Oral Presentation/Viewgraphs Summary:

For many years NASA has used the decay of Pu-238 (in the form of the General Purpose Heat Source (GPHS)) as a heat source for Radioisotope Thermoelectric Generators (RTG), which have provided electrical power for many NASA missions. While RTG's have an impressive reliability record for the missions in which they have been used, their relatively low thermal to electric conversion efficiency (~5% efficiency) and the scarcity of Plutoinium-238 (Pu-238) has led NASA to consider other power conversion technologies. NASA is considering returning both robotic and human missions to the lunar surface and, because of the long lunar nights (14 earth days) isotope power systems are an attractive candidate to generate electrical power. NASA is currently developing the Advanced Stirling Radioisotope Generator (ASRG) as a candidate higher efficiency power system that produces greater than 160 watts with 2 GPHS modules at the beginning of life (BOL) (~30% efficiency). The ASRG uses the same Pu-238 GPHS modules, which are used in RTG, but by coupling them to a Stirling convertor provides a 4-fold reduction in the number of GPHS modules. This study considers the use of Americium 241 (Am-241) as a substitute for the Pu-238 in Stirling convertor based Radioisotope Power Systems (RPS) for power levels from 10's of watts to 5 kWe. The Am-241 is used as a replacement for the Pu-238 in GPHS modules. Depending on power level, different Stirling heat input and removal systems are modeled. It was found that substituting Am-241 GPHS modules into the ASRG reduces power output by about 1/5 while maintaining approximately the same system mass. In order to obtain the nominal 160 watts electrical output of the Pu-238 ASRG requires 10 Am-241 GPHS modules. Higher power systems require changing from conductive coupling heat input and removal from the Stirling convertor to either pumped loops or heat pipes. Liquid metal pumped loops are considered as the primary heat transportation on the hot end and water pumped loop/heat pipe radiator is considered for the heat rejection side for power levels above 1 kWe.

Lunar Surface Stirling Power Systems Using Am-241

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Study and Presentation Overview

- Study: Conceptually Model Stirling Radioisotope Power Systems using Americium-241 as the heat source
    - Motivation for study is the limited availability of Pu-238
    - Size systems from 10's of Watts to 5 kWe
    - Lifetime 10 years
    - Environment – Lunar Surface- Equator
- **Current Isotope Systems**
- **Alternative Isotope Candidates**
- **Stirling Convertor Designs**
- **System Layouts**
- **Environment**
- **Results**
- **Conclusions**

Radioisotope Power Systems

- RTG- Multiple NASA Missions, Cassini, Galileo
- MMRTG-MSL
- ASRG-Discovery Mission ~2014
- All of these RPS are based upon the GPHS Heat Source Building Block

|	MMRTG	Galileo RTG	ASRG
Mass (kgs)	44	34	22
Power Output BOM (watts)	125	>300	160
# GPHS Modules	8	18	2
Efficiency (%)	5.5%	6.6%	32 %
Dimensions			
Diameter	64 cm	42 cm	46 cm
Length	66 cm	1.14 cm	72 cm

GPHS-RTG
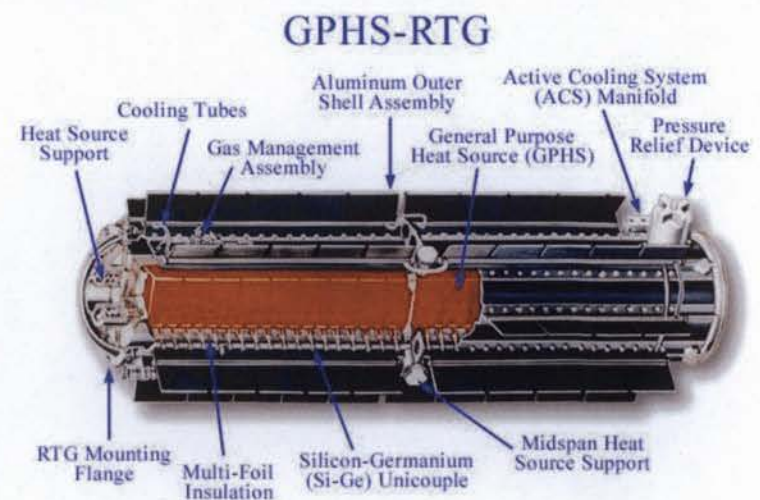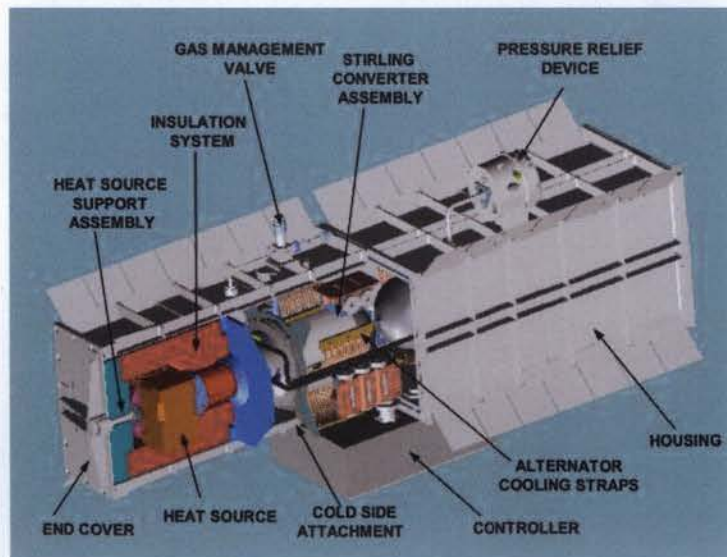
General Purpose Heat Source (GPHS)

- The GPHS is a DOE standardized isotopic heat source designed to withstand launch failures

- Each produces ~250 watts BOL, has a mass of 1.6 kg and a half life of 88 years

- 4, Pu-238 PuO_2 pellets are encased in an iridium cladding and then placed within a carbon liner and surrounded by a aeroshell
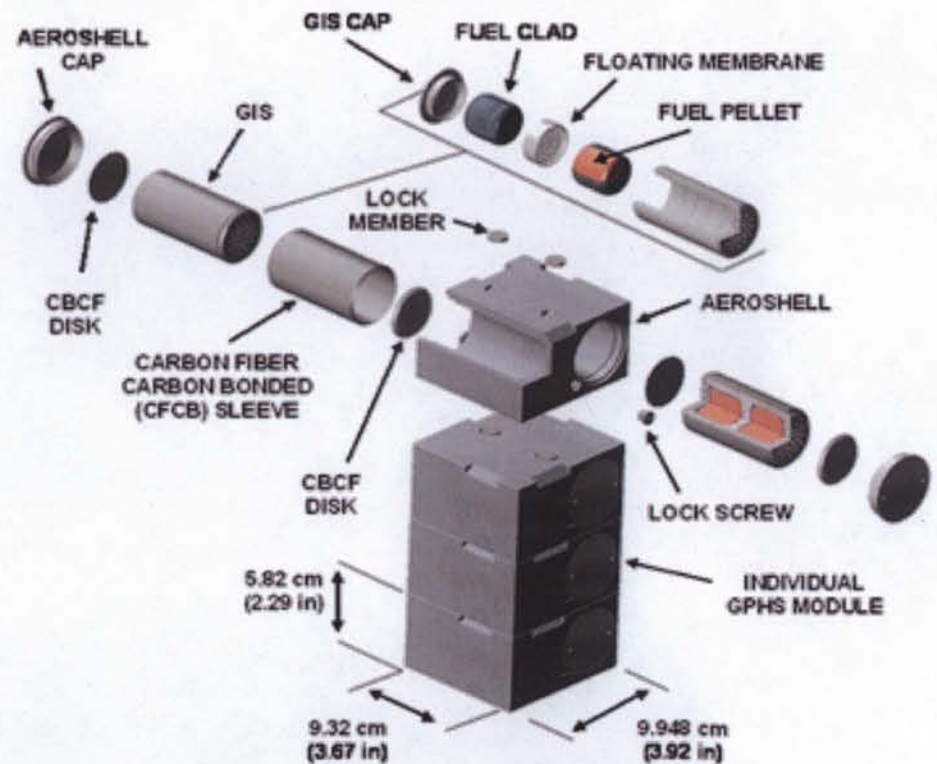
Other Isotope Candidates

- For this study we will replace the PuO_2 with another isotope

- Desired isotope should have:
  - Long half-life
  - High energy output per unit mass
  - Alpha emitter
  - High temperature capability in its fuel form

Half-Life for Various Isotopes

Isotopes Considered with Half-Lives greater than 5 years
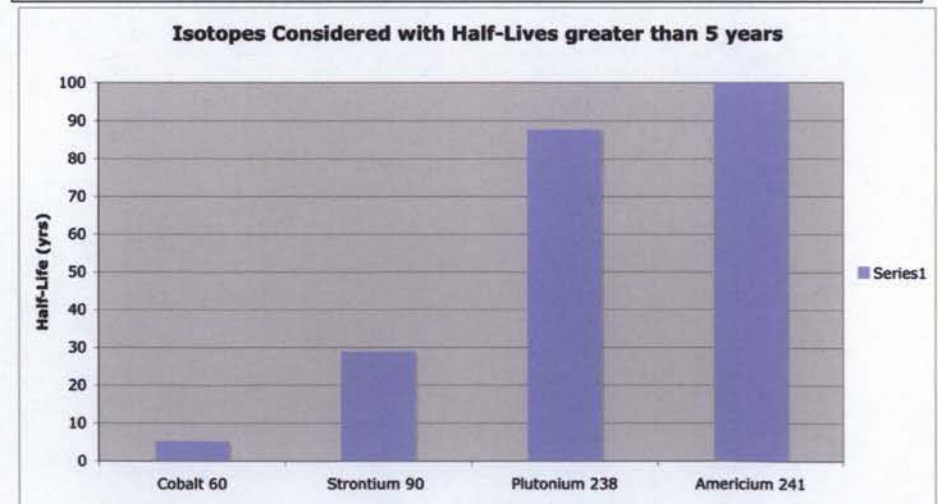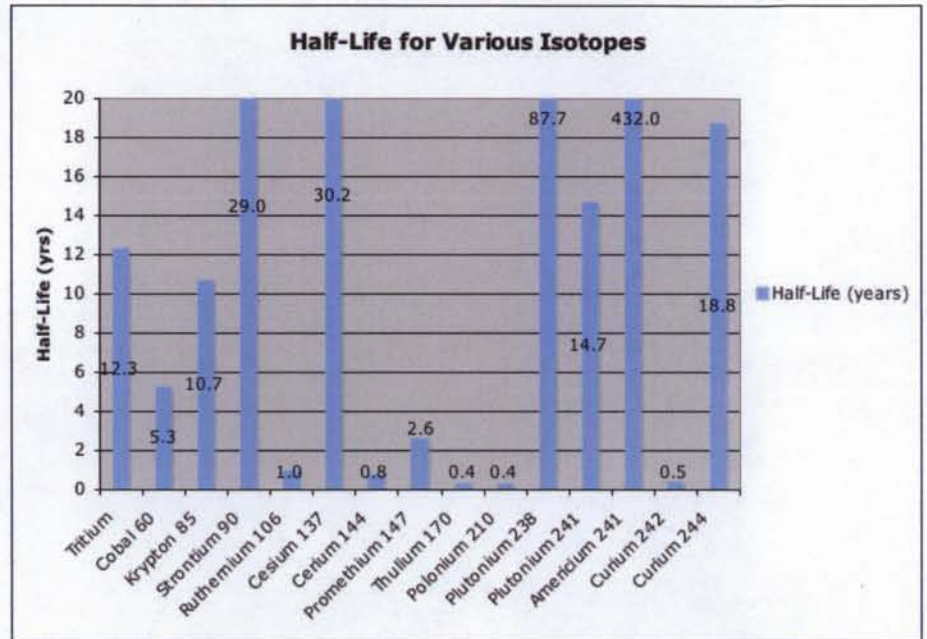
Isotope Comparison

	PuO_2	AmO_2	SrO
Pellet Mass (g)	188	191	83
Half Life (yrs)	87.7	432.7	28.8
Melting Temperature (K)	2637	2273	1661
Total Fuel Mass (g)	751	766	334
GPHS Module Thermal Power (watts)	250	56.9	42.8
Neutron Dose rate at 1 m radius from GPHS (Sv/hr)	6.5345 E-4	8.238 E-5	0
Gamma Dose rate at 1 m radius from GPHS (Sv/hr)	1.88E-6	1.74E-7	1.137
Worker maximum recommended exposure time (hours/year)	31	242	.018

Data from: R.C. O'Brien, et al., "Safe Radioisotope Thermoelectric Generators and Heat Sources for Space Applications," Journal of Nuclear Materials, Issue 377 (2008) pp 506-521.

Thermal Environment

- Power operation on the lunar surface is a challenge due to the wide range of temperatures encounter as both latitude and time of day change
- Lunar soil has a high solar absorptivity and low thermal conductivity
- Typical space based systems use Beginning of Life (BOL) emissivity of >0.9 for modern space radiators, surface treatments limit solar absorptance to 0.06
- Due to dust accumulation an emissivity of 0.86 and a solar absorptivity of 0.5 was assumed.
- The sink temperature extreme's used in this study are 340 K and 60 K for a equatorial full sunlight and a pole crater respectively
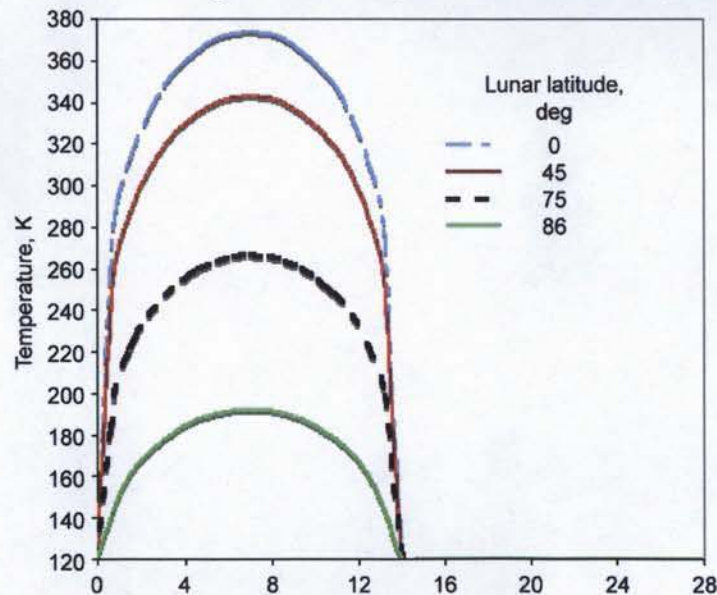
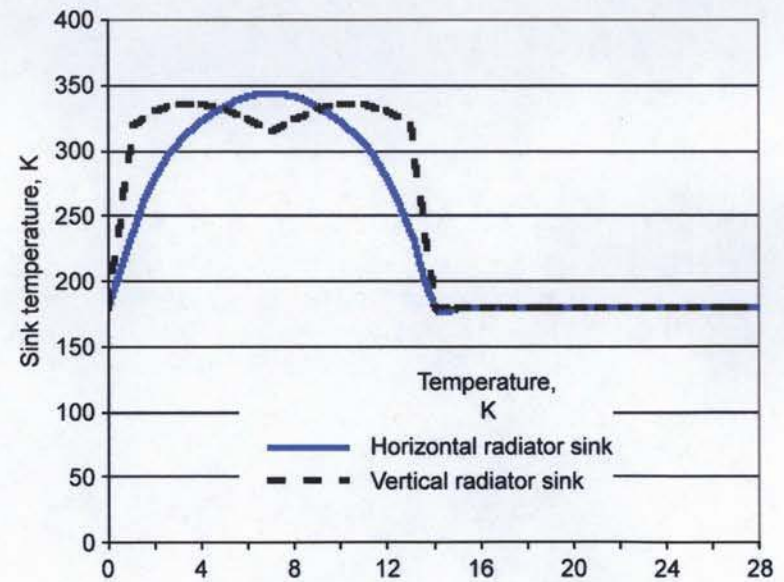Figure 1.—Lunar surface temperature as a function of time and latitude.

Figure 2.—Sink temperature as a function of Earth days.

# Heat Source Integration and Rejection Integration Options

- Heat Flux out of a GPHS (largest face) is 2.69 w/cm2
- Stirling's require about 15 w/cm2 at heater/cooler heads
- Conductively Coupled Source and Sink
  - Practical up to ~ 6 GPHS modules per Stirling
- Heat pipe or Pumped Fluid Loop Interface between GPHS and Stirling and Stirling and Radiator as heat flows increase
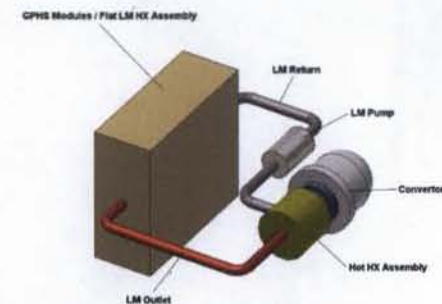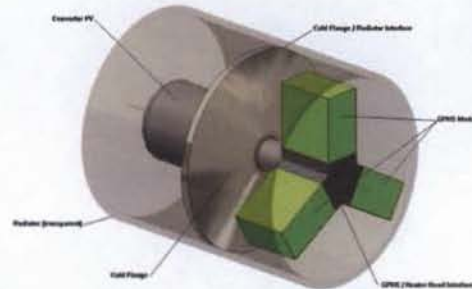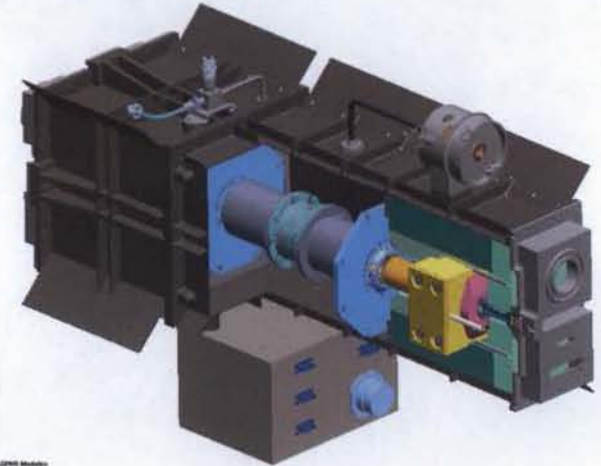
Number of GPHS Modules per Convertor	1		2 to 6		>6	
Power Level (watts)	Pu-238	Am-241/ Sr-90	Pu-238	Am-241	Pu-238	Am-241
	160	~20	~300 to 1000	60 to 240	>1120	>210
GPHS to Stirling Interface	Cond.	Cond	Cond	Cond	PL	PL
Stirling to Radiator Interface	Cond	Cond	HP or PL	Cond	PL	PL

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CONDUCTIVELY COUPLED SYSTEMS

Convertor Heater Head / Alternative GPHS Interface

GPHS Module (3 of 5)

Thermal Interface
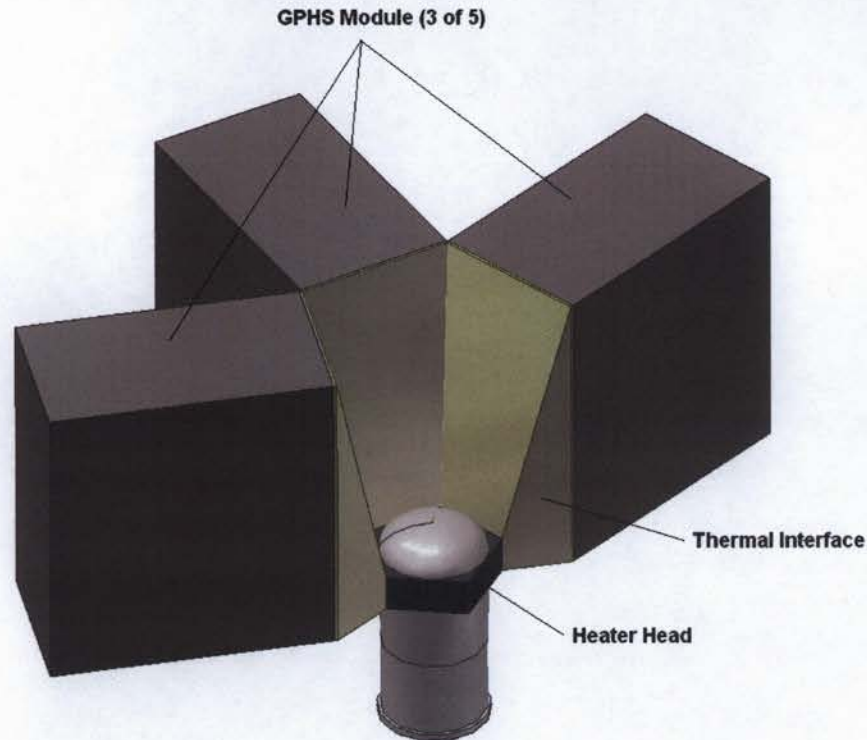
Heater Head

- **Various options available for alternative isotope fueled GPHS interface with ASC class heater head geometries**
- **Key component is the thermal interface between heater head and GPHS**
- **Use of materials with highly directional thermal conductivities have significant advantages over simple metallic structures - Significant heat flux "concentration" required**
- **Simple heat pipe / vapor chamber also options**

Low Power Convertors
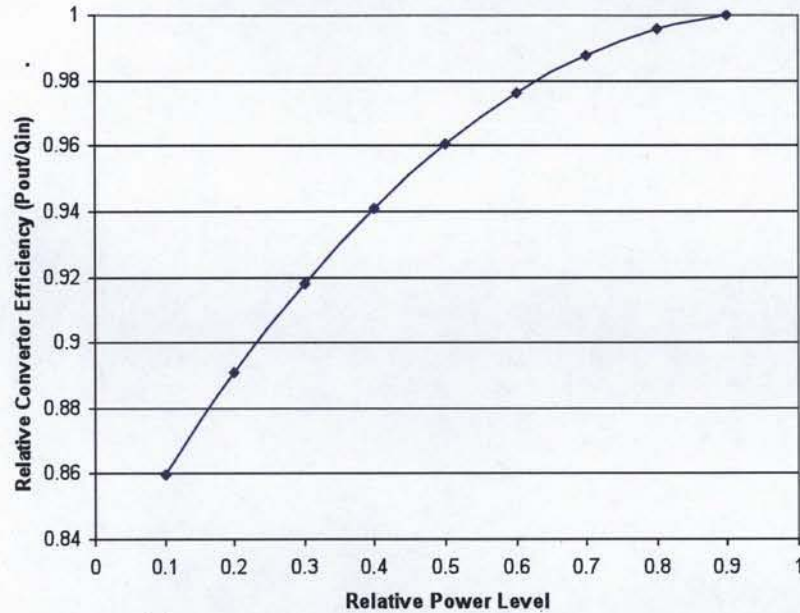
- Use of existing "ASC class" convertor at low power levels (20 to 50 W) has significant advantages from viewpoint of development cost and technical risk
- However:
  - Performance of the current convertor tends to fall as the power level decreases due to fixed thermal losses
  - "New" convertor design will have somewhat higher performance but will still be constrained by materials and fabrication methods

160 watt Stirling Systems

- If rather than simply replacing the two GPHS modules in the ASRG we require 160 Watts of BOL Power how do systems change?

- Am-241 Systems now require 10 GPHS Modules and the mass for the Am-241 system is about double that of the Pu-238 ASRG

Description	ASRG Pu-238	Optimized ASRG Am-241
Mission Duration (years)	10	10
Stirling Hot End Temp (deg C)	850	850
Stirling Cold End Temp (deg C)	90	87
BOM Heat (watts)	500	569
AC Output (watts)	176	171
PC&C Power (watts)	12	11
BOM DC Power-Nominal (watts)	164	160
EOM DC Power-Nominal (watts)	148	157
BOM Daytime Power (est.) (watts)	143	146
BOM Nightime Power (est.) (watts)	172	174
# GPHS Modules	2	10
Mass (kgs)	20.2	41
Specifi c Power (w/kg)	8.1	3.9
BOM Effi ciency (%)	33%	28%

PUMPED LOOP INTEGRATION

High Power Alternative Isotope Configurations

GPHS Modules / Flat LM HX Assembly

LM Return

LM Pump

Convertor

Hot HX Assembly

LM Outlet
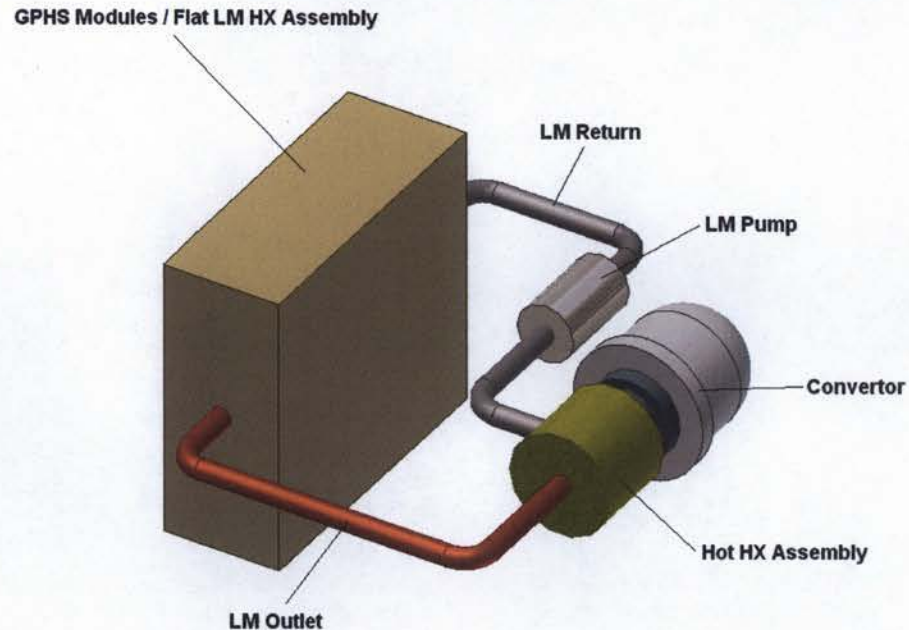
- **Alternative isotope thermal out is low relative to Pu fueled GPHS – physically larger package for same convertor power output**
- **Previously evaluated concepts based on natural circulation systems – for example thermosyphon**
- **Current evaluation involved pumped loop systems**
- **Presumed existing LM pump technology is applicable**

Pumped LM HX / Alternative Isotope HX Option
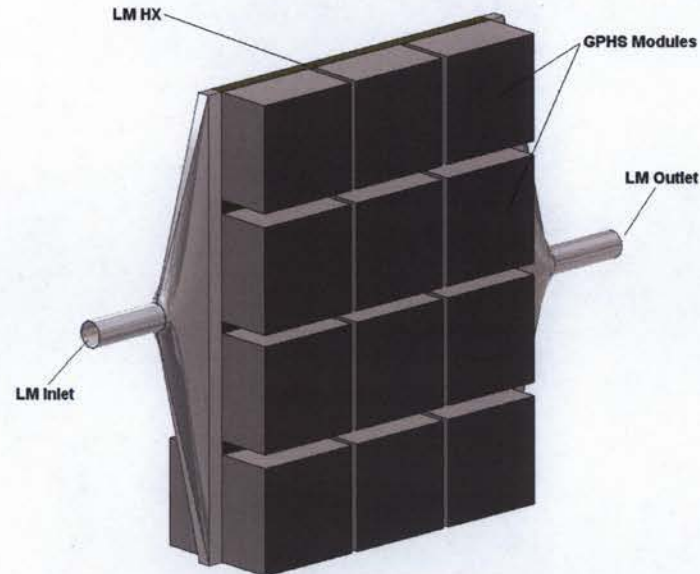
- **Low thermal output allows the use of relatively simple interface between GPHS and HX**
- **Flat plate HX with core "sheets" forming the fluid flow passages – well established technology**
- **Diffusion bonded all SS-316 structure insures LM compatibility / long life**
- **No contact of GPHS materials with LM loop**
- **Early clamping "structure" failure insures dispersal of GPHS modules from primary HX package**
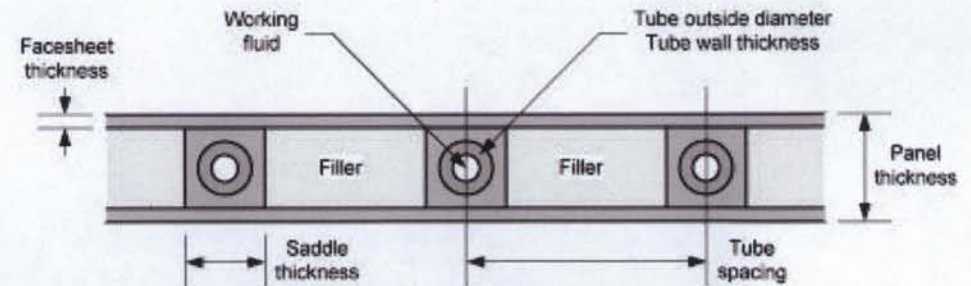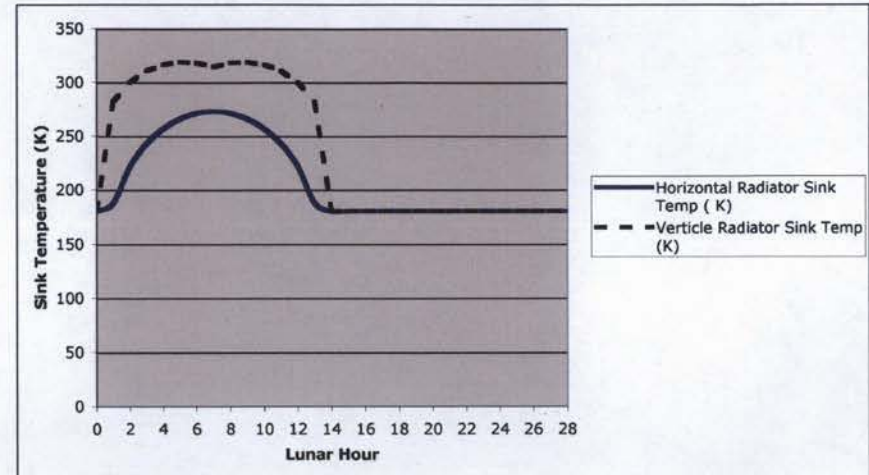
Stirling Convertors – Pumped LM Loop
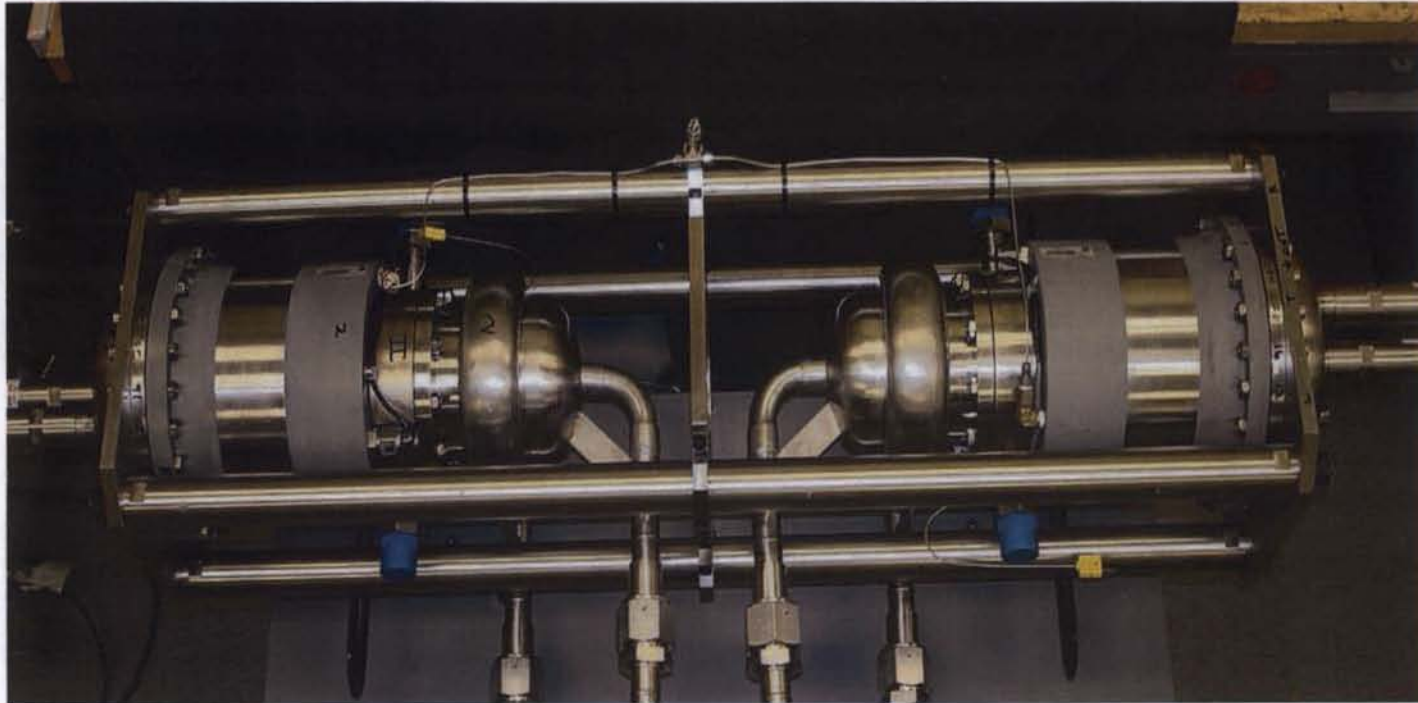
- **Recent testing of a pair of 1 KW class convertors (Sunpower Inc.) on a pumped LM heat transport system (joint NASA/GRC / MSFC effort) has clearly demonstrated the potential for this configuration**
- **Results indicate the same or superior performance on the LM loop compared to conventional heat source**

Heat Rejection Subsystem

- The heat rejection subsystem consists of radiator panels (including the heat pipes), water ducts, pumps, accumulators and a backup pump.
- Each convertor has its own heat rejection subsystem
- Water is pumped over the cold end of each Stirling convertor and flows out to a water heat pipe radiator, the water heat pipes are attached to the water ducts and send the heat to the panel facesheets
- Radiator Panel/Pump similar in configuration to space station ammonia system with heat pipes placed between two facesheets
  - For the horizontal radiator configuration the bottom facesheet is not used ,rather Multi-layer insulation is used on the bottom surface to prevent heat transfer from the lunar surface
- Usually, systems are designed to take advantage of two sided radiators (requiring a vertical orientation on the lunar surface) but, because we are operating close to the sink temperature to reduce GPHS count a horizontal radiator, not seeing the lunar soil but providing a lower sink temperature may be an advantage.
- Max/Min temps based on configuration
  - Horizontal Radiator 180 and 270 K
  - Veritcal Radiator 180 and 314 K
- Lunar Soil provides a significant amount of the incident energy onto vertical radiator panels during the lunar day.


Chart: Sink Temperature (K) vs Lunar Hour — Horizontal Radiator Sink Temp (K), Verticle Radiator Sink Temp (K)

Diagram labels: Facesheet thickness, Working fluid, Tube outside diameter, Tube wall thickness, Filler, Filler, Panel thickness, Saddle thickness, Tube spacing

16

Results

# ASRG with Alternative Isotopes

- Replace the two Pu-238 GPHS modules with both Am-241 and Sr-90 Modules

- Results

  – Am-241 and Sr-90 Systems have about 20% of the power of Pu-238 Systems at BOL

  – Sr-90 System produces at EOL only about 10% of ASRG with Pu-238

  – Am-241 power output is nearly constant with mission life

| Description	ASRG Pu-238	ASRG Am-241	ASRG Sr-90
Mission Duration (years)	10	10	10
Stirling Hot End Temp (deg C)	850	850	850
Stirling Cold End Temp (deg C)	90	47	44
BOM Heat (watts)	500	112	85.6
AC Output (watts)	176	38	29
PC&C Power (watts)	12	9	9
BOM DC Power-Nominal (watts)	164	29	20
EOM DC Power-Nominal (watts)	148	28	14
BOM Daytime Power (est.) (watts)	143	25	17
BOM Nightime Power (est.) (watts)	172	34	25
# GPHS Modules	2	2	2
Mass (kgs)	20.2	20.2	19.4
Specific Power (w/kg)	8.1	1.4	1.0
BOM Efficiency (%)	~32%	~26%	~23%
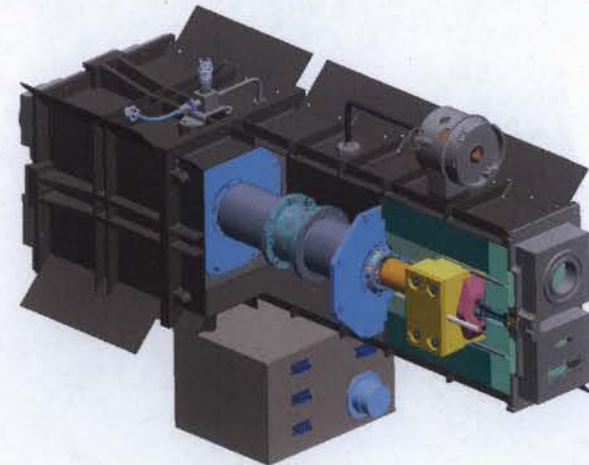
Power Profiles Pu-238 ASRG

- Power Output Varies from about 150 watts to 170 watts over the day night cycle at BOL

- Nominal Power Drops from 160 watts to 148 watts over the 10 year life
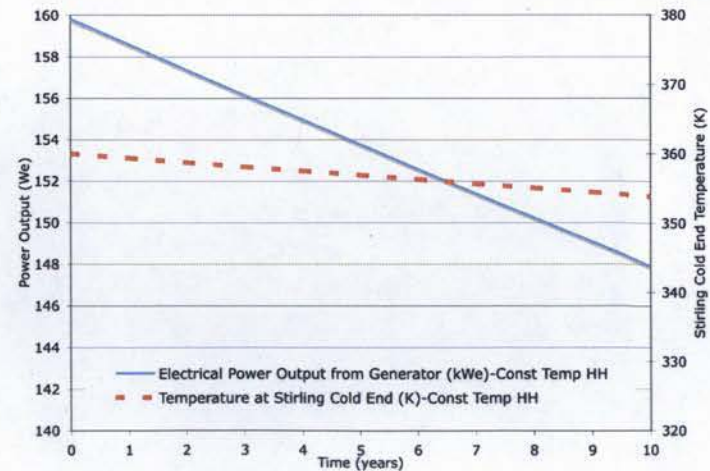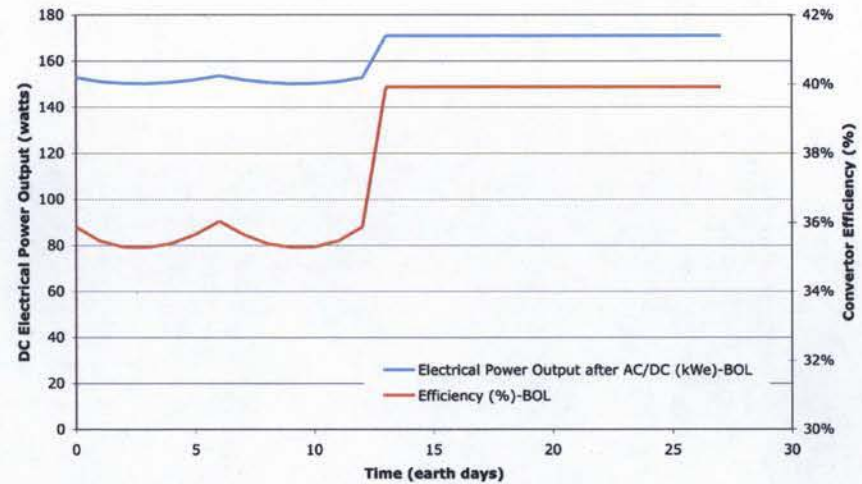
AM-241 and Sr-90 ASRG

- Because of the very long half-life of Am-241 the nominal power output is nearly constant (falling by less than 1 watt over 10 years)

- For the SR-90 system, power falls from 19 watts to 10 watts over the same 10 year mission
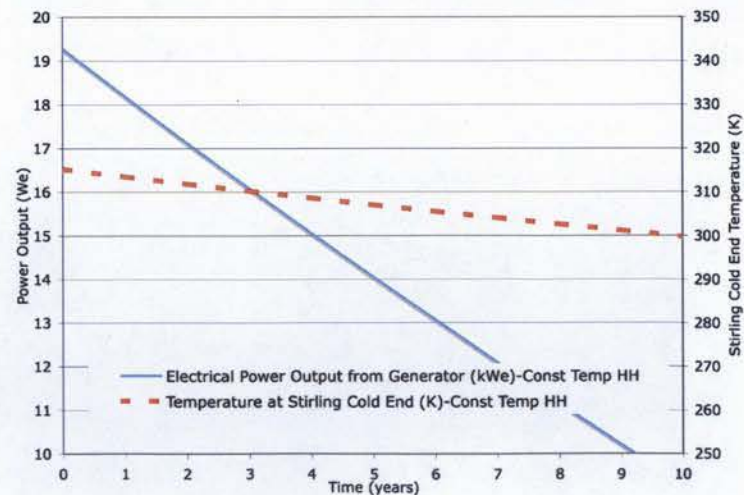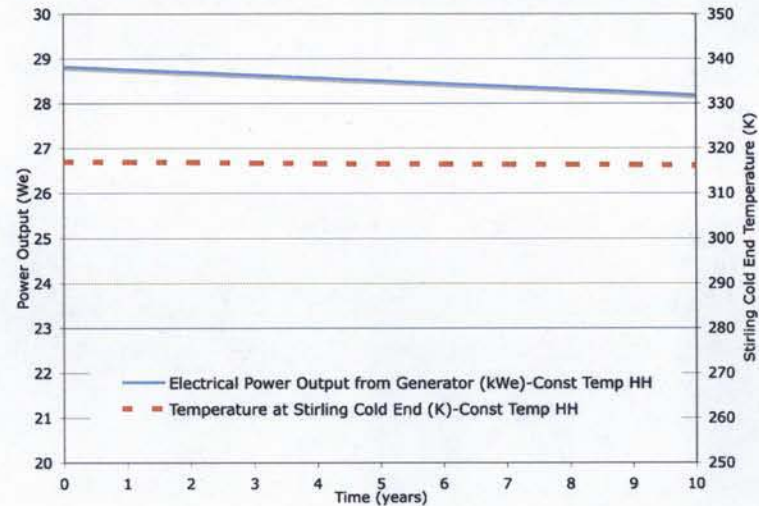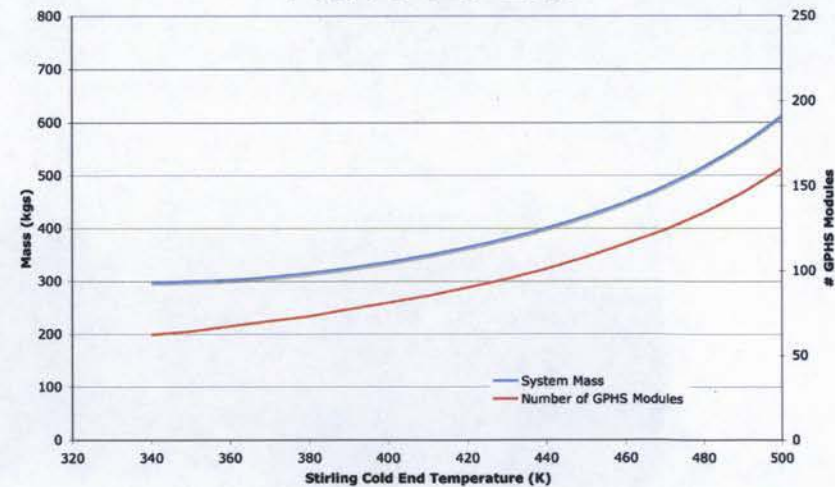
PUMPED LOOP SYSTEMS

Pumped Loop Systems

- When the GPHS count exceeds ~ 6 per Stirling Convertor, conductive coupling between the heat source and Stirling convertor becomes mass prohibitive

- When the heat rejected from the Stirling is above 500 watts, conductive coupling for geometries, temperature limits and environment becomes prohibitive

- For these cases a pumped loop is used for both heat addition and removal from the Stirling

- Two Stirling hot end temperatures (923 K and 1123 K) were used to represent both the Inconel 718 super alloy which is used in the 1 kWe class convertor developed by Sun Power and now on test at MSFC and a future MarM-247 convertor which would allow operation up to 1123 K

Mass and GPHS Count Comparison

- Hot End temperature is fixed and Cold End Temp is varied to see how system mass and GPHS count vary with changes in convertor efficiency

- The Pu-238 system has a wide temperature band where system mass varies little, choosing either a smaller radiator (higher low end temperature) or lower GPHS count can be made with little impact to system mass

- The Am-241 system, because of the much higher GPHS mass fraction pushes the minimum mass point down in temperature
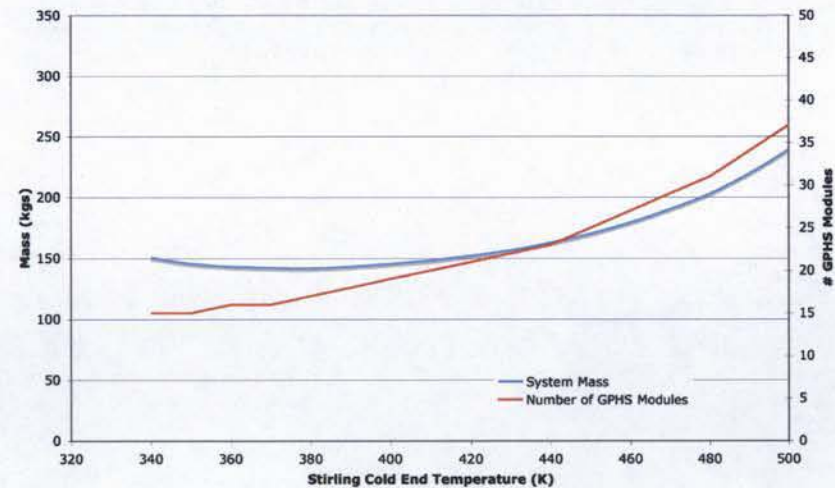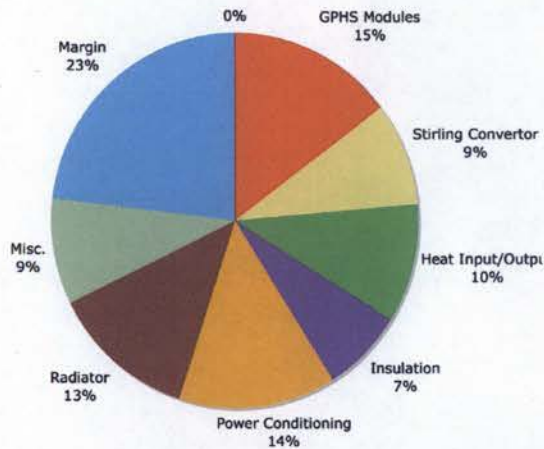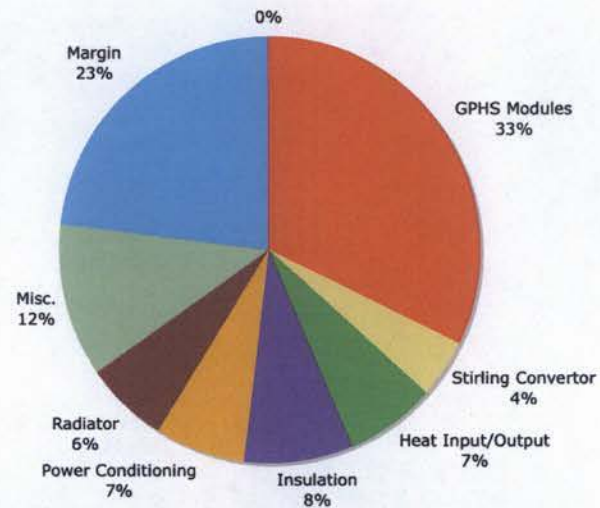

1 kWe Pu-238

1 kWe Am-241

Comparison of Pu-238 and Am-241 Pumped Loop Mass Fractions

- GPHS mass has increased from 15% in the PU-238 System to 33% in the Am-241 system

1 kWe Pu-238 Mass Fractions

1 kWe Am-241 Mass Fractions

Pumped Loop Systems (1123 K HH)

- Pu-238 RPS are about ½ the mass of their Am-241 counterparts at 1 kWe and that difference grows to almost 200% at 5 kWe

- Mass differences of about 10% at 1 kWe and 20% at 5 kWe result from the changes in Heater Head Temperature
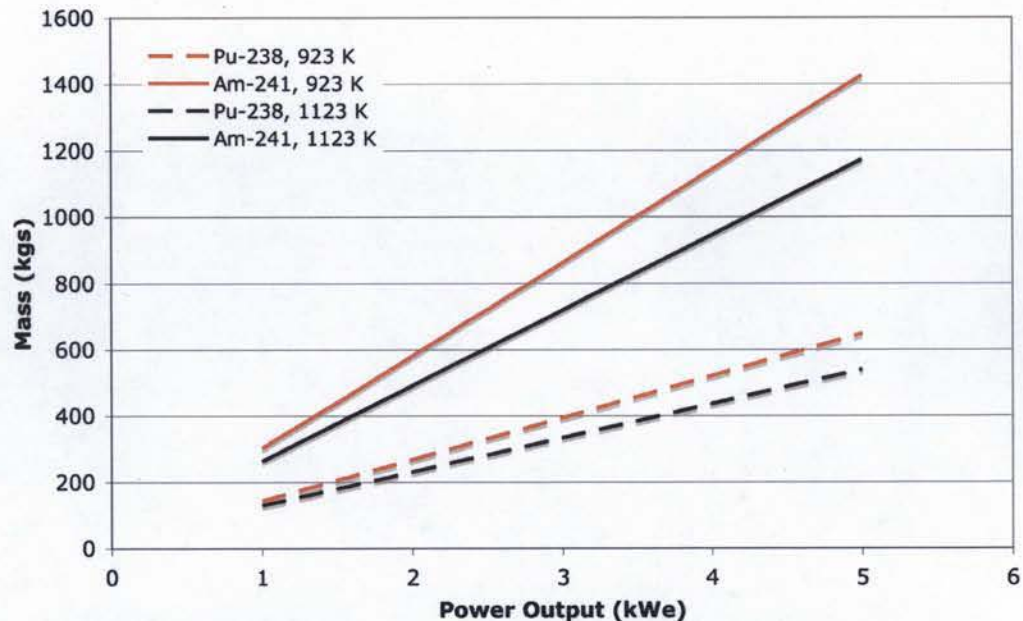
Conclusion

- This preliminary analysis suggests that further consideration should be given to using Am-241 as a heat source

- Direct replacement of the Pu-238 based ASRG with Am-241 based GPHS modules lower the BOL power output from 160 watts to 29 watts while the mass of the ASRG does not change

- To achieve 160 watts of output, 5 Am-241 GPHS modules per Stirling are required

- Am-241 systems have between double and triple the mass of Pu-238 based systems from 1 to 5 kWe