PLAUSIBILITY OF USAGE OF TEG MODULES ON BOARD SHIP FOR WASTE HEAT RECOVERY.

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Abstract

With the advent of modern low speed long stroke marine diesel engines, thermal efficiencies higher than ever have been achieved. But despite all the advancements, a good chunk of energy is still lost via the exhaust gases. Thermoelectric generator modules, which work on the Seebeck effect, can be an exciting prospect in the merchant marine industry for further optimization of the waste heat recovery system.

This paper aims to discuss the plausibility and viability of the use of Thermoelectric Generator modules on board the ship as a means to further enhance the efficiency of the marine engines.

Keywords- Thermoelectric effect, Seebeck effect

Introduction

Owing to a highly efficient waste heat recovery system, marine diesel engines, unlike the high speed engines used on land, are able to achieve much higher efficiencies and cost effectiveness. But even though an overall efficiency of 60% might sound good on paper, an enormous amount of energy still goes waste.

A good chunk of this heat is lost via the exhaust gases, which if recovered effectively could further enhance the efficiency of the engine.

One of the solutions to this problem could be the use TEGs (thermoelectric generators) on board. TEGs, which produce an electrical power when subjected to a temperature differential, can be planted on the exhaust gas paths/passages, in order to extract heat in return for electrical power. This electrical power can then be brought into use, thereby decreasing the load on the generators.

The focus of the paper shall be to discuss the implementation of the same; primarily on the exhaust manifold.

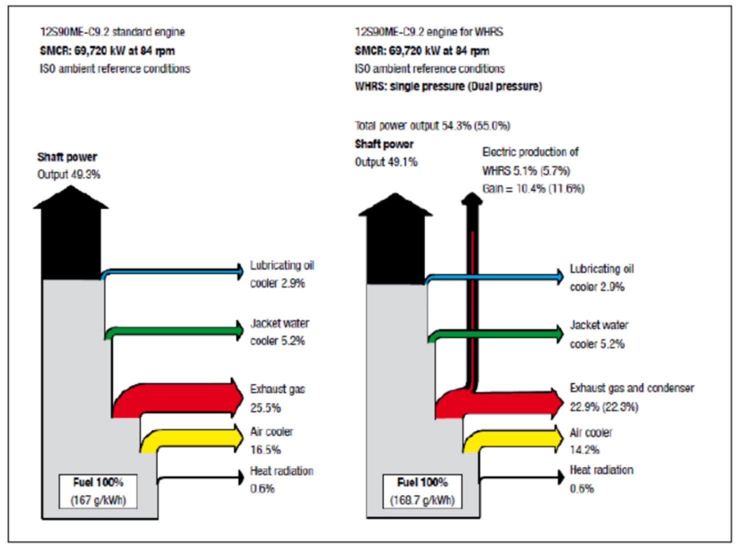


Figure 1. San Key diagram of the Main Engine of marine vessel. (Provided by MAN Diesel)

TEGs: Principle, Construction and Materials

Principle: By and large, TEGs are solid state devices that generate electricity upon being subjected to a temperature gradient. Principally, their operation is governed by the Seebeck effect, i.e., when two dissimilar conductors A and B, constitute a circuit, a current will flow as long as the junctions of the two conductors are at different temperatures. This generated current/voltage is proportional to the temperature differential.

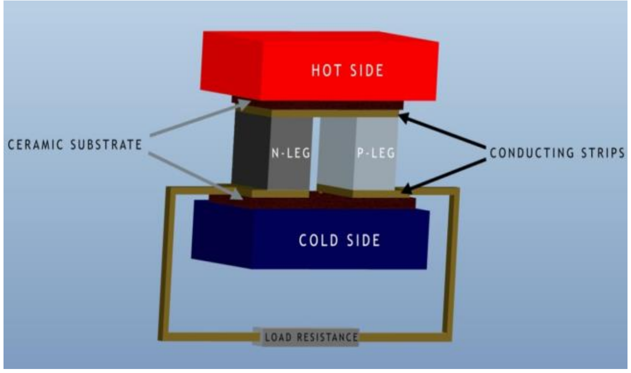
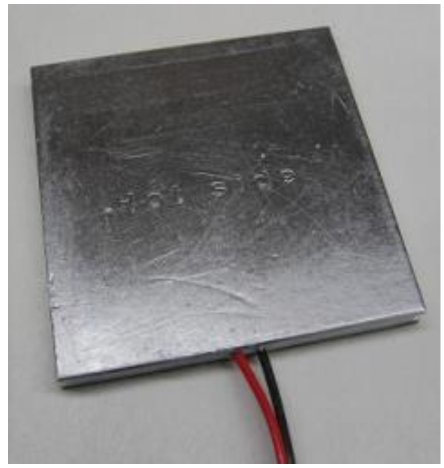


Figure 2. Schematic model of a thermoelectric couple.

Construction: Thermocouples are the main building blocks of a TEG assembly. These thermoelectric couples, quintessentially, are nothing but a pair of n-type and p-type semiconductor legs (whose length is in the order of millimetres) that are electrically connected at one end, using conducting strips. These conducting strips are then attached to ceramic substrates in order to electrically isolate the thermoelectric elements from the heat sink. But one such thermoelectric couple produces power in the order of milli-amperes, so these thermocouples are then electrically combined in series to increase the voltage and power output. One notable point here is that despite the series electrical connection, these couples are placed thermally parallel.

The ceramic substrates, as discussed above are an integral part of the thermoelectric design. A ceramic substrate, ideally, must have the following attributes-

- Low electrical conductivity
- High thermal conductivity
- Thermal expansion coefficients that must be in accordance with the internal components, as an incompatibility shall result in building up of thermal stresses eventually leading to micro-fractures.
- Such material properties so that complexities don't arise when attaching the thermocouples to the substrate.



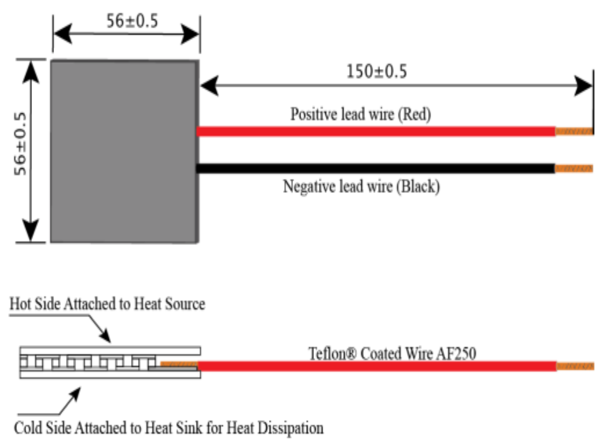


Figure 3. Picture of an actual TEG
Figure 4. (Bottom) Drawing showing the dimensions of the TEG module.

Materials: With advancements in production processes, an array of thermoelectric materials is present in the market today. Various classification parameters such as temperature range of operation, conversion efficiency, cost, etc. are used these days to segregate these materials. But the most significant and perhaps the most relevant of all, happens to be *the temperature range of operation*. On this basis, they can be divided into four groups:

- Bi2Te3(Bismuth Telluride) SERIES 1. Up To 320°C
- PbTe-BiTe (Lead Telluride/Bismuth Telluride) HYBRID SERIES 1 PB. Up to 360°C
- (Bismuth Telluride cold side) calcium Manganese Oxide hot side CMO CASCADE. Up to 800°C
- Calcium Manganese Oxide hot side CMO Up to 900°C

The selection of these thermoelectric materials is done on the basis of their operating efficiencies, given by the relation:

$$efficiency_{max} = \frac{\Delta \mathrm{T}}{\mathrm{T_h}} \frac{\sqrt{1 + \mathrm{Z}.\mathrm{T_{avg}}} - 1}{\sqrt{1 + \mathrm{Z}.\mathrm{T_{avg}}} + \frac{\mathrm{T_c}}{\mathrm{T_h}}}$$

Where,

T_c & T_h = $Cold\ side\ and\ hot\ side\ temperatures\ respectively$,

$T_{avg} = (T_c + T_h)\frac{1}{2}$,

$\Delta T = Temperaure\ Gradient$,

$Z = Figure\ of\ Merit$

From the above relation it can be seen that aside from the operating temperature ranges, the Figure of Merit Z is an instrumental factor in defining the efficiency of a thermoelectric system. Z can be expressed from the relation:

$$Z = \frac{\alpha^2}{k \times p}$$

Where,

$\alpha = Seebeck\ coeffecient$

$k = Thermal\ conductivity$

$p = Electrical\ resistivity$

Therefore, it can be concluded that the selection of a thermoelectric material should be so done that the Figure of Merit values should be as high as possible in the operating temperature range, which subsequently implies that a material with a High Seebeck coefficient, low thermal conductivity and high electrical conductivity shall be best suited for thermoelectric applications.

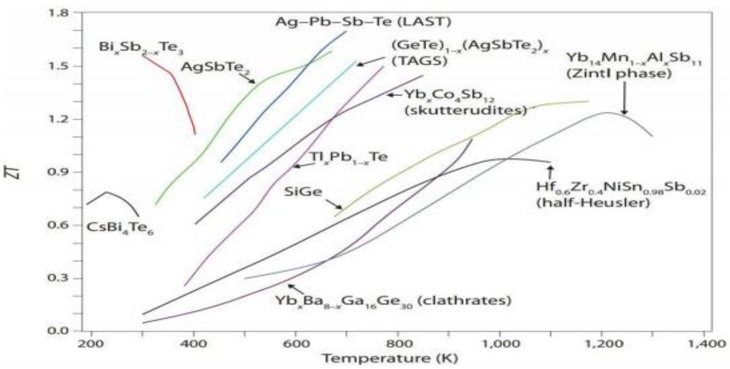


Figure 5. Overview of the ZT of different materials as a function of temperature.

Why TEGs

So far, a lot has been discussed about the specifics pertaining to the construction and working principle of these TEGs, but not a lot has been talked about as to what its advantages are, over other methods of power generation. Following is a non-exhaustive list of reasons for the same-

- **Smooth operation-** TEGs, due to their principle of operation work rather seamlessly. They produce no sounds and vibrations whatsoever.

- **Robust-** Owing to the complete absence of moving parts, TEGs, for the most part, are highly reliable.
- **Zero Maintenance-** Similar to the reasons mentioned above, because of the absence of vibrations and moving parts, TEGs are maintenance free and do not require overhauling.
- **Operating temperature versatility-** Unlike other pieces of technologies that are highly susceptible to anomalies at extreme working temperatures, TEGs can handle huge temperature differentials and show immense versatility in terms of operating temperatures, which range from 200 to over a 1000 Kelvins.
- **Small and lightweight-** Owing to the simple construction and small internal components, TEGs are not only robust but also lightweight.
- **Environmentally safe-** With zero emissions or expulsions of any sort, TEGs are the one of 'greenest' means of generating power.

Implementation

Before talking about the implementation, we shall first classify the power generated by these TEGs into two categories. This classification shall be done on the basis of their point of installation on board the ship. They are as follows-

1. **Primary power**- Since the emphasis of this paper right from the beginning has been to install the TEG modules in the exhaust manifold of the main engine, the power developed from the exhaust manifold shall be referred to as the primary power.
2. **Secondary power**- Since the exhaust manifold is not the only place where high temperature gradients can be achieved, the installation of TEG modules in other auxiliary machineries such as incinerators is also possible- this shall be discussed later. So, by and large, all the other sources of power generation except the exhaust manifold can be referred to as secondary power sources.

In this section, we shall only talk about the Primary power, i.e., from the exhaust manifold. So, now a question arises; why the exhaust manifold? So far, we have established that the power generated by a thermoelectric module is proportional to the temperature gradient it is subjected to. Thus, the exhaust manifold was identified as the best suited location for the following reasons-

- High hot side temperatures
- Considerably large surface area thereby allowing the fitment of a large number of modules

But, as seen from the construction of the thermoelectric modules, we learnt that they are plate type structures. Our exhaust manifold, on the other hand, happens to be of a circular cross section. This presented the following problems-

- **Tedious fitment**- Due to certain constraints, thermoelectric modules are usually fabricated with a plate type geometry. Attachment of plate type modules to a circular manifold is a tedious job and poses a variety of design difficulties.

- **Complex Cooling Arrangements-** As a continuation to the previous point, TEG modules, if attached in the aforementioned fashion, shall pose difficulties in cooling.

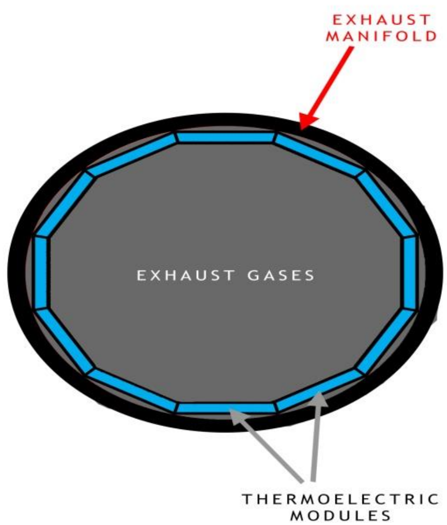


Figure 6. Assembly showing TEG modules installed on the inner periphery of the exhaust manifold (circular in cross section).

In Figure 6, we can see that plate type TEG modules are attached to the circular exhaust manifold. There are various drawbacks to this design. *Firstly,* because of the much smaller size of TEG modules in comparison to the diameter of the exhaust manifold, little to no room shall be left between the outer surface of the modules and inner surface of the manifold. This shall greatly restrict the mass flow rate of cooling air required to cool the TEG modules. *Secondly,* a situation might so arise that fins might be needed to aid the cooling of the cold junction of the TEG modules. In that case, the fitment of fins shall be practically impossible because of very less gap between the cold junction of the TEGs and the inner wall of the exhaust manifold. *Thirdly,* any breach/loss in the air tightness of these TEG modules with the exhaust manifold shall lead to the leakage of cooling air into the exhaust manifold. This shall not only hamper the temperature gradients but will also have undesirable effects on the rest of the components of the waste heat recovery system. *And, lastly,* the fitment of TEG modules inside the exhaust manifold shall leave no room for inspection if need arises.

Thus, for the aforementioned reasons, an exhaust manifold with a square cross section is proposed. A square cross-sectional area shall present many advantages, with the most notable one being the easy installation of TEG modules. From an engineering viewpoint too, this shall not present any complexities as the exhaust manifold doesn’t cater to very high pressures. And while it is understood that an exhaust manifold with a circular cross section shall have inherent resistance to pressure and stresses, a square manifold shall also be able to withstand the low pressures inside the manifold. The following two designs are suggested-

Design 1

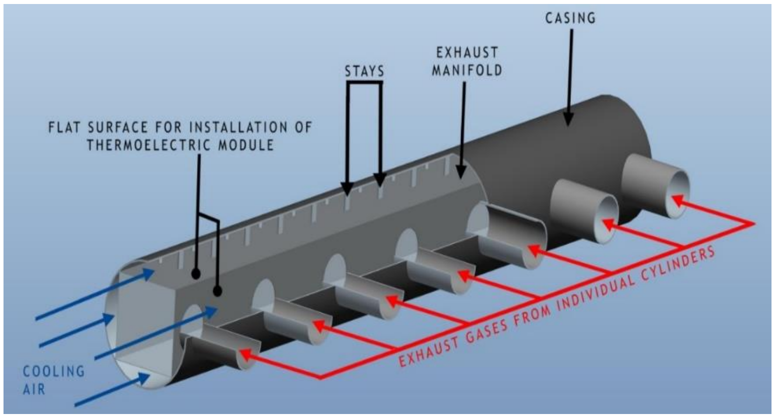


Figure 7. Proposed design of exhaust manifold (square cross section) with TEG modules on its flat outer surfaces.

Following are some salient points regarding the first design (figure 7)-

- Exhaust gases from all individual units/cylinders shall flow into the exhaust manifold of square cross section.
- An outer pipe of circular cross section shall be provided, enveloping the main exhaust manifold.
- Stays shall be present between the circular and square pipes for support.
- TEG modules shall be attached on the outer periphery of all the four sides of the exhaust manifold. The hot side temperature of the modules shall depend upon the conductive heat from the exhaust manifold material.
- Cooling air shall be made to flow between the square manifold and circular pipe.
- Owing to the square design of the exhaust manifold, the corners may be susceptible to ash depositions carried along with exhaust gases. To overcome the same, fillets shall be provided on all the 4 corners.

Design 2

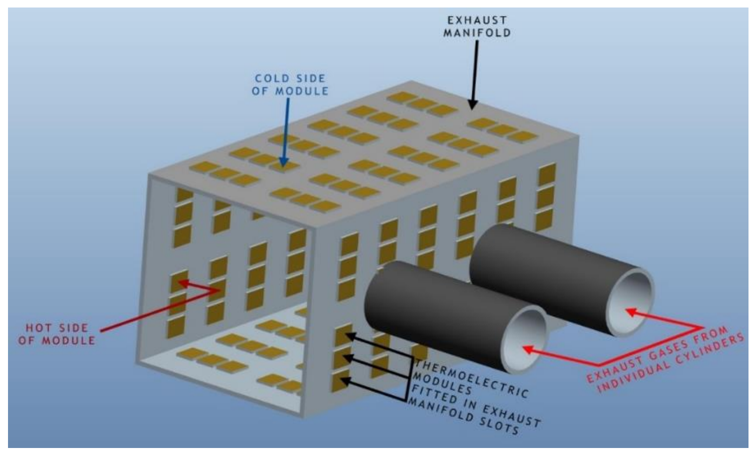


Figure 8. Exhaust manifold with slotted design. (TEG modules exposed directly to exhaust gas temperatures.)

Salient features of the second design are (figure 8) -

- Most of the design aspects of the first design are retained.
- But unlike the first design, where the modules were present on the outer periphery of the exhaust manifold, here, there are slots cut out in the

exhaust manifold itself. TEG modules shall be fitted in these slots in such a way that they align perfectly with the exhaust manifold.

- This shall imply that the hot side of the TEG modules will be directly exposed to the exhaust gas temperatures.
- The rest of the assembly comprising the outer circular pipe, the stays and the cooling system shall remain the same.

One key point of difference between the two designs, as mentioned above, shall be the direct exposure of TEG modules to exhaust gases in the second design. This shall not only mean that higher temperature gradients will be achieved in the second design because of relatively lossless transmission of heat, but this will also call upon for the installation of modules with higher temperature resistance in the second design. There shall also be a pressing need of a tight sealing between the modules and the exhaust manifold in the second design in order to prevent any sort of leakage of the exhaust gases to the cooling air channel.

Cooling System- A good temperature gradient is integral to the power generation process through a TEG module. To achieve this, continuous removal of heat shall be done by the effective cooling of the cold junction of the module. Air will be the best suited cooling medium for this application for the following reasons-

- Availability and abundance. Ambient air from the engine room can be used for this purpose.
- Heated air leaving the system shall have high temperatures, which can be further utilized in boiler for combustion.

In order to enhance the cooling of the cold junction, fins can be built into the system. This way, two parameters, namely the fins and the mass flow rate, can be adjusted to get the desired cooling effect. This cooling air shall be circulated by the help of blowers.

Design Considerations- For optimum efficiency of the system, some very important design considerations will have to be made. The cross section of the exhaust manifold will have to be adjusted accordingly, as a cross section too large shall result in an undesirable decrease in the enthalpy of the exhaust gases because of high rate of heat dissipation (greater the cross-sectional area of manifold, greater the surface area for heat exchange), thus affecting the working of the turbocharger. While on the other hand, a small area of cross section shall create a higher back pressure on the engine. Therefore, a balance between these three parameters will have to be achieved.

Electrical System- In order to extract the desired current and voltage outputs, TEG modules will be connected in series and parallel. Internal resistance of the modules here shall be the deciding factor here for the number of modules that will need to be paralleled.

One more important factor that will have to be considered is that each cylinder shall produce one exhaust blowdown pulse per engine cycle. Each of these pulses will contain high pressure and temperature values that will create differing temperatures in the exhaust manifold. Consequently, the modules' heat flux will be affected, thus producing varying DC voltages. In order to rectify this, power stabilizing electronic circuits shall be used.

Figure shows the specification sheet of one such thermoelectric module. (MODULE TEG1-PB-12611-6.0 manufactured by TECTEG Mfr.)

Module Specifications

Hot Side Temperature (°C)	350
Cold Side Temperature (°C)	30
Open Circuit Voltage (V)	9.2
Matched Load Resistance (ohms)	0.97
Matched Load Output Voltage (V)	4.6
Matched Load Output Current (A)	4.7
Matched Load Output Power (W)	21.7
Heat Flow Across the Module (W)	≈310
Heat Flow Density (W cm^{-2})	≈9.88
AC Resistance (ohms) Measured under 27 °C @ 1000 Hz	0.42~0.52

Table 1. Specification sheet of module to be installed (Model no.- TEG1-PB-12611-6.0)

Calculations- The following calculations are performed for a large size marine diesel engine with 6 cylinders. The design considered here is design 2.

CALCULATION OF EFFECTIVE AREA AVALABLE FOR FITMENT OF MODULES

Considering, length of manifold = 12m

Dimensions of square manifold (cross section) =2m× 2m

Area available for fitment of modules =12m × 2m × 4 = 96m^2 (total surface area)

Effective area for fitment of modules i.e., 50% of the total area (because of slotted design)

=50% × 96m^2= 48m^2

Specified dimensions of module = 56mm × 56mm

Effective dimensions of module including sealing on boundary = 70mm × 70mm

Effective area of module = .0049m^2

Total no. modules that can be installed = $\frac{effective\ area\ avialable\ on\ exhaust\ manifold}{effective\ area\ of one\ module}$

= $\frac{48m^2}{0.0049m^2}$ ~ 9700 modules

Power produced by each module = 21.7 watts

Therefore, total power that can be harvested = 9700 × 21.7 = 210490 watts

The above calculations give us an idea about the theoretical upper bound of the power that can be produced from these modules. For actual results, simulations and experimental results considering an actual test rig will be required.

Secondary Power Generation

On board the ship, there is more than but one location where temperature gradients high enough for power generation via TEGs can be achieved. *One of them happens to be the exhaust funnel.* Generally, a ship making use of an exhaust gas boiler finally discharges the exhaust gases into the air at a temperature of at least 180°C. This is done to prevent the sulphuric acid attack, also known as cold corrosion or dew point corrosion. As evident from the name, this corrosive attack on the metal surface takes place when the Sulphuric acid, upon coming in contact with a relatively cool metal surface (at ~150°C) condenses.

Thus, the temperature of the final exhaust gases is kept higher than the dew point, with at least 30℃ maintained as a safe margin.

Ergo, if the problem of cold corrosion can be mitigated, there stands a further scope of generating electricity by installing TEG modules of lower temperature ranges in the funnel as well. And with length of the funnel being a better part of 10 metres, a considerable amount of power can be produced. But how can the corrosion of metal surfaces from this acid attack be prevented?

One of the ways of mitigating this corrosive attack is by coating the exhaust gas duct by an anti-corrosive coating. This shall allow us to further extract energy from the exhaust gases. Some of the materials that are suggested are as follows-

- **Kynar PVDF**- PVDF resins are used in the power, renewable energies, and chemical processing industries for their excellent resistance to temperature, harsh chemicals and nuclear radiation. It can also be used in the mining, plating and metal preparation industries for its resistance to hot acids of a wide range of concentrations. PVDF is also used in the automotive and architectural markets for its chemical resistance, excellent weather-ability and resistance to UV degradation.
- **Halar (ECTFE)**- A copolymer of ethylene and chlorotrifluoroethylene, Halar is a semi-crystalline melt process able partially fluorinated polymer. Halar (ECTFE) is particularly suitable for use as a coating material in protection and anti-corrosion applications thanks to its unique combination of properties. It offers high impact strength, chemical and corrosion resistance over a wide temperature range, high resistivity and a low dielectric constant. It also has excellent cryogenic properties.

So, by the application of these anti-corrosive coatings, the temperature of the exhaust gases can be made to further drop without fear of cold corrosion. Another place where TEG modules can be fitted is the incinerator, as good temperature differentials can be attained there as well.

Future prospects

Predicting the future advancements in a particular field is always a difficult task. Generation of electrical power using thermoelectric materials is still a relatively novel concept. And with new manufacturing techniques now present in the market, thermoelectric modules with efficiencies greater than ever are now being fabricated. This is evident from the fact as to how the values of Z (figure of merit) have almost doubled in the last 2 decades, thanks to the advancements in the field of nanostructured materials. And with the constant improvement in efficiency of these modules, this technology shall be seen as a close competitor to solar energy. Other new advancements include the development of thermoelectric pipes, which generate power, simply by the flow of hot fluids through them. The scope of Skutterudites and Half Heusler materials is now also being studied as these materials are predicted to have a great scope in terms of enhancement in their figure of merit.

Present day usage of these modules is already seen in space missions from NASA, where power is generated with the combined effect of radioisotopes, and with giants like Porsche and Nissan already conducting extensive research in the field of thermoelectric power generation, the future of Thermoelectric Generators appears to be anything but bleak. And as mankind edges closer and closer to greener modes of power generation, the assimilation of TEGs in general applications in the future appears to be inevitable.

Conclusion

In the end, it can be concluded that TEGs can prove more than capable of catering to the ship's electrical loads, partially to say the least, if not fully. And this system, if implemented properly, shall ultimately help boost the efficiency of the engine as a whole.

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