ALTERNATIVES FOR ELECTRICAL POWER PRODUCTION FROM A NUCLEAR THERMAL PROPULSION ENGINE

Emily Wood and Dr. Dale Thomas
Ductile-to-Brittle Transition Temperature (DBTT)

- DBTT of 373 K
- Past this temperature, the fuel elements will experience embrittlement issues
- At idle, the reactor will generate around 10 MWt
- Fuel elements near the center need this heat actively removed
- Current design is a non-propulsive hydrogen coolant loop
Decay Heat vs Idle Heat

Decay Heat
- Occurs due to the continued radioactive decay of fission products
- Reactor will continue to generate decay heat until power level is increased

Idle Heat
- Reactor intentionally generates enough heat to keep the fuel elements above the DBTT of 373 K.
Bimodal NTP

- Two modes of operation – propulsion mode and electrical production mode
- Proposed capability to provide 50 kWe of power
- Intrusive changes to the engine design
Minimally Intrusive Power generation System (MIPS)

• Convert extra heat produced in idle mode and removed by the coolant loop to usable electric power for the vehicle
• No changes to the reactor core and minimal changes to the engine design
• For use in a Mars Transfer Vehicle (MTV) for a round-trip to Mars
Mass and Power

- Requirements estimated to range from 25 kWe to 100 kWe
- This study aims to determine the mass and power relationship of each of the MIPS alternatives
- Alternatives are: thermoelectric generators, closed-loop Brayton cycle, and a Stirling engine
Thermoelectric Generators

• Convert heat directly into electricity without any moving parts
• Used on Voyager 1, Voyager 2, Cassini, and New Horizons
Closed-Loop Brayton Cycle

• Used to power cryocoolers on Near Infrared Camera and Multi-Object Spectrometer on the Hubble Space Telescope
Stirling Engine

- Extensively researched at Glenn Research Center
- Stirling Power Demonstrator Engine
- Stirling Power Research Engine
- Stirling Technology Demonstrator Converters
Mission Profile

- Total 940 days in idle
Thermoelectric Generators
Mathematical Model

• Power output depends on material properties
• Material selected: Silicon Germanium
• General Purpose Heat Source Radioisotope Thermoelectric Generator (GPHS-RTG) uses SiGe
• Efficiency = 6.3%

\[ P = \eta \dot{Q}_{in} \]
Closed-Loop Brayton Cycle Mathematical Model

• Power limited to maximum temperature turbine can withstand and by working fluid properties
• Nitrogen chosen as working fluid
Closed-Loop Brayton Cycle Mathematical Model

\[ P = G \left[ m \left( (h_3 - h_4) - (h_2 - h_1) \right) \right] \]
Stirling Engine Mathematical Model

• Helium was chosen as the working fluid
Stirling Engine Mathematical Model

\[ CR = \frac{T_H}{T_C} \]

\[ m = \frac{\dot{Q}_{in}}{c_v(T_H - T_C) + c_v T_C \ln(CR)} \]

\[ \eta = \frac{mc_v T_C \ln(CR)}{mc_v(T_H - T_C) + mc_v T_C \ln(CR)} \]

\[ P = G\eta \dot{Q}_{in} \]
Creo Parametric

- Results of most interest are the power output and the mass of the system
- Creo Parametric was used to model each power conversion system for each increment of desired power from 25 kWe to 100 kWe
Power vs Mass

• Mass of the systems will be estimated and plotted against the power output
25 kWe Brayton Engine Design

Turboalternator Assembly

<table>
<thead>
<tr>
<th>Specification</th>
<th>Measurement</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall length</td>
<td>87.7 cm</td>
<td>(34.5 in)</td>
</tr>
<tr>
<td>Overall diameter</td>
<td>50.4 cm</td>
<td>(19.8 in)</td>
</tr>
<tr>
<td>Weight</td>
<td>145 kg</td>
<td>(320 lb)</td>
</tr>
<tr>
<td>Compressor tip diameter</td>
<td>15.1 cm</td>
<td>(5.97 in)</td>
</tr>
<tr>
<td>Turbine tip diameter</td>
<td>18.3 cm</td>
<td>(7.20 in)</td>
</tr>
<tr>
<td>Alternator rotor diameter</td>
<td>11.8 cm</td>
<td>(4.66 in)</td>
</tr>
<tr>
<td>Bearing journal diameter</td>
<td>6.5 cm</td>
<td>(2.55 in)</td>
</tr>
<tr>
<td>Rotor weight</td>
<td>21.6 kg</td>
<td>(47.7 lb)</td>
</tr>
</tbody>
</table>
25 kWe Brayton Engine Design
Turboalternator Assembly
25 kWe Brayton Engine Design
Turboalternator Assembly
25 kWe Brayton Engine Design

Radiator
25 kWe Brayton Engine Design

Radiator
25 kWe Brayton Engine Design

Heat Receiver
25 kWe Brayton Engine Design

Heat Receiver
25 kWe Brayton Engine Design
Recuperator
25 kWe Brayton Engine Design

Recuperator
25 kWe Brayton Engine Design

Gas Cooler

Figure 8.3.—Dual-fluid, eight-pass, cross-counterflow, plate-fin gas cooler. Weight, 188 lb. (Dimensions are in inches.)
25 kWe Brayton Engine Design

Gas Cooler
25 kWe Brayton Engine Design
Bleed Cooler

Figure 8.4.—Dual-fluid, counterflow, plate-fin bleed cooler. (Dimensions are in inches.)
25 kWe Brayton Engine Design

Bleed Cooler

SCALE 0.400

<table>
<thead>
<tr>
<th>Emily Wood</th>
<th>Brayton Engine</th>
</tr>
</thead>
<tbody>
<tr>
<td>25 kWe</td>
<td>Bleed Cooler</td>
</tr>
</tbody>
</table>
## 25 kWe Brayton Engine Design

### Mass Breakdown

<table>
<thead>
<tr>
<th>Part</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor Inlet</td>
<td>4.51</td>
</tr>
<tr>
<td>Compressor</td>
<td>25.78</td>
</tr>
<tr>
<td>Compressor Impeller</td>
<td>1.46</td>
</tr>
<tr>
<td>Conversion Unit</td>
<td>113.57</td>
</tr>
<tr>
<td>Turbine</td>
<td>74.50</td>
</tr>
<tr>
<td>Turbine Impeller</td>
<td>87.24</td>
</tr>
<tr>
<td>Turbine Nozzle</td>
<td>7.48</td>
</tr>
<tr>
<td>Heat Receiver</td>
<td>19681.00</td>
</tr>
<tr>
<td>Radiator</td>
<td>1493.70</td>
</tr>
<tr>
<td>Recuperator</td>
<td>335.56</td>
</tr>
<tr>
<td>Gas Cooler</td>
<td>186.94</td>
</tr>
<tr>
<td>Bleed Cooler</td>
<td>3.95</td>
</tr>
</tbody>
</table>

**Total: 22036 lbm**
25 kWe Stirling Engine Design
25 kWe Stirling Engine Design
# 25 kWe Stirling Engine Design

## Mass Breakdown

<table>
<thead>
<tr>
<th>Part</th>
<th>Mass (lbm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heat tubes</td>
<td>9.02</td>
</tr>
<tr>
<td>Regenerator</td>
<td>0.32</td>
</tr>
<tr>
<td>Cooler Tubes</td>
<td>10.47</td>
</tr>
<tr>
<td>Displacer Dome</td>
<td>10.61</td>
</tr>
<tr>
<td>Displacer Piston</td>
<td>2.80</td>
</tr>
<tr>
<td>Post and Flange</td>
<td>32.19</td>
</tr>
<tr>
<td>Gas Spring</td>
<td>17.10</td>
</tr>
<tr>
<td>Plungers</td>
<td>0.32</td>
</tr>
<tr>
<td>Alternator</td>
<td>29.60</td>
</tr>
<tr>
<td>Pressure Vessel</td>
<td>51.35</td>
</tr>
<tr>
<td>Radiator</td>
<td>8019.39</td>
</tr>
<tr>
<td>Ducting/Miscellaneous</td>
<td>69.84</td>
</tr>
</tbody>
</table>

Total: 8253.01 lbm
Brayton Engine Scaling

Brayton Mass Scalability

\[ y = 65.514 \ln(x) - 12.662 \]

\[ R^2 = 0.9788 \]

SSF SDPM

BRU

miniBRU

Power (kWe)

Mass (lb)
Scaling

Stirling Scalability

\[ y = 15.198x + 141.15 \]

- 75 kWe
- 25 kWe
- 150 kWe

\[ R^2 = 0.9904 \]
The GPHS-RTG has an overall mass of 123.24 lbm.

The General Purpose Heat Source (GHPS) is made up of 18 modules providing about 245 Wt from the decay of the encapsulated plutonium-238. Each module has a mass of 3.15 lbm, this includes the mass of the encapsulated plutonium.
TEG Mass

- It can be seen in the figure that the GPHS includes the alias heat shield to shield the conversion equipment from the plutonium-238. The mass of all 18 modules at 3.15 lbm each is 56.75 lbm. Subtracting this weight from the total mass of the GPHS-RTG, we are left with 66.49 lbm. This is the mass of the thermoelectric conversion equipment in the converter.
- Therefore, for the purpose of the MIPS, the mass of the thermoelectric generators can be taken to be 66.49 lbm each.
Solar Array Mass

According to Aerojet Rocketdyne’s Ground Rules and Assumptions document:

• Specific Mass of Array and Array Harness is 20.41 lbm/kWe at Earth BOL
• Array Production at EOL is 75% of BOL due to array degradation
Master Graph of Power Generation Systems

Mass of Power Generation Systems

- Stirling
- Brayton
- TEG
- Solar Arrays

Power Output (kWe) vs. Mass (lb)
Master Graph of Power Generation Systems Plus IMRs

Mass of Power Generation Systems with IMRs

- Brayton
- Solar Arrays
- Stirling
- TEGs

Vertical (Value) Axis Major Gridlines
Validation with Historical Masses

Brayton

Stirling

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE
Conclusion

- NTP is a viable option for missions to Mars and beyond
- Bimodal NTP has previously been favored, but it requires substantial changes to the engine design
- MIPS could convert the thermal energy from the reactor core at idle to an adequate amount of electricity to power the MTV, without changing the reactor design
- MIPS results in mass savings
Future Work

• Sensitivity Analysis
• Reliability Analysis
• Cost Analysis
Questions?
References

References

References

[17] Mitchell, R., “Powering the Voyager Spacecraft with Radiation: The RTG (Radioisotope Thermoelectric Generator),” *All About Circuits*, June 2017,
