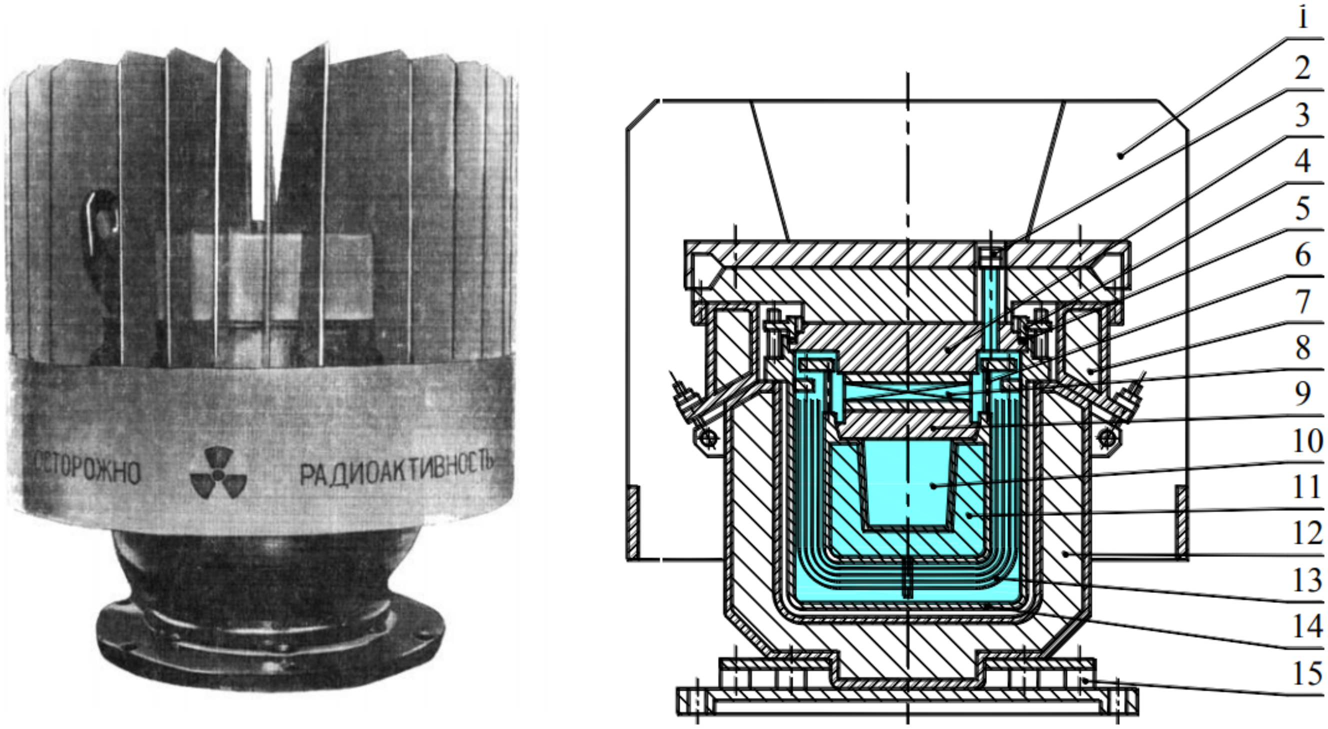
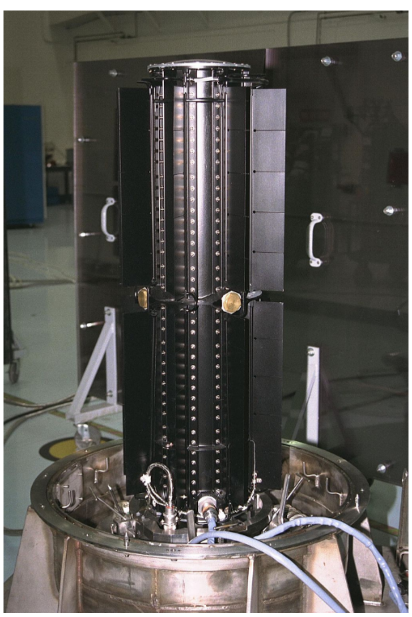


Figure 1. External view and cross-section of a Beta-M/S RTG:

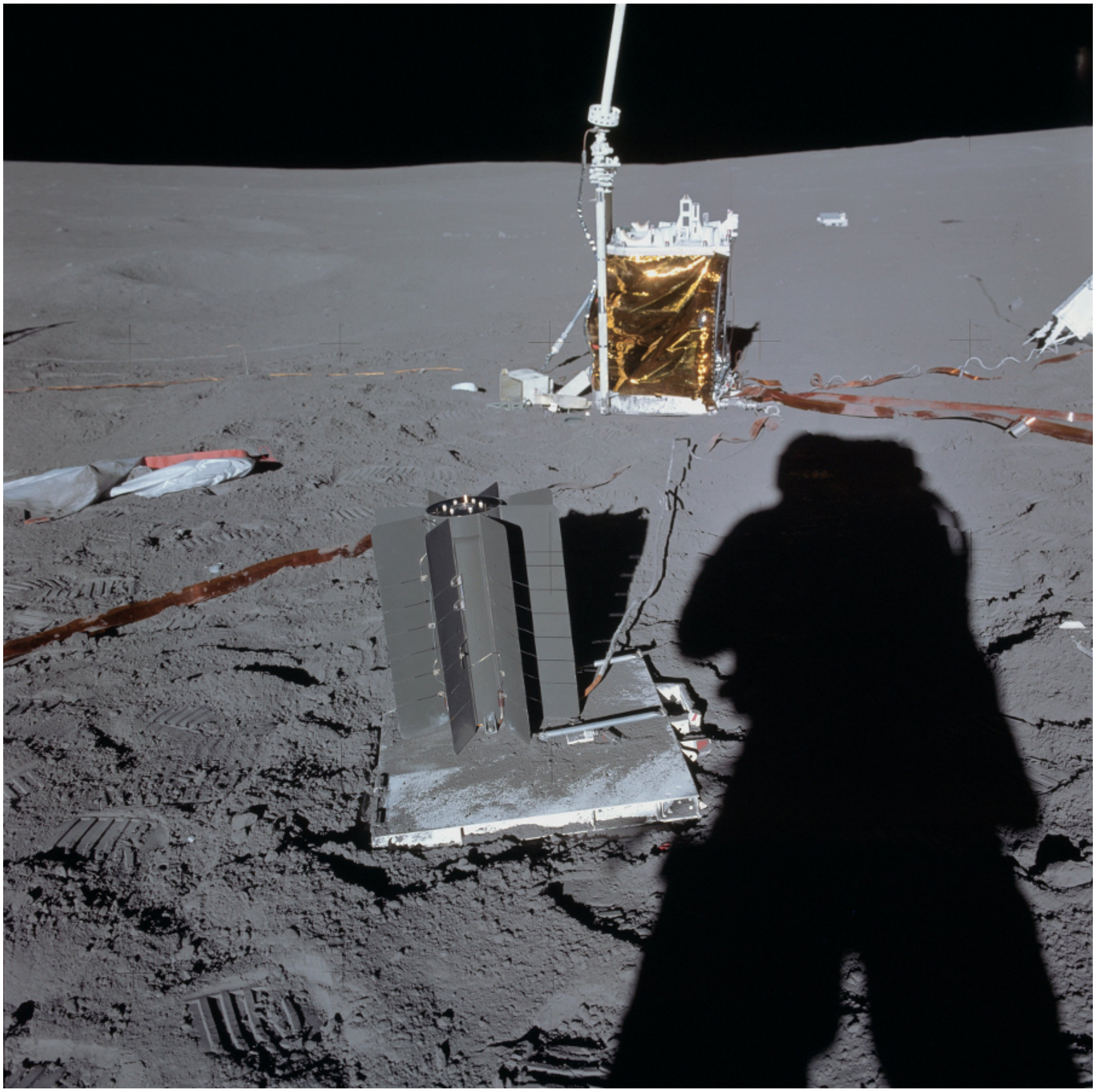
1—radiator; 2—electrical lead; 3—lid; 4—flange; 5—lining; 6—radiation source support; 7—radiation shielding; 8—thermoelectric unit; 9—lid; 10—heat source; 11—protective unit; 12—radiation shielding; 13—screens; 14—housing; 15—base

Antarctica Thermoelectric Generator



Cassini Spacecraft Thermoelectric Generator

Thermoelectric Generator Pacemaker



Lunar Thermoelectric Generator

Other extreme environments where thermoelectric generators are used include, well heads, offshore platforms, pipelines (oil, gas, water), telecommunication sites and navigational aids. These applications typically use heat sources other than radiological.

Waste Heat Recovery

Waste heat is defined as heat lost to the environment. This heat is the byproduct of any energy conversion process. Examples of energy conversion processes are, the conversion of chemical energy in gasoline to thermal energy and thermal energy to mechanical power in a combustion engine. Every time energy is converted to another form, heat is lost to the environment. The use of fossil fuels results in up to 72% of fossil fuel energy being unutilized for any useful process. This heat is dispersed or wasted into the environment.

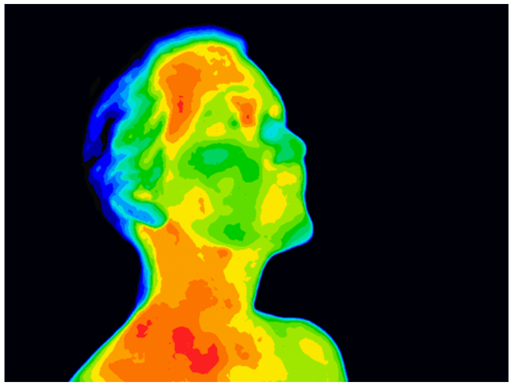
Power plant waste heat

Waste Heat from a Gas Flare

Recovering this waste heat makes any conversion process more efficient. This means less fuel is required to generate the same power output or the same amount of fuel will produce more power. Thermoelectric generators have been used to recover and utilize waste heat from automotive exhaust, steel foundries, wood stoves, gas flares, candles, hot water pipes, solar photovoltaic panels and electronics.

Microgeneration for Sensor and Electronics

Microgeneration thermoelectric generator applications can be classified by a heat source that is very small, or the heat source is large with a very small temperature difference between the ambient and the heat source. Or where the thermoelectric generator itself is very small. This leads to microwatt or milliwatt thermoelectric generator power output levels.



Energy Harvesting from Body Heat

Some applications include wireless sensor networks (WSN) for environmental monitoring, low power Internet of Things (IoT) applications, body heat powered wrist watches, body heat powered flashlights and body heat powered medical sensors (https://thermoelectricsolutions.com/introduction-thermoelectrics-medical-applications/).

Combined Heat and Power (CHP)

Combined heat and power, or CHP (also known as cogeneration) is the practice of generating power from a heat source and using waste heat from the energy conversion process to provide some type of heating for cooking, space heating or process preheating. This leads to very high energy efficiency since most of the heat that would normally be wasted is utilized for a useful purpose.

Some examples of thermoelectric generator applications include biomass cooking stoves, camping stoves and grills.

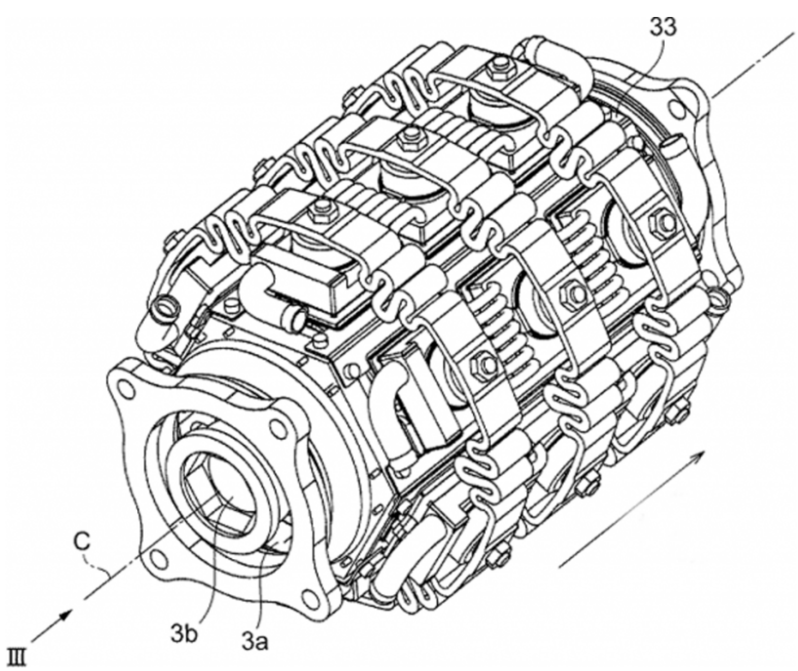
Solar Thermal

Solar thermal applications utilize solar energy that is concentrated onto a thermoelectric generator hot side at very high temperatures. The ambient air is used for the heat sink. The high temperature delta improves the energy conversion efficiency of the thermoelectric generator.

Concentrated Solar for Thermoelectric Generator

How are Thermoelectric Generators Designed?

Thermoelectric generator modules can be bought “off-the-shelf”. These modules are not designed for any specific application. Rather they are a “one-size fits all” product. Theses thermoelectric modules look simple and easy to apply. However, the simple looks can lead to very poor performance and high cost. Without a high level of application knowledge and engineering expertise, theses modules produce very little useful power output.



Automotive Thermoelectric Generator - Toyota

With some rules of thumb applied and an assembly of cobbled together parts, most hobbyists obtain a small electrical output from a thermoelectric generator. However, for real products and applications, engineered system level solutions are required. Without an engineered solution, many months or years of trial and error usually lead to a product that produces too little power and / or costs too much.

One tool that can be used to verify the design of a thermoelectric generator is modeling and simulation. Recent thermoelectric generator modeling research (https://thermoelectricsolutions.com/join-us-at-the-37th-annual-international-conference-on-thermoelectrics-ict-2018/) has significantly improved the accuracy and speed of thermoelectric generator modeling.

Advantages of Improved Modeling and Simulation

Cost Savings

- Lower lifetime product or project cost – continuous prototype Iterations and tests are expensive
- Design problems out now Instead of fix later at very high cost

Huge Time Savings

- Reduced product development cycle
- Design by prototyping and testing is too time consuming

Makes Impossible Possible

- Investigate complex systems and interactions that are not linear or Intuitive
- Many product development tasks are cost and time prohibitive using prototypes and tests

Better Product Design

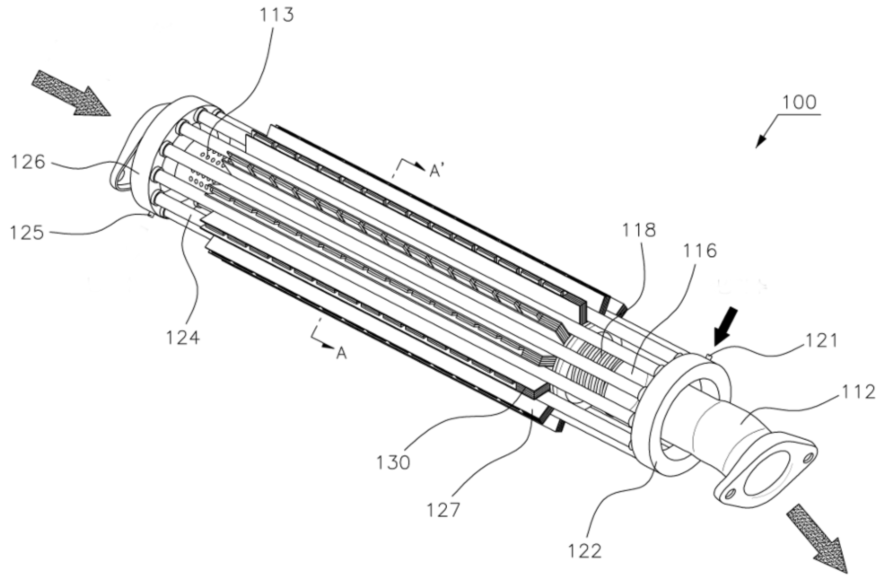
- More sales, repeat customers and better product reviews

Disadvantages of Improved Modeling and Simulation

- Available thermoelectric generator (TEG) modeling expertise not common
- Higher up-front cost but cost savings overall
- No standard approach. Every project is different
- A simulation cannot solve problems by Itself. Human Interpretation is required

How much Power can a Thermoelectric Generator Produce?

Thermoelectric generators are fully scalable from microwatts to kilowatts and beyond. The amount of power generated depends on the characteristics of the heat source, the cold sink and the design of the thermoelectric generator.



Hyundai Automotive Thermoelectric Generator

About Applied Thermoelectric Solutions

At Applied Thermoelectric Solutions LLC, we are passionate about solid-state thermoelectric thermal management, thermal energy harvesting, and the limitless opportunities to apply the technology to the world around us. We design, engineer, build and test thermoelectric systems for your product or application.

We are a Michigan based engineering and R&D company. While other companies focus on manufacturing thermoelectric modules, our focus is on the full system. We specialize in custom and optimized thermoelectric modules and systems.

We apply thermoelectric technology to your product or application with unconventional thinking, a high level of multidisciplinary engineering expertise, innovation, and design.

We strive to make the whole process of obtaining a prototype as simple and straightforward as possible. Whether your product or application is one of a kind or will be high-volume mass produced, we can help. We will design any system no matter the complexity.

We care about quality, performance, and cost-effective design. We believe that balance between the theoretical and the practical is important when designing a system. We continuously question the status quo and push the boundaries of conventional thinking to provide you with the best solution.

Get Started Today

Do you need help designing a thermal management or energy harvesting system?
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2 Comments on “How Thermoelectric Generators Work”

Barbara Beirnes

January 19, 2019 at 11:36 am (https://thermoelectricsolutions.com/how-thermoelectric-generators-work/#comment-238)

Very interesting writing kept my interest from beginning to end. My son-inlaw Kevin James Murphy is a mechanical engineer and I’m sure would be interested. He designs all automotive and aircraft for company’s like ford GM Chrysler Boeing and others.

Reply

Alfred

January 21, 2019 at 9:45 pm (https://thermoelectricsolutions.com/how-thermoelectric-generators-work/#comment-242)

Thank you, Barbara

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★★★★★

"I have personally worked with Alfred concerning details related to one or more patent applications for which he was an inventor. Alfred's technical...

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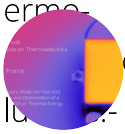
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NOVI

26°

haze
humidity: 50%
wind: 8mph W
H 44 • L 33

48°	46°	43°	52°
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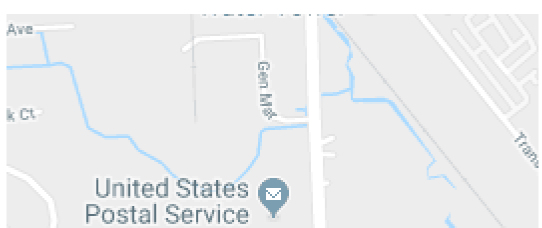
CONTACT INFO



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TESTIMONIALS

Skills to realize innova-tive ideas to suc-cessful fruition...

"Alfred was a pleasure to work with designing and fabricating advanced thermoelectric thermal management systems. Alfred's excellent understanding of thermal hydraulic systems was invaluable while designing high output thermoelectric liquid-liquid heat pumps. His calm clear focus of project objectives were instrumental to insuring performance and milestone dates were met."

"It is rare to find engineers with the creativity, ingenuity, and hands on skills to realize innovative ideas to successful fruition. Al has an excellent grasp for the physics along with skills needed to fabricate and test prototypes to desired outcomes. A real team player who knows how to respect, encourage, and generate consensus.”

Glen P. Roumayah
Thermal Engineer at Hussmann