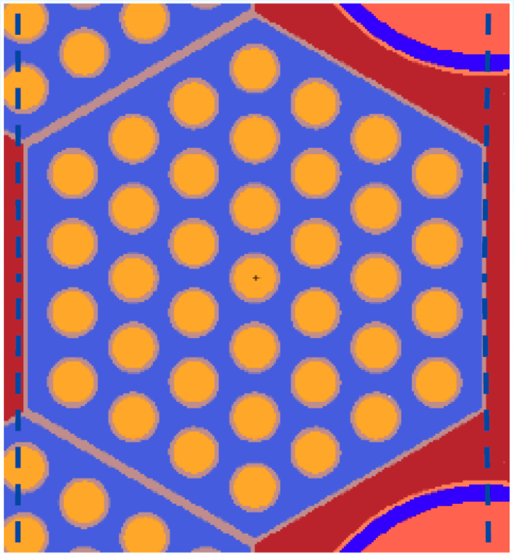
ALTERNATIVES FOR ELECTRICAL POWER PRODUCTION FROM A NUCLEAR THERMAL PROPULSION ENGINE

Emily Wood and Dr. Dale Thomas

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Complex Systems Integration Laboratory
The University of Alabama in Huntsville

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

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Decay Heat vs Idle Heat

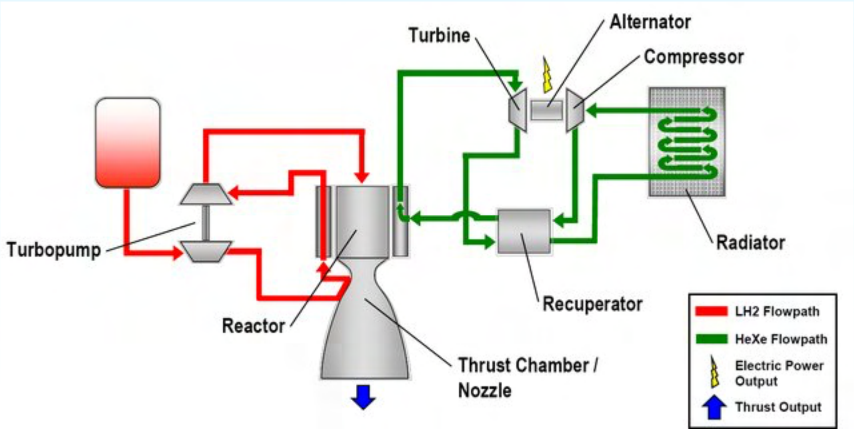
Decay Heat

- 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

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

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

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

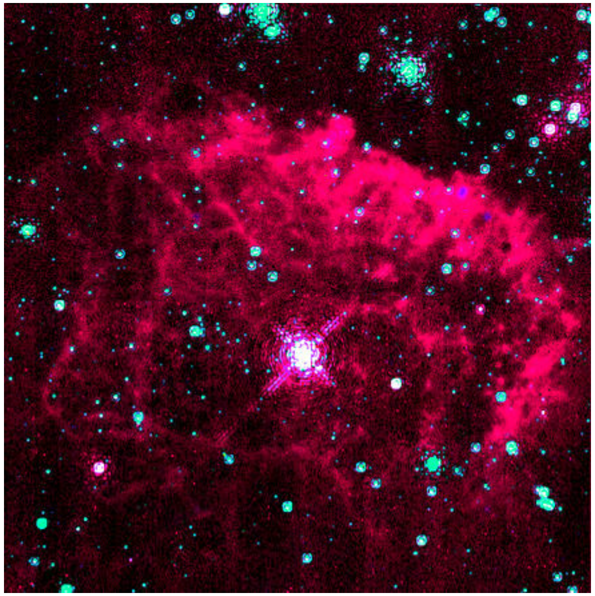
Thermoelectric Generators

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

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

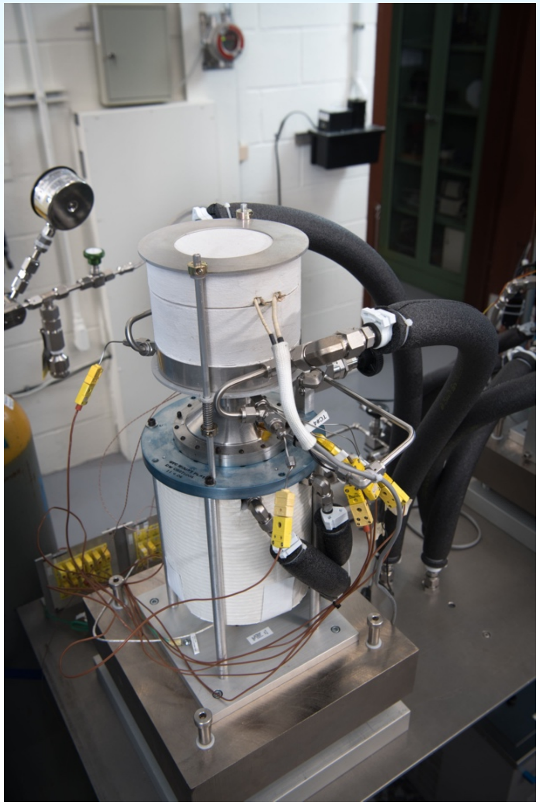
Closed-Loop Brayton Cycle

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



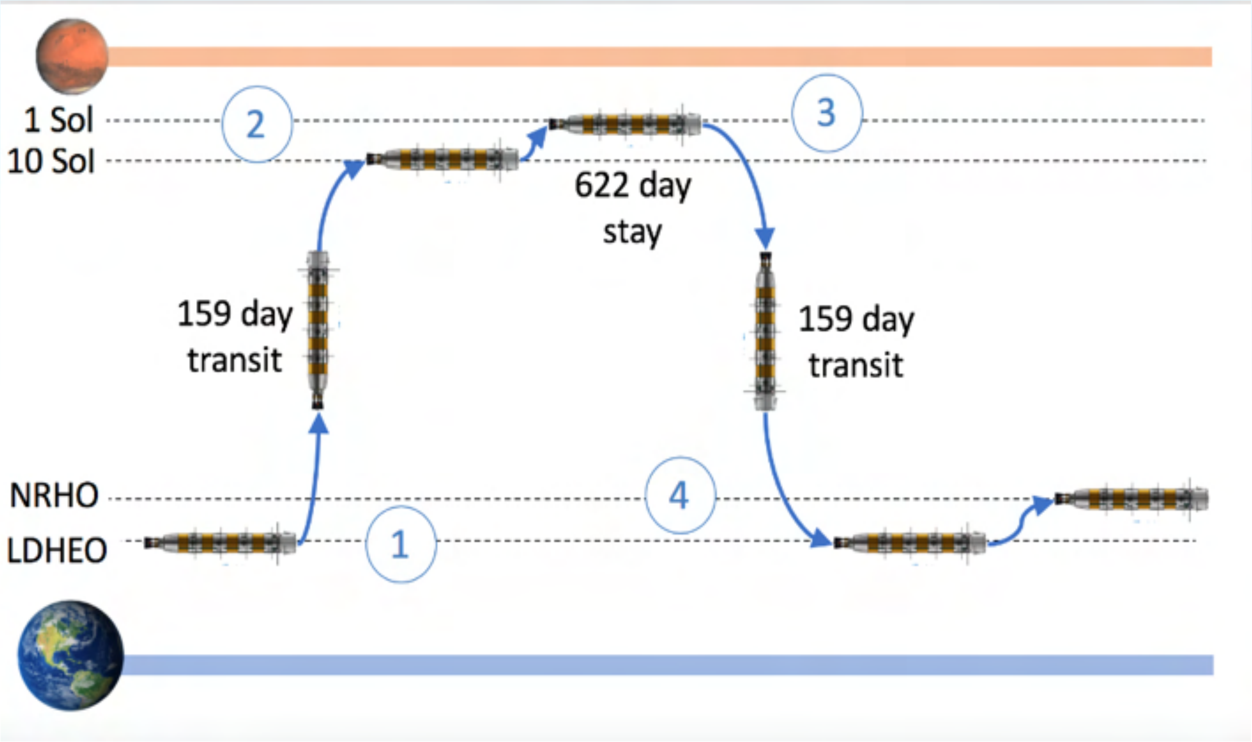
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

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

THE UNIVERSITY OF
ALABAMA IN HUNTSVILLE

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%

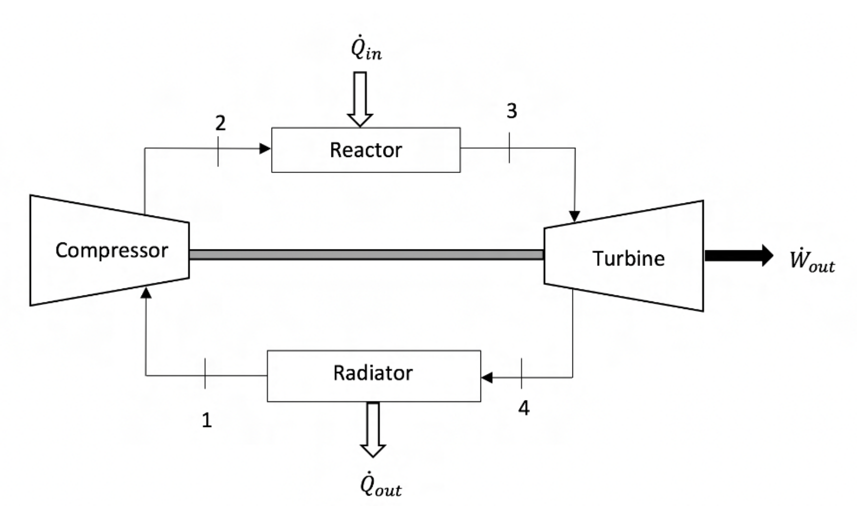
$$P = \eta \dot{Q}_{in}$$

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

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

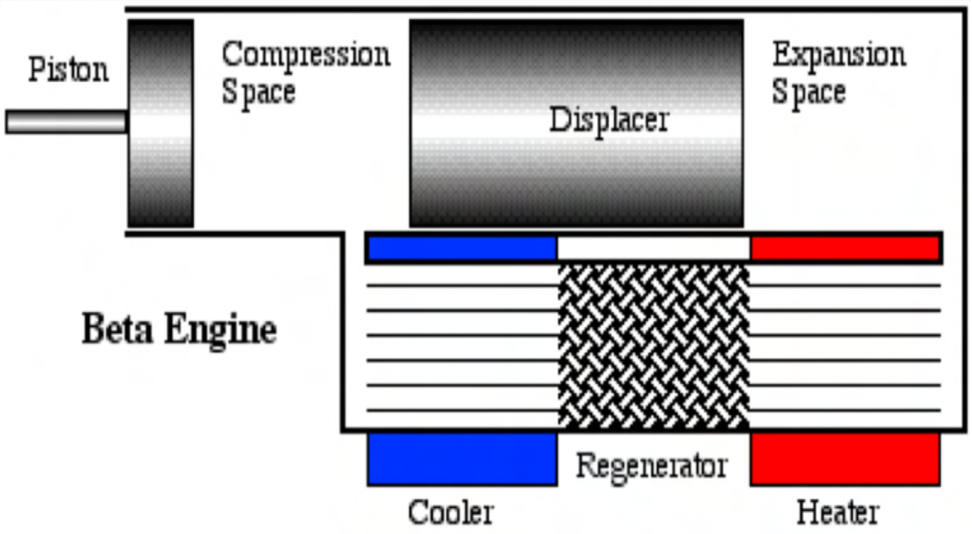


$$P = G[\dot{m}((h_3 - h_4) - (h_2 - h_1))]$$

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Stirling Engine Mathematical Model

- Helium was chosen as the working fluid



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Stirling Engine Mathematical Model

$$CR = \frac{T_H}{T_C}$$

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

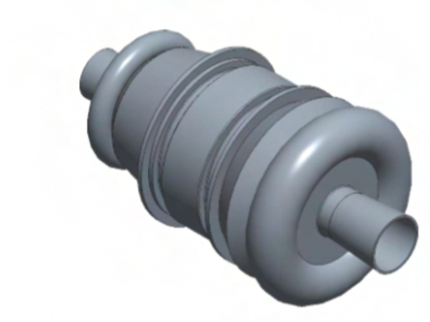
$$\eta = \frac{m c_v T_C \ln(CR)}{m c_v(T_H - T_C) + m c_v T_C \ln(CR)}$$

$$P = G \eta \dot{Q}_{in}$$

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

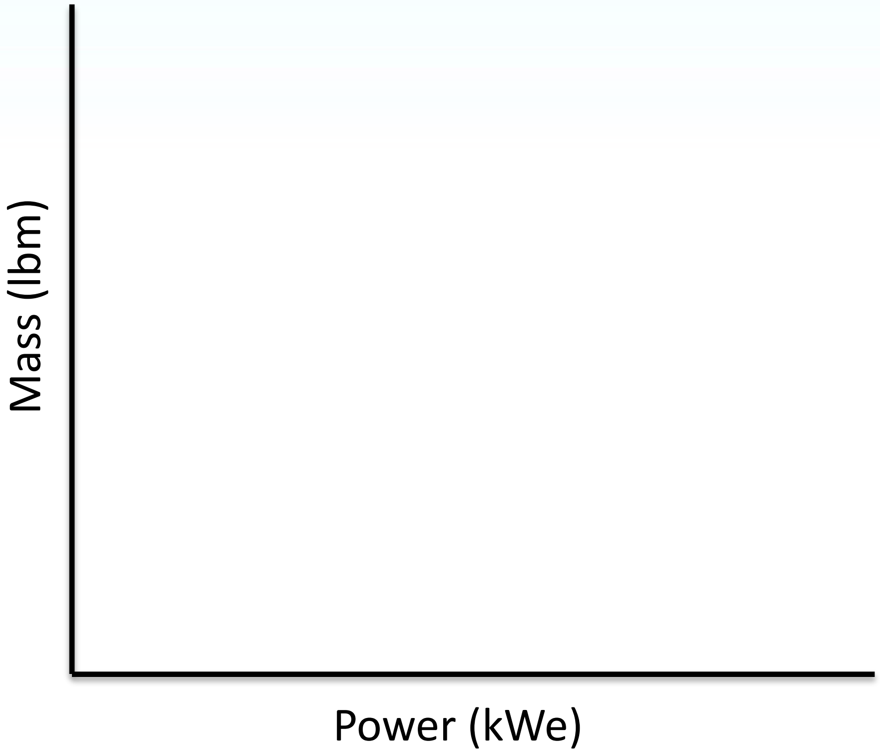
Creo Parametric

- 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

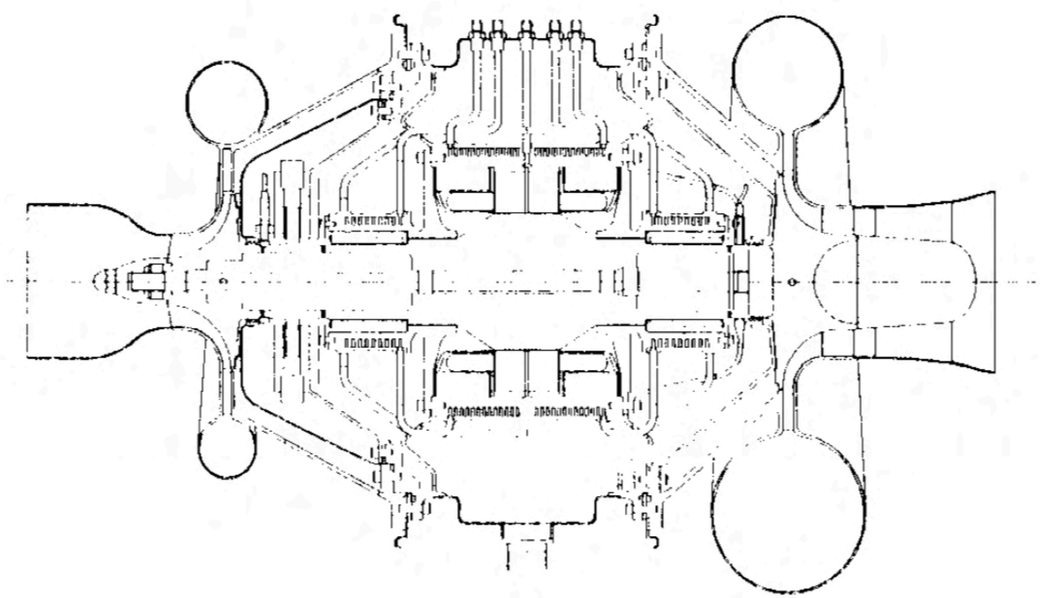
- Mass of the systems will be estimated and plotted against the power output



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Brayton Engine Design

Turboalternator Assembly

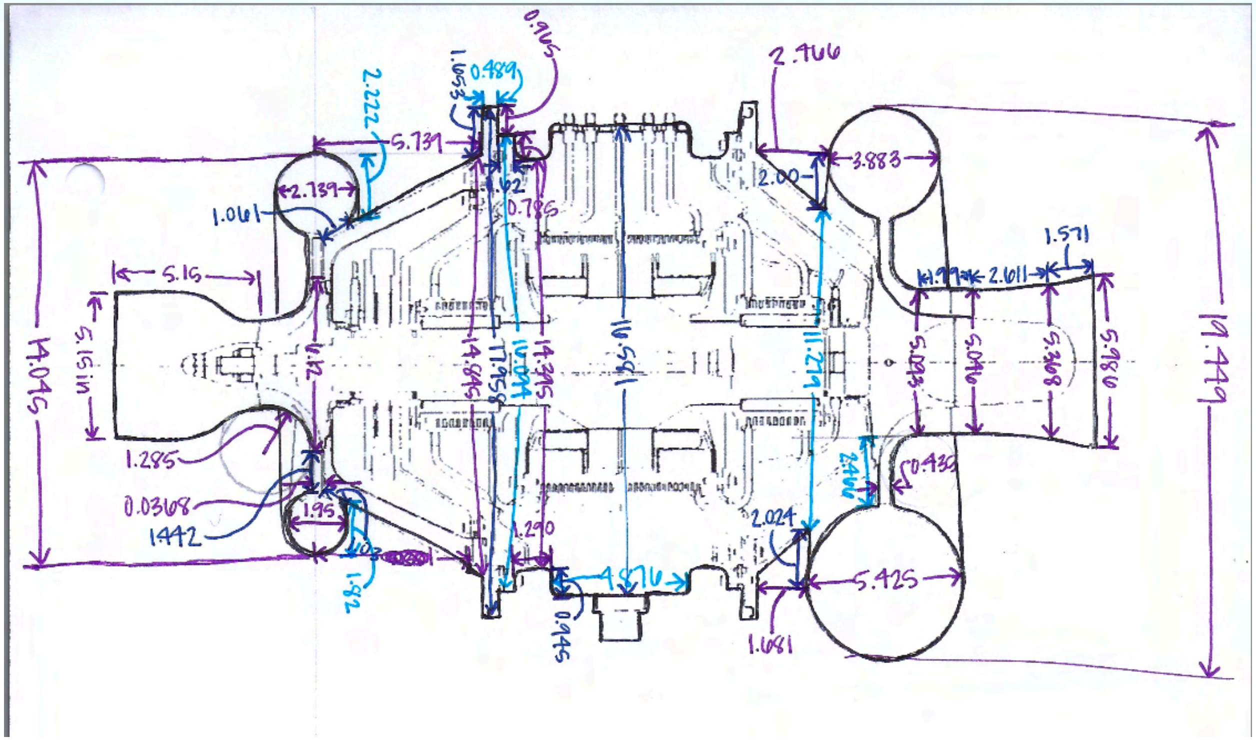


Overall length	87.7 cm (34.5 in)
Overall diameter	50.4 cm (19.8 in)
Weight	145 kg (320 lb)
Compressor tip diameter	15.1 cm (5.97 in)
Turbine tip diameter	18.3 cm (7.20 in)
Alternator rotor diameter	11.8 cm (4.66 in)
Bearing journal diameter	6.5 cm (2.55 in)
Rotor weight	21.6 kg (47.7 lb)

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

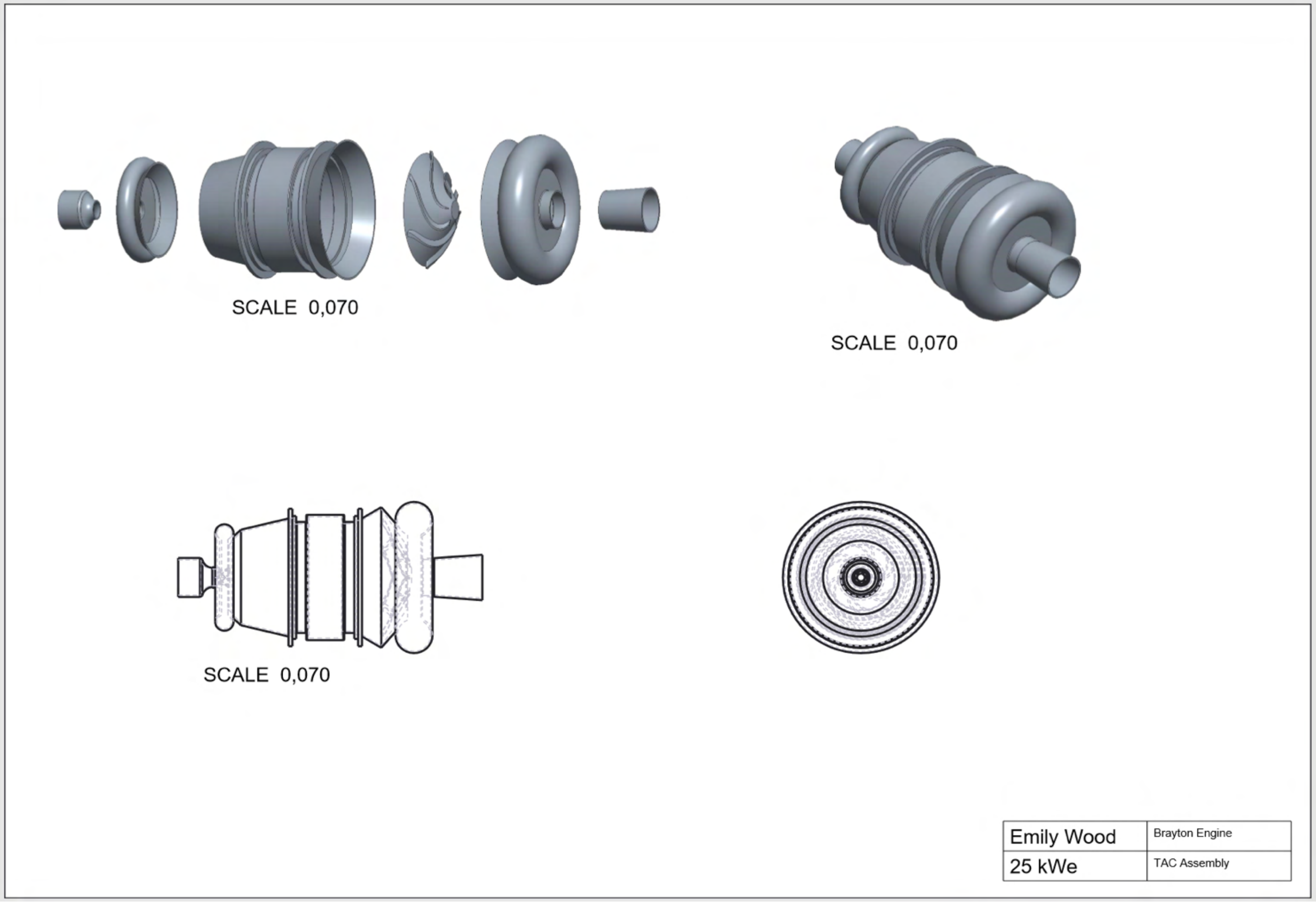
25 kWe Brayton Engine Design

Turboalternator Assembly



25 kWe Brayton Engine Design

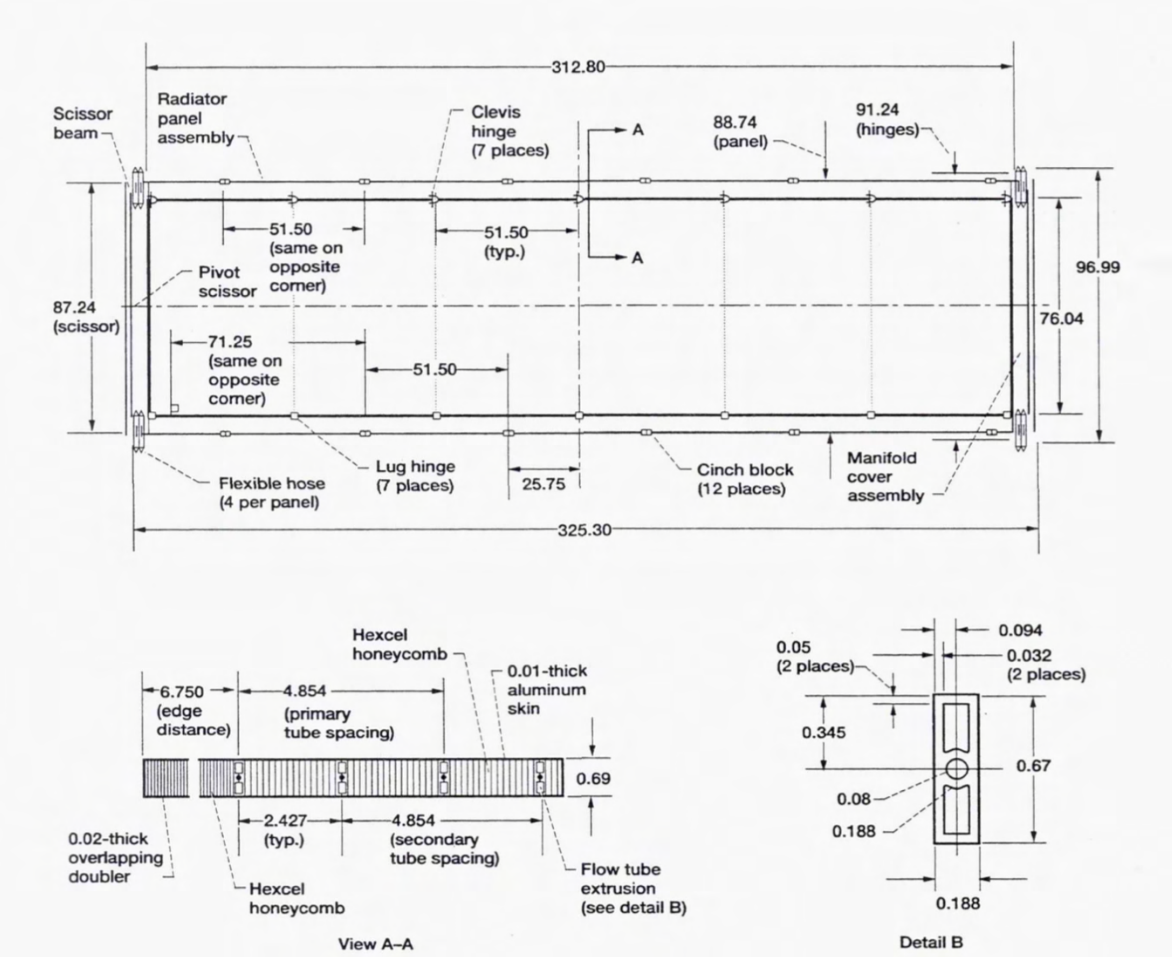
Turboalternator Assembly



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Brayton Engine Design

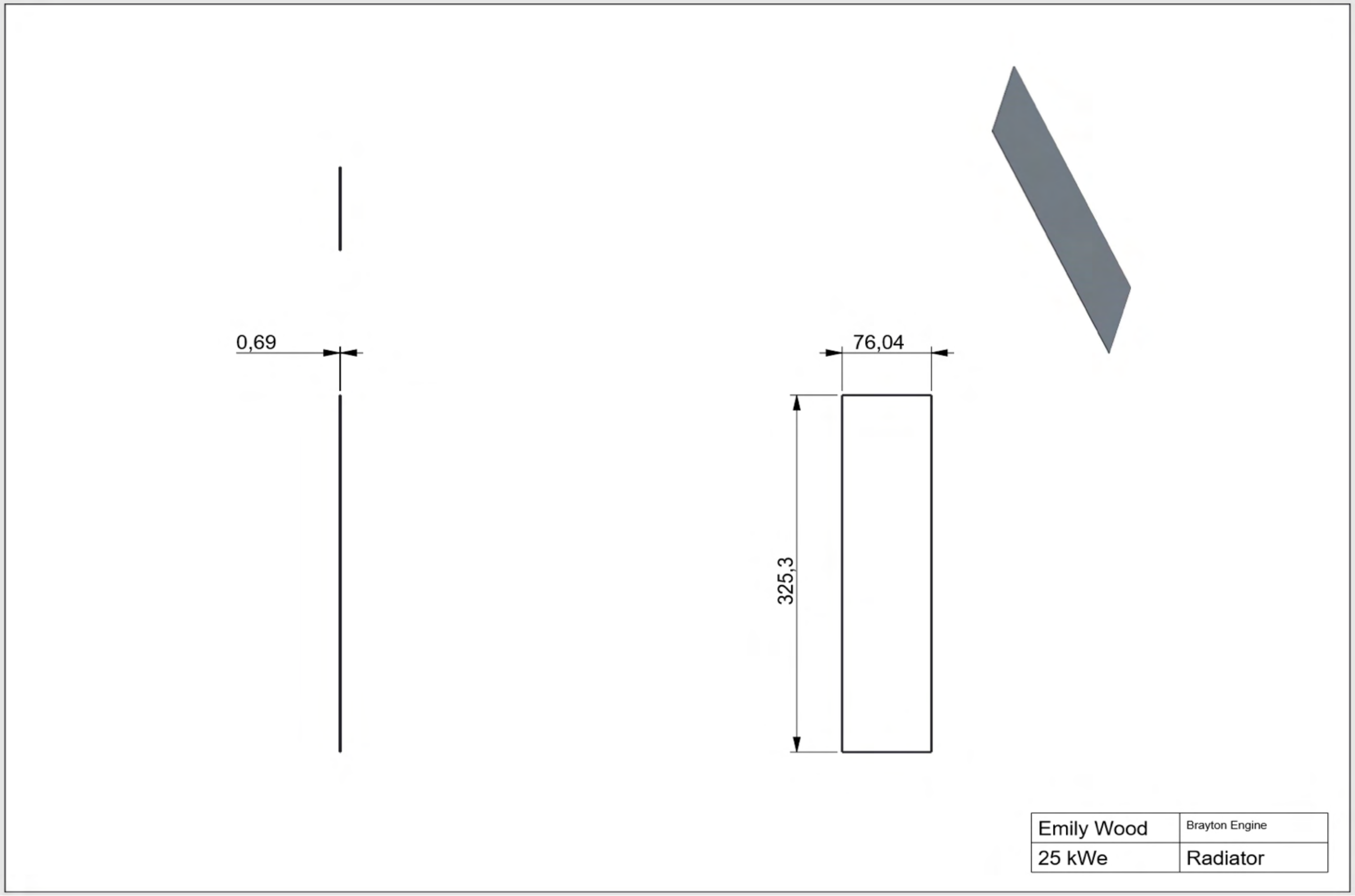
Radiator



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Brayton Engine Design

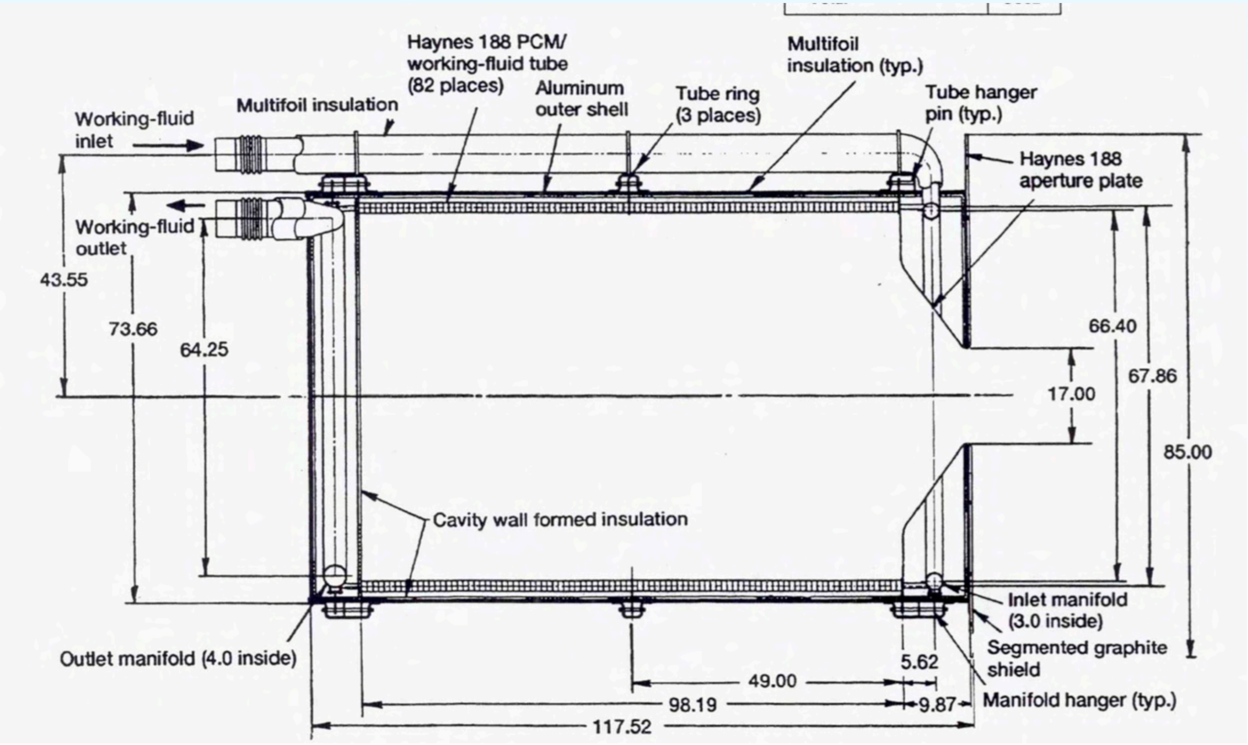
Radiator



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Brayton Engine Design

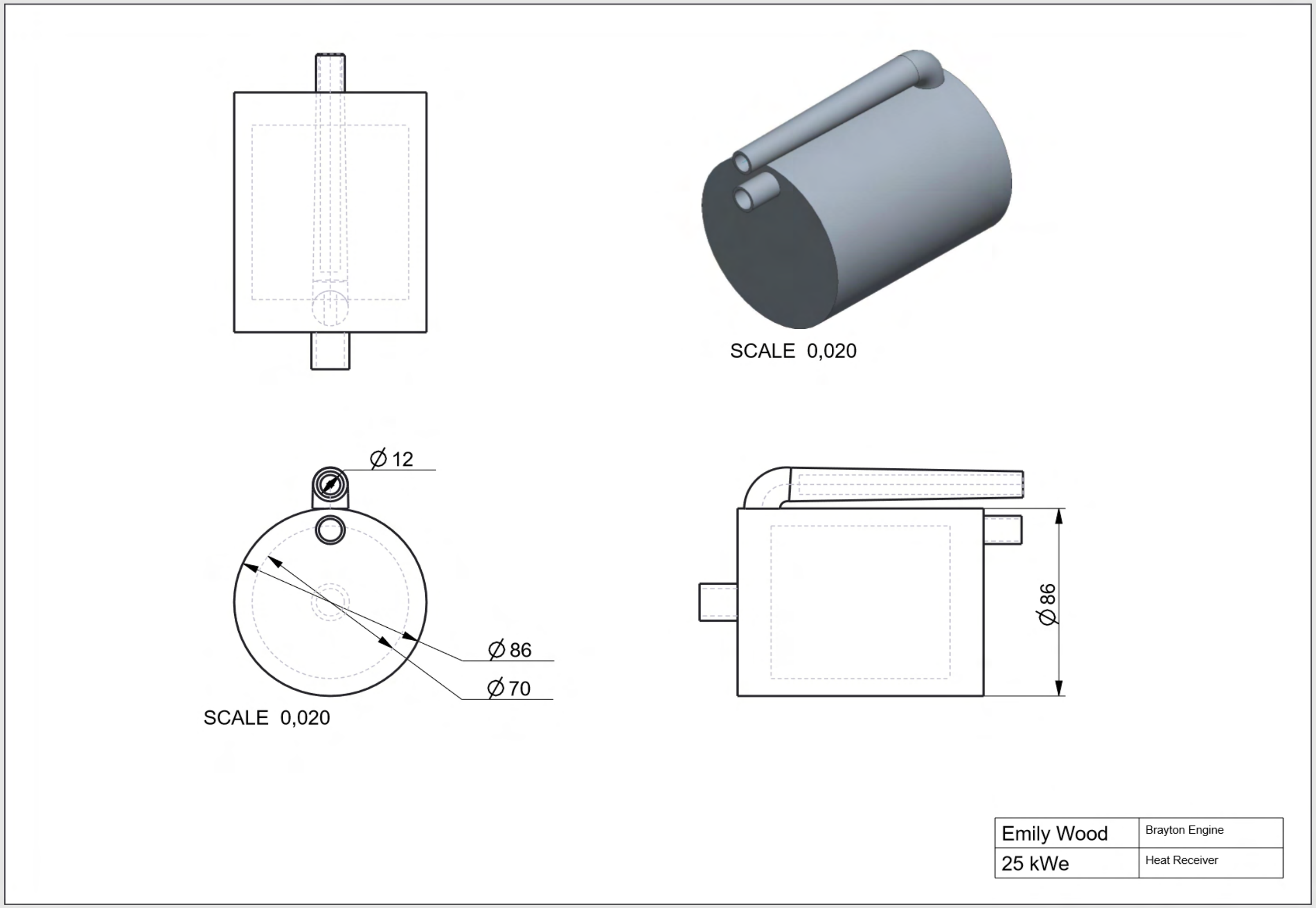
Heat Receiver



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Brayton Engine Design

Heat Receiver



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Brayton Engine Design

Recuperator

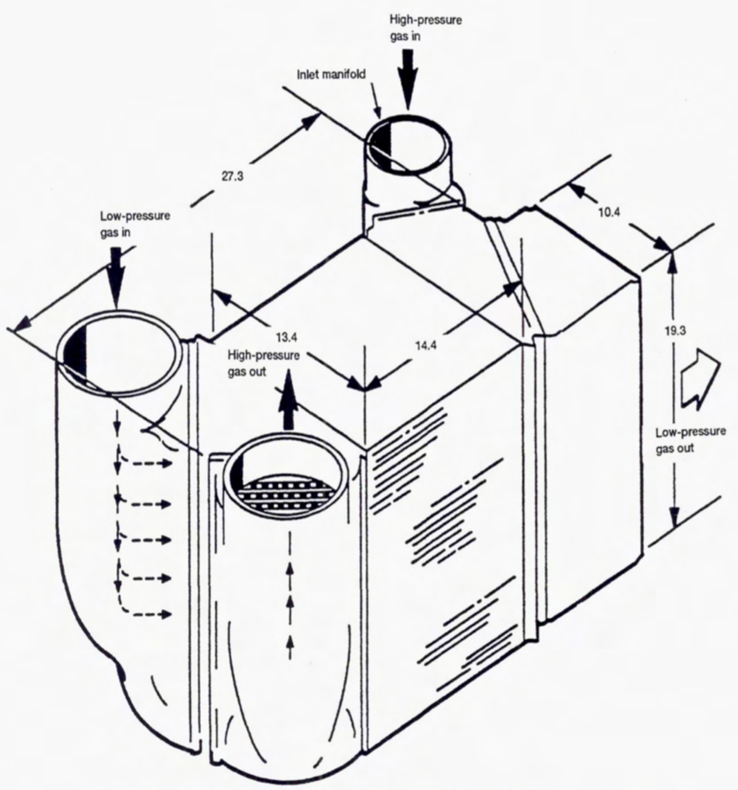
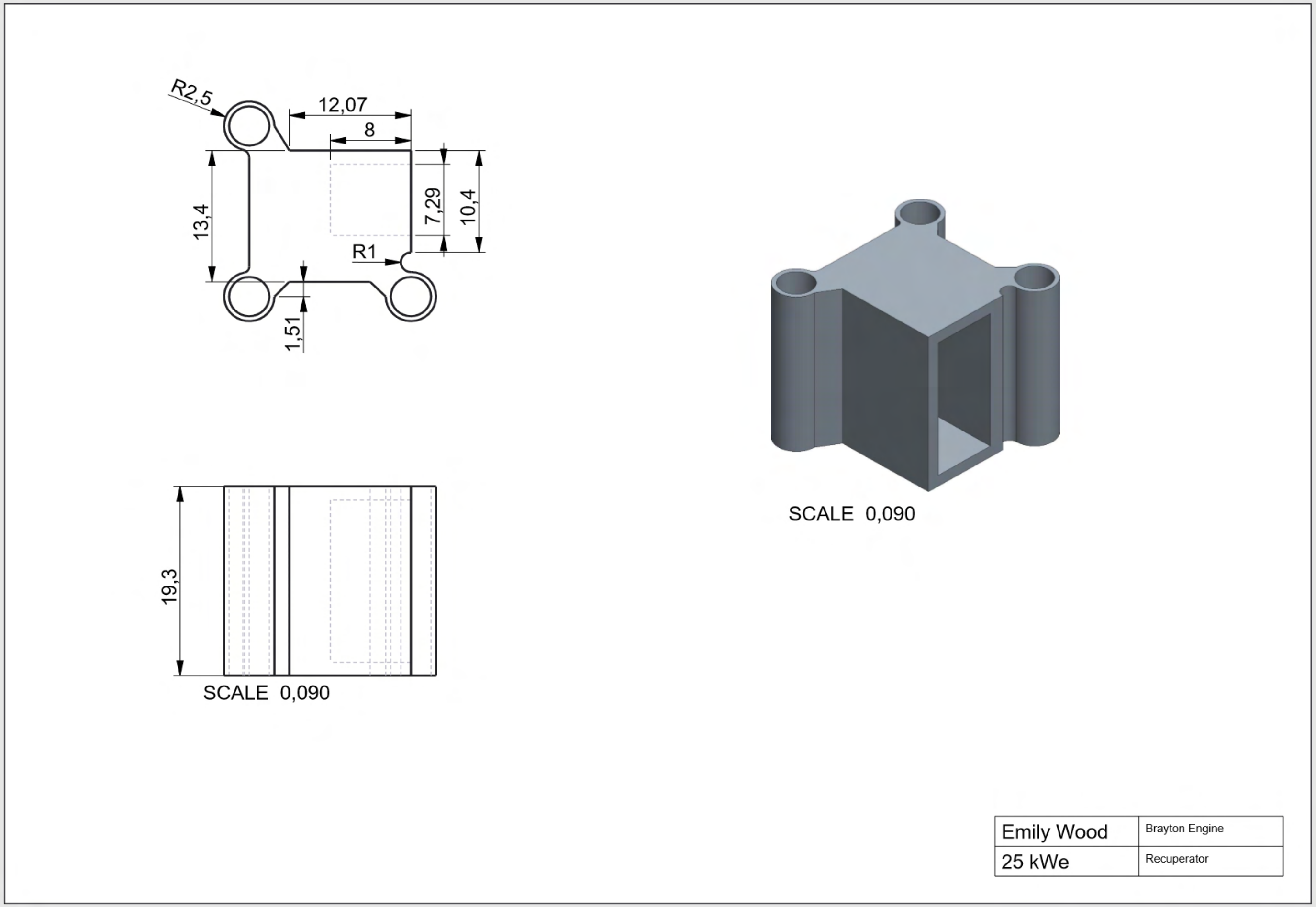


Figure 8.2.—Closed Brayton cycle counterflow recuperator. Weight, 357 lb. (Dimensions are in inches.)

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Brayton Engine Design

Recuperator



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Brayton Engine Design

Gas Cooler

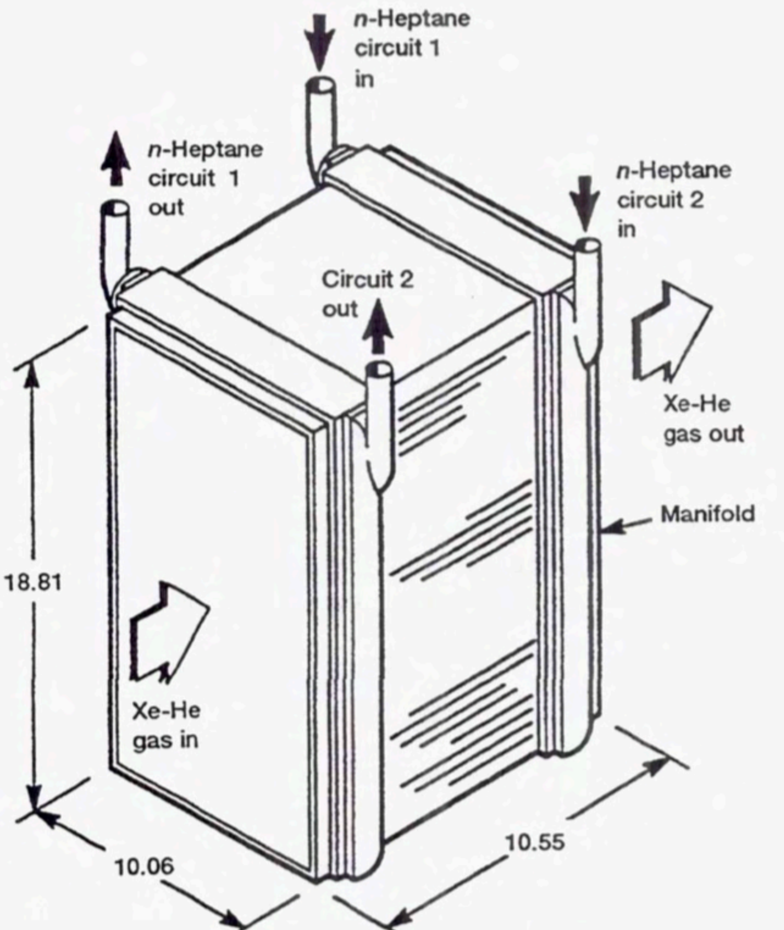
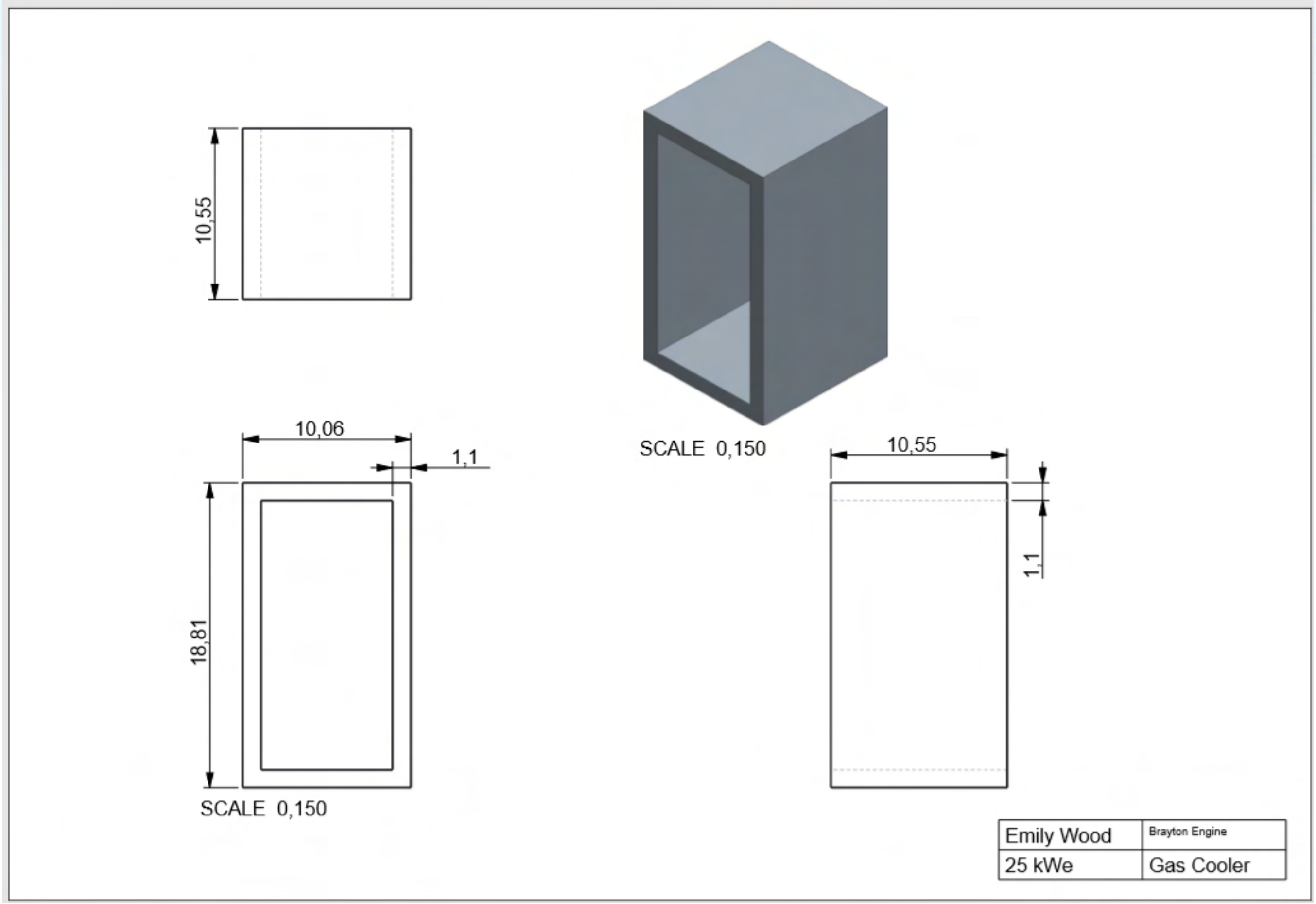


Figure 8.3.—Dual-fluid, eight-pass, cross-counterflow, plate-fin gas cooler. Weight, 188 lb. (Dimensions are in inches.)

25 kWe Brayton Engine Design

Gas Cooler



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Brayton Engine Design

Bleed Cooler

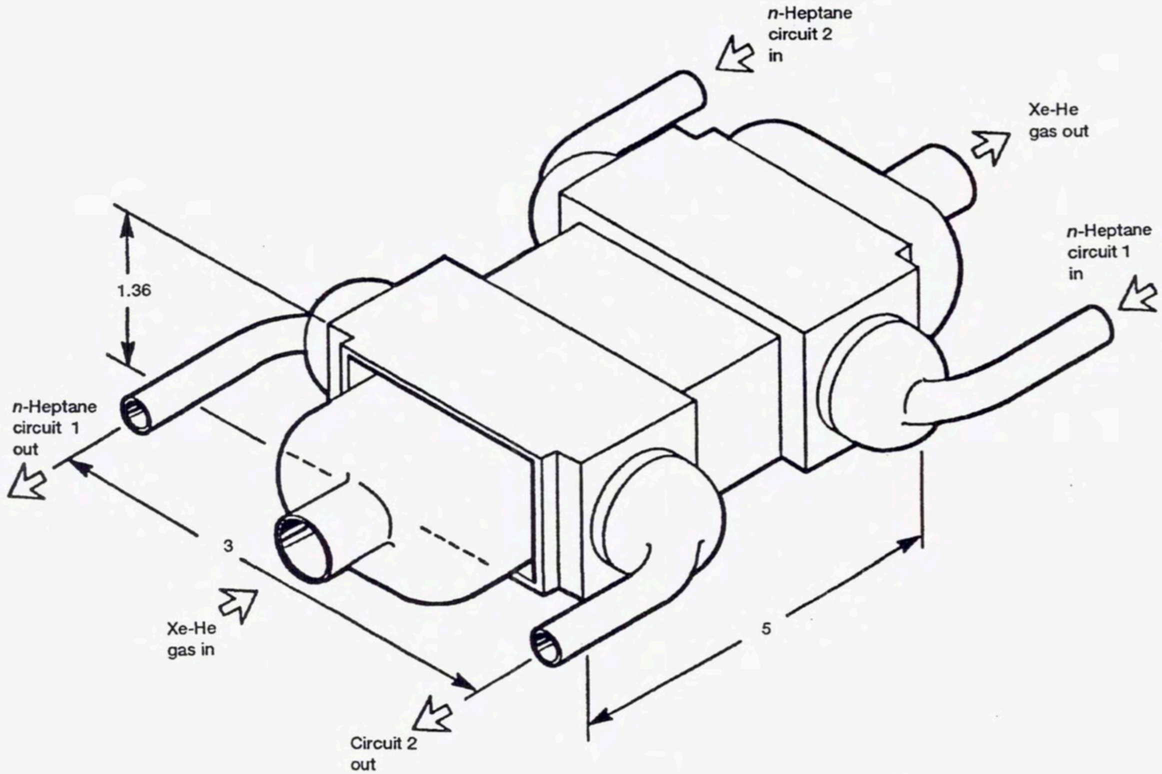
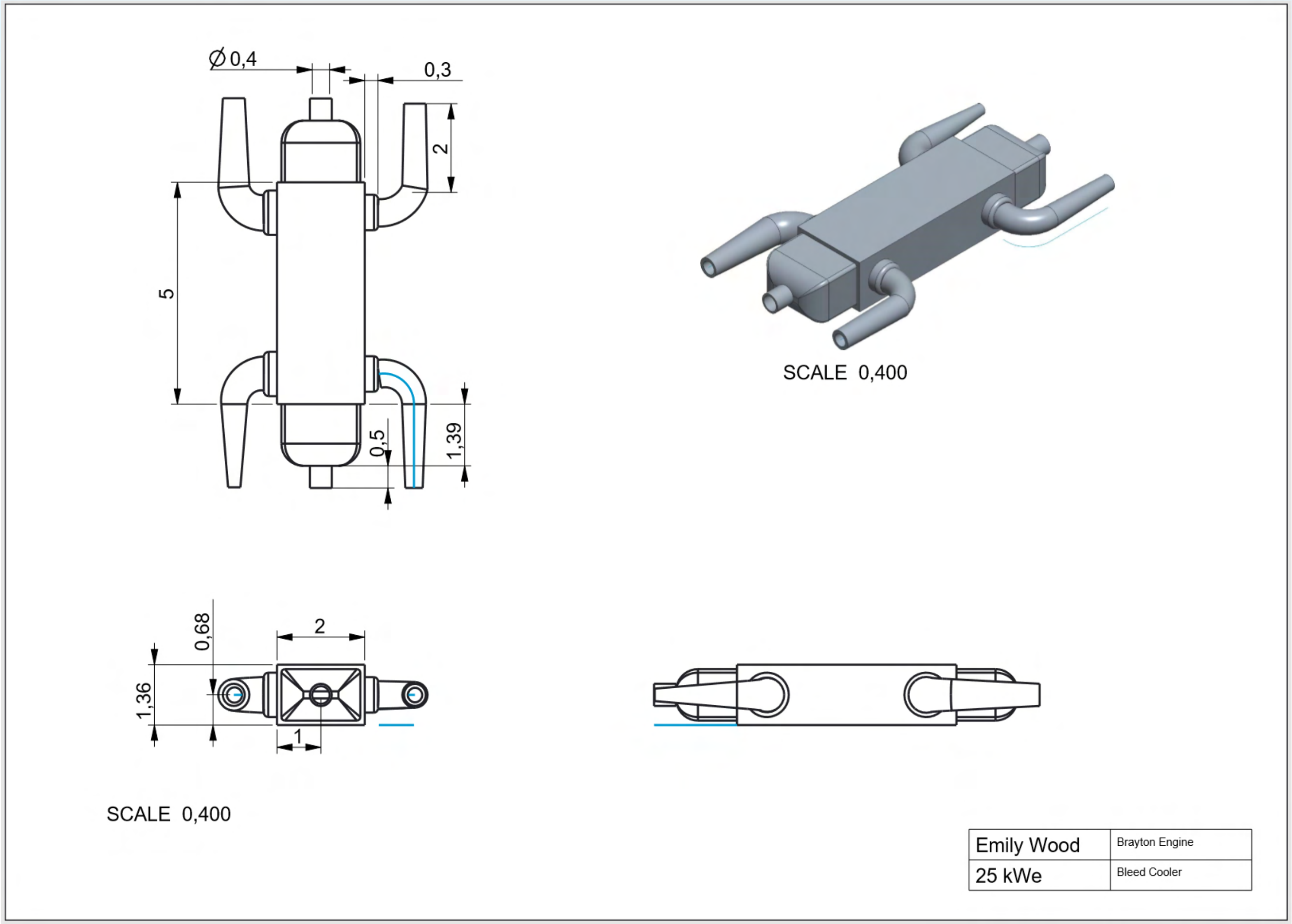


Figure 8.4.—Dual-fluid, counterflow, plate-fin bleed cooler. (Dimensions are in inches.)

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Brayton Engine Design

Bleed Cooler



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Brayton Engine Design

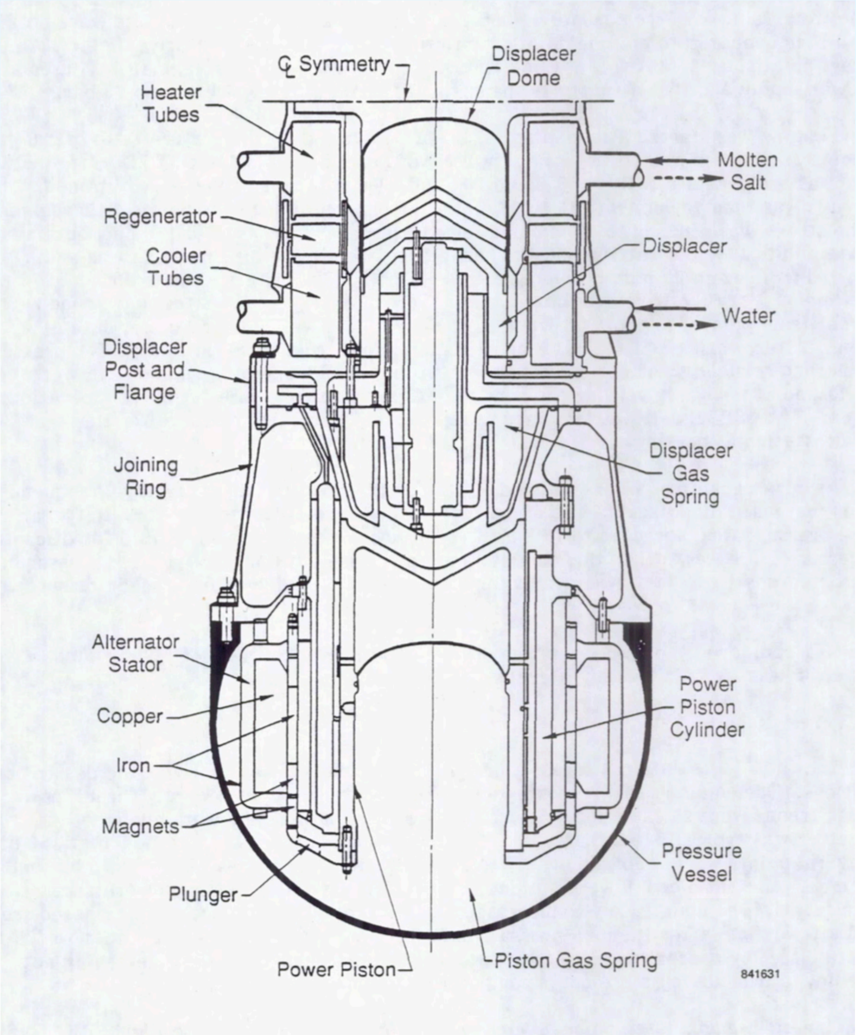
Mass Breakdown

Part	Mass
Compressor Inlet	4.51
Compressor	25.78
Compressor Impeller	1.46
Conversion Unit	113.57
Turbine	74.50
Turbine Impeller	87.24
Turbine Nozzle	7.48
Heat Receiver	19681.00
Radiator	1493.70
Recuperator	335.56
Gas Cooler	186.94
Bleed Cooler	3.95

Total: 22036 lbm

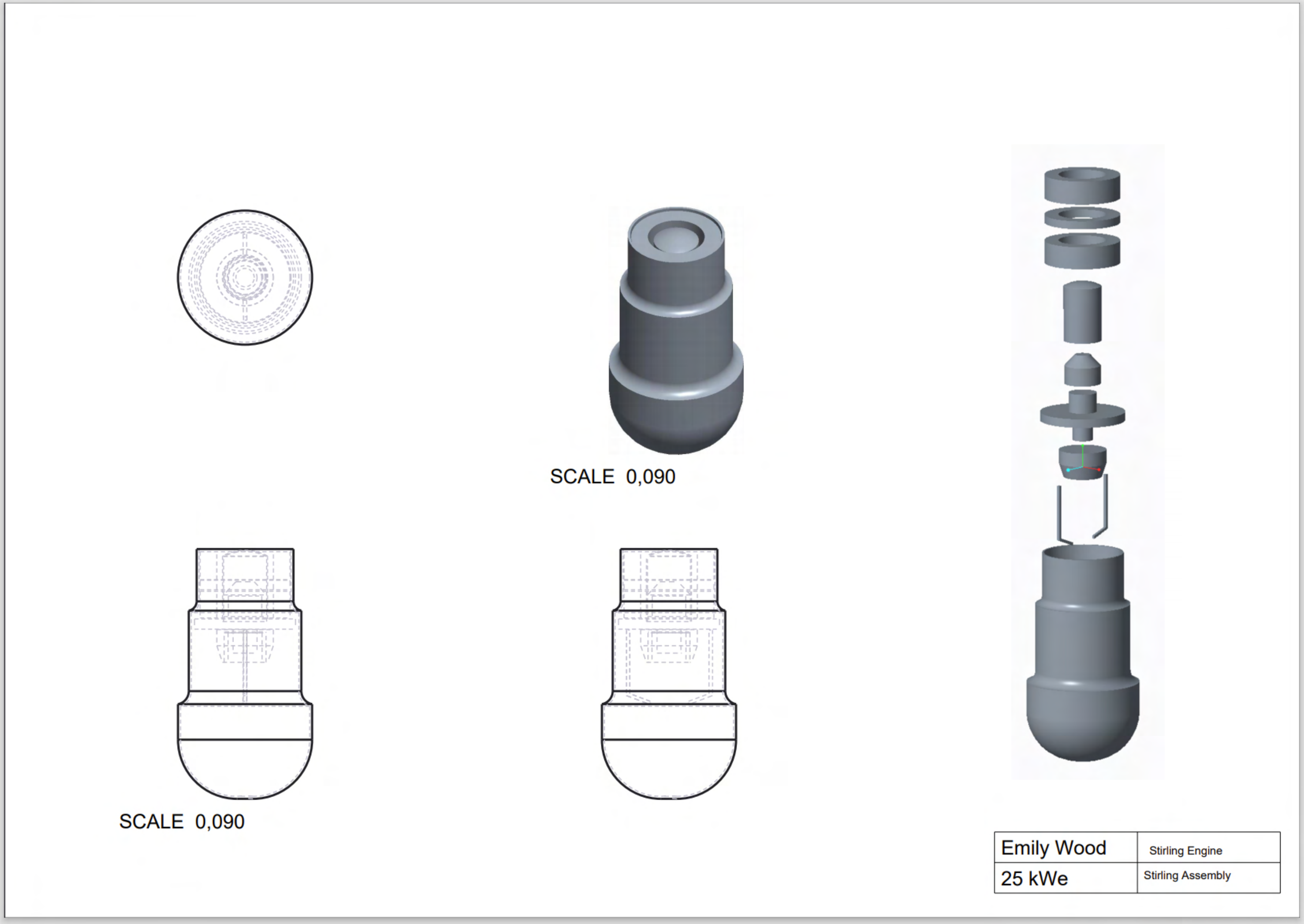
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Stirling Engine Design



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Stirling Engine Design



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

25 kWe Stirling Engine Design

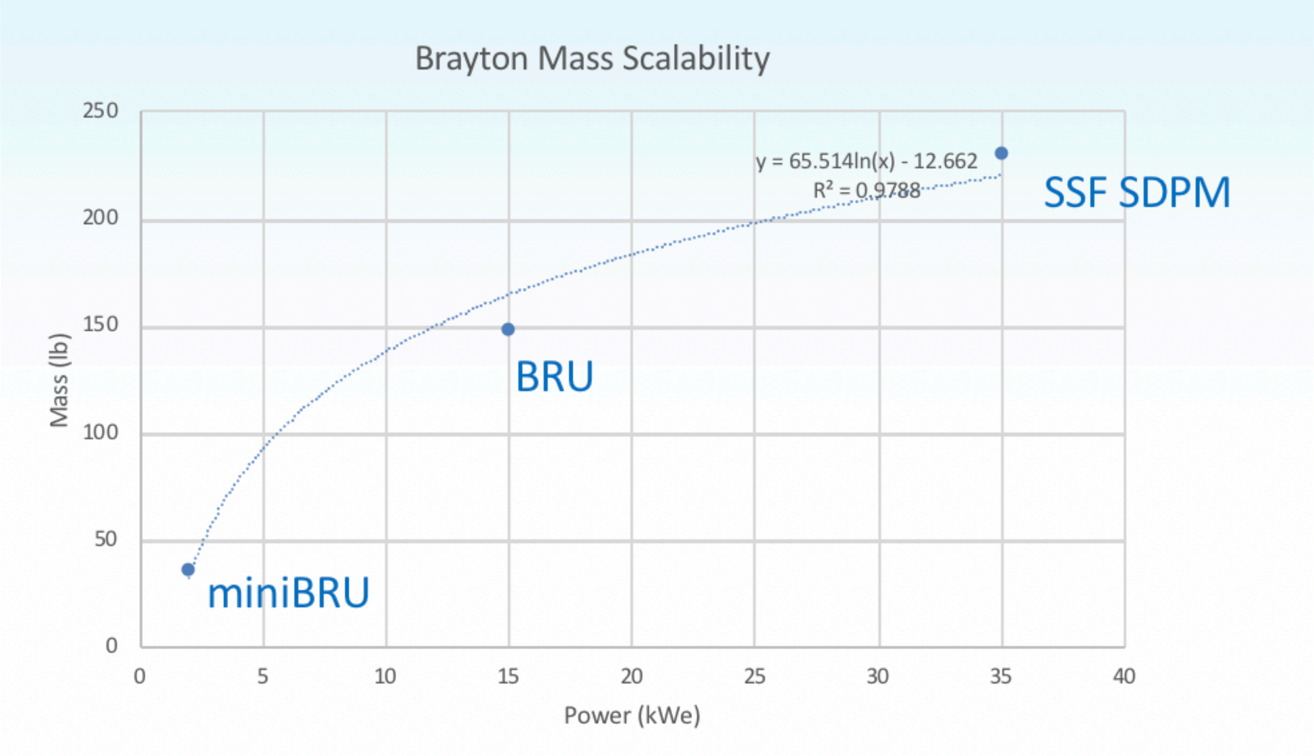
Mass Breakdown

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

Total: 8253.01 lbm

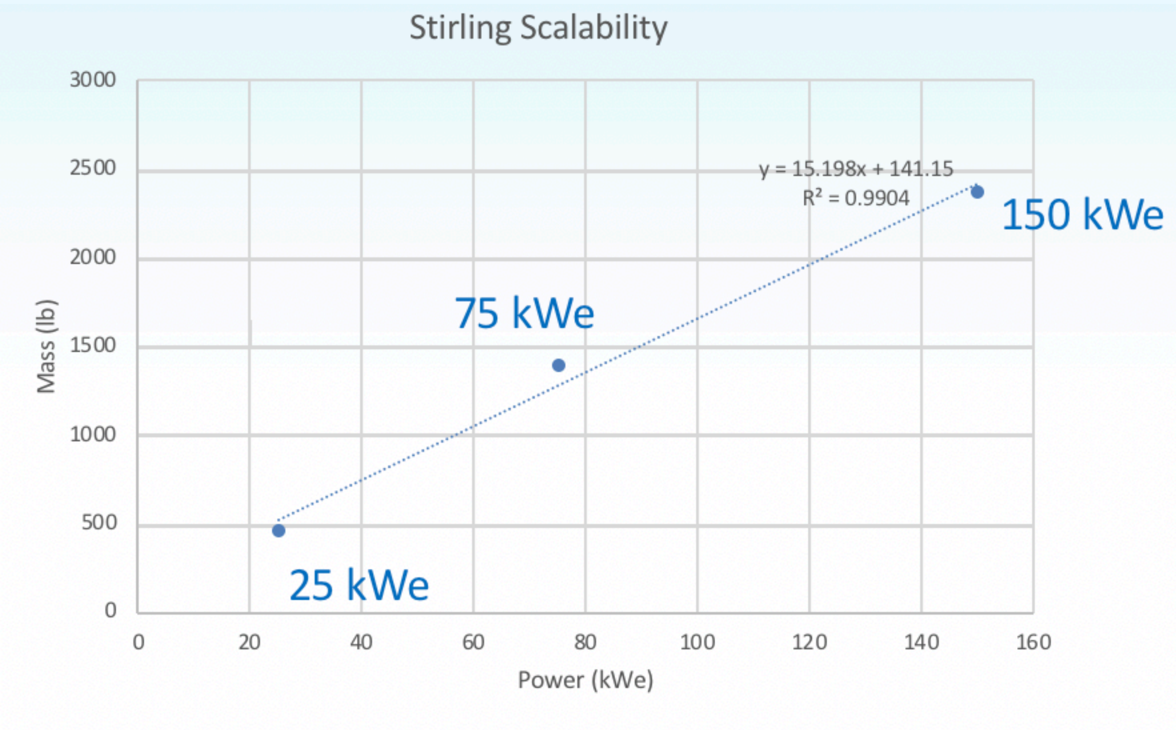
THE UNIVERSITY OF
ALABAMA IN HUNTSVILLE

Brayton Engine Scaling



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

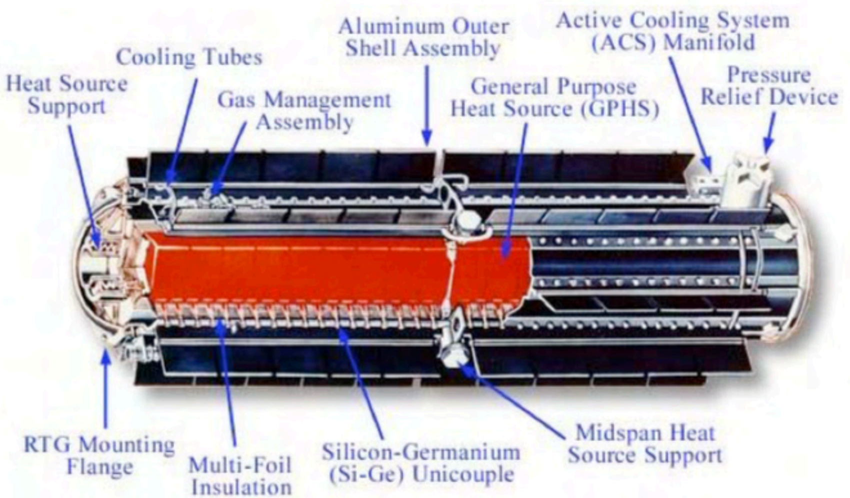
Scaling



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

TEG Mass

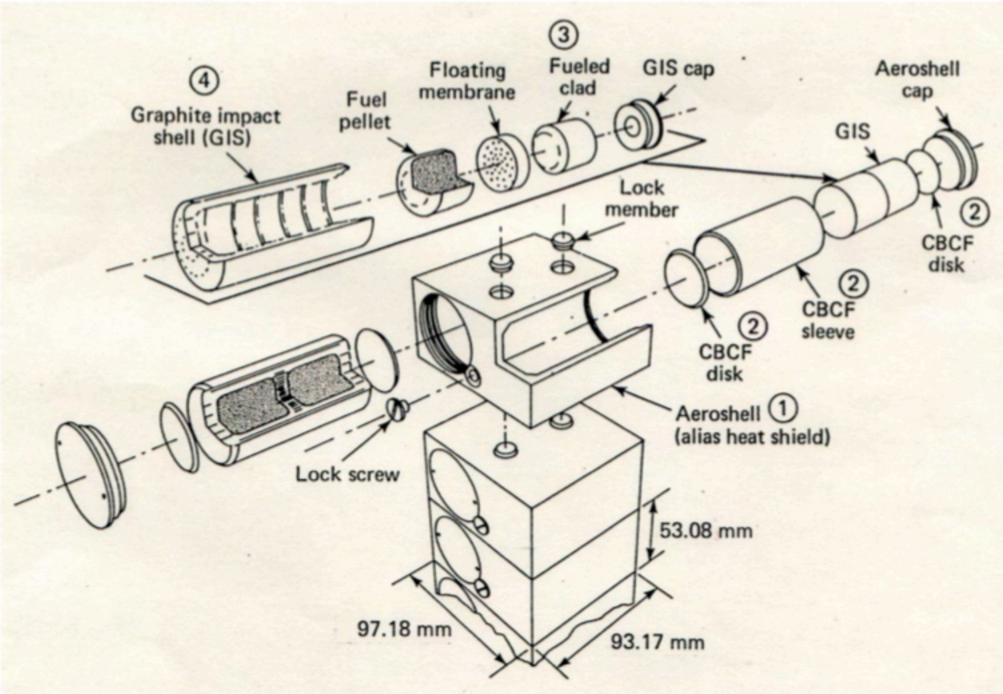
- The GPHS-RTG has an overall mass of 123.24 lbm
- The General Purpose Heat Source (GHPS) is made up of 18 modules providing about 245 Wt from the decay of the encapsulated plutonium-238. Each module has a mass of 3.15 lbm, this includes the mass of the encapsulated plutonium.



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

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.

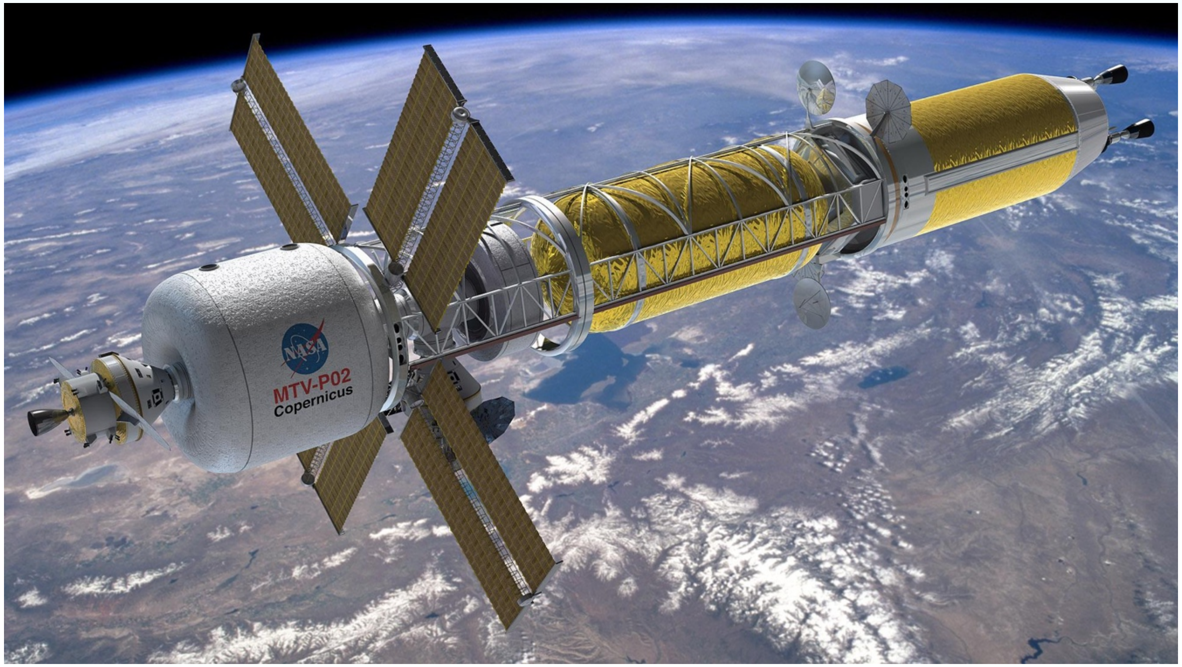


THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Solar Array Mass

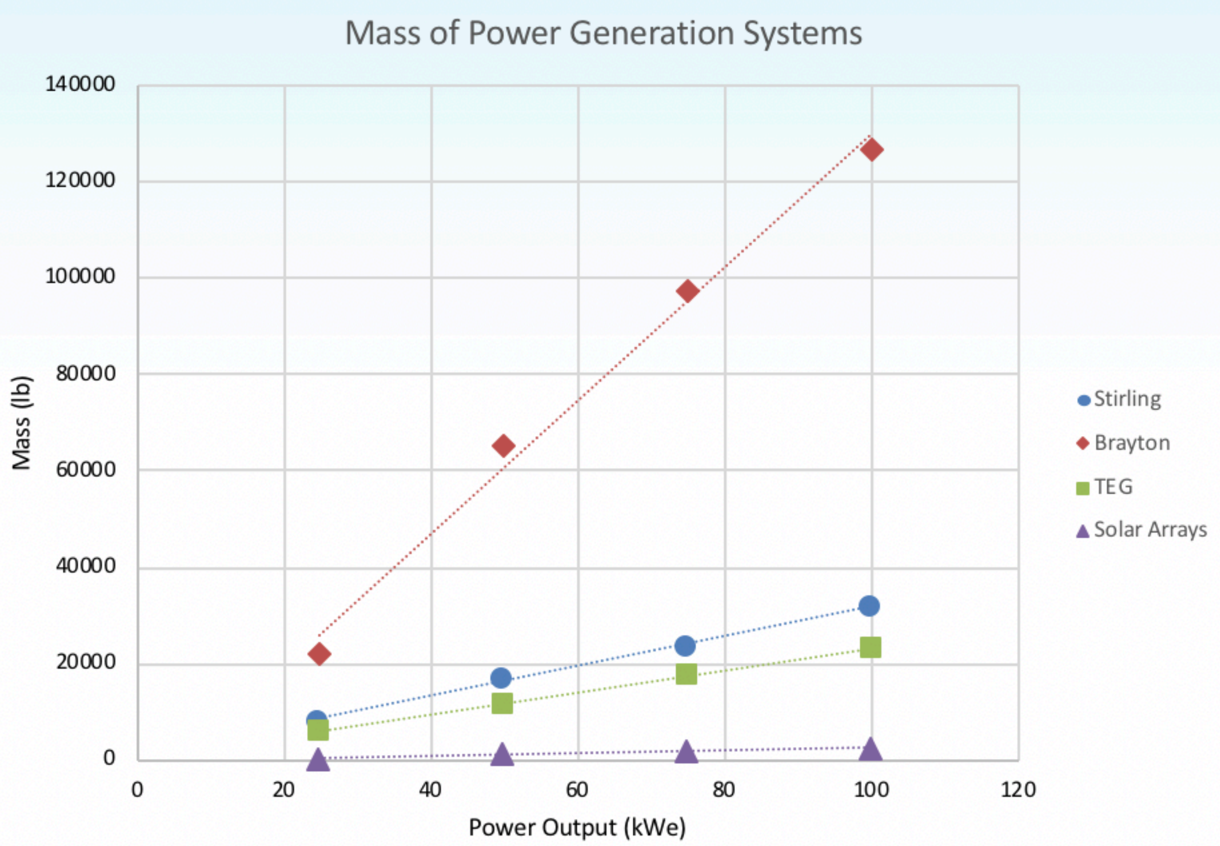
According to Aerojet Rocketdyne's Ground Rules and Assumptions document:

- 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



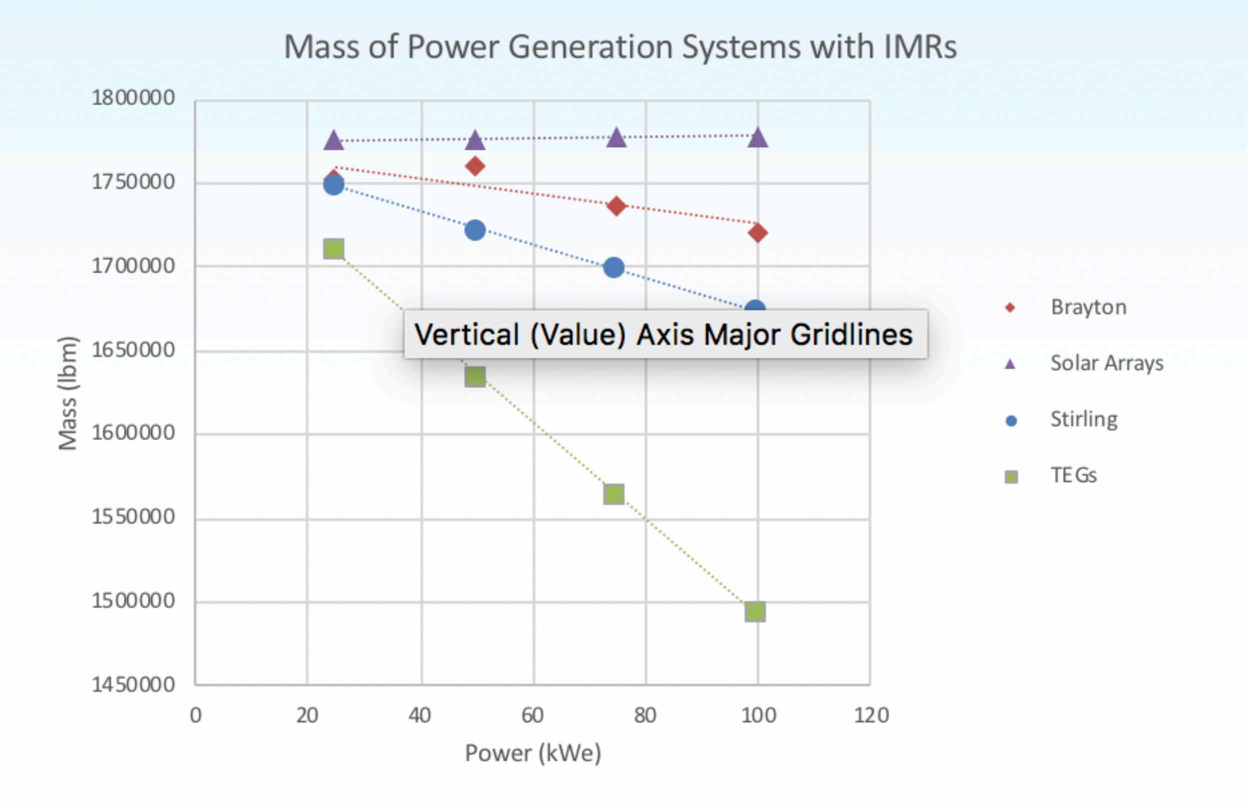
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Master Graph of Power Generation Systems



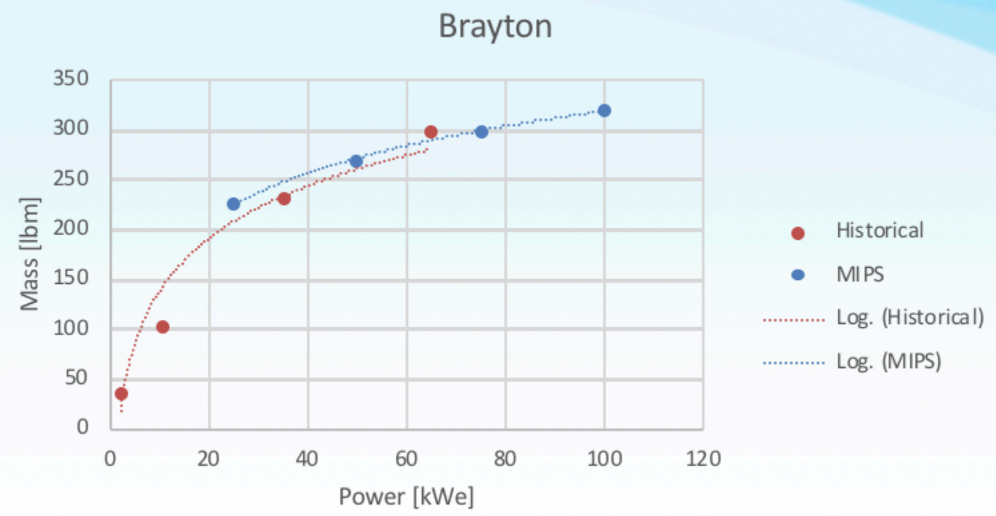
THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

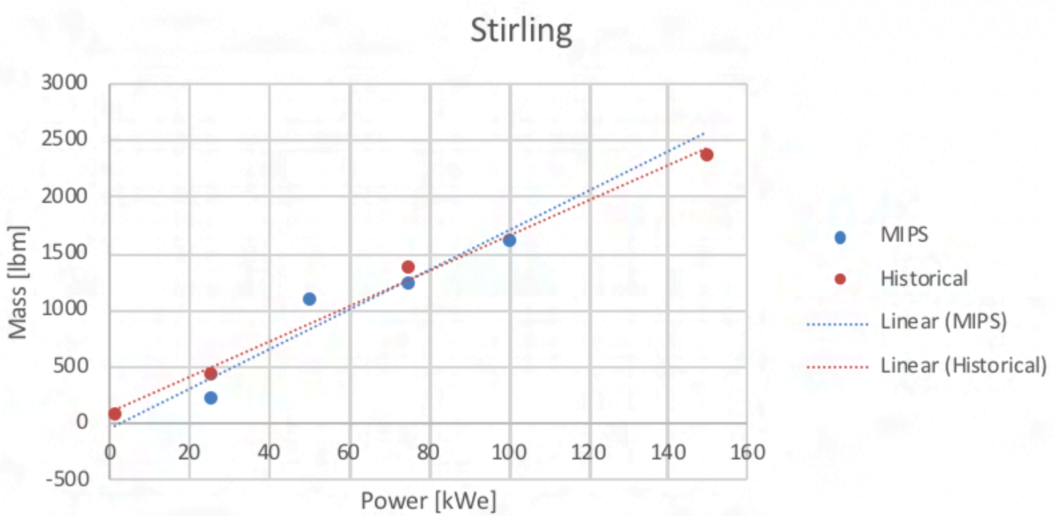
Master Graph of Power Generation Systems Plus IMRs



THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

Validation with Historical Masses





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?

THE UNIVERSITY OF
ALABAMA IN HUNTSVILLE

References

[1] Tokino and CommiM, "Nuclear Thermal Rocket," *Wikimedia Commons*, September 2006

[2] Finseith, J. L., "Overview of Rover Engine Tests: FINAL REPORT," NASA CR – 184270, *George C. Marshall Space Flight Center Science and Engineering Contract*, February 1991

[3] Wade, M., "NERVA-1," Astronautix.com

[4] Nikitaev, D., "Seeding Hydrogen Propellent in Nuclear Thermal Propulsion Engines," *University of Alabama in Huntsville*, 2019

[5] Wronski, A., and Foukdeux, A., "The Ductuile-Brittle in Polycrystalinne Tungsten," *Journal of the Less Common Metals,* Vol 8, Issue 3, March 1965

[6] Rawlins, S., "A Proposed Solution to Address Nuclear Thermal Propulsion Fuel Embrittlement and Cryogenic Hydrogen Requirements," *Nuclear and Emerging Technologies for Space,* Richland, WA, February 25 – February 28, American Nuclear Society Topical Meeting (2019)

[7] Wilson, M., Wilhite, A., Komar, D. R., "Bimodal Nuclear Thermal Rocket Propulsion Systems for Human Exploration of Mars," *AIAA Joint Propulsion Conference*, August 2009

THE UNIVERSITY OF ALABAMA IN HUNTSVILLE

References

[8] Garcia, M., "Engineer Refine Thermal Protection System for Orion's Next Mission," *NASA.gov*, November 2015
[9] Smith, Y., "20 Years Ago, Construction Began on the International Space Station," *NASA.gov,* November 2018
[10] Cheng, F., "Calculation Methods for Thermoelectric Generator Performance", *IntechOpen,* December 2016
[11] Dockrill, P., "All Alone in Interstellar Space, Voyager 2 is About to Lose Contact with Home," *sciencealtert.com*, March 2020
[12] "NICMOS – Restoring Sight to the Hubble Space Telescope," Creare, Hanover, New Hampshire, 2016
[13] "Near Infrared Camera and Multi-Object Spectrometer," *Wikipedia*
[14] Sands, K., "Stirling Converter Sets 14-year Continuous Operation Milestone," *NASA.gov,* April 2020
[15] Rawlins, S., "A Proposed Solution to Address Nuclear Thermal Propulsion Fuel Embrittlement and Cryogenic Hydrogen Requirements," *Nuclear and Emerging Technologies for Space Conference,* February 27, 2019
[16] "Orion Docked to Mars Transfer Vehicle," *Wikimedia*

THE UNIVERSITY OF
ALABAMA IN HUNTSVILLE

References

[17] Mitchell, R., “Powering the Voyager Spacecraft with Radiation: The RTG (Radioisotope Thermoelectric Generator)”, *All About Circuits*, June 2017,
[18] Moran, M. J., Shapiro, H.N., Boettner, D. B., Bailey, M. B., *Fundamentals of Engineering Thermodynamics,* 8th Ed. Wiley, 2014
[19] Nam, S. H., Venneri, P., Kim, Y., Lee, J. I., Chang, S. H., Jeong, Y. H., “Innovative Concept for an Ultra-Small Nuclear Thermal Rocket Utilizing a New Moderated Reactor,” Nuclear Engineering and Technology, Vol. 47, Issue 6, October 2015

THE UNIVERSITY OF
ALABAMA IN HUNTSVILLE