OVERVIEW

• The Need
• Mission Statement
• Project Organization
• Goals
• Project Description
• Description and Analysis of the MSR Systems
  – Core
  – Power Conversion Unit (PCU)
  – Radiator
  – Shielding
• Total Mass Analysis
• Conclusion
Motivation for MSR

Comparison of Solar and Nuclear Power on the Moon

Martian Surface Power Options

- Solar power becomes much less feasible
  - Mars further from Sun (45% less power)
  - Day/night cycle
  - Dust storms
  - Too-short Lifetime for Martian missions

- Nuclear Power dominates curve for Martian missions.

Mass (kg)

Power (kWe)

Solar Reactor

0.0E+00
5.0E+03
1.0E+04
1.5E+04
2.0E+04
2.5E+04

0 50 100 150 200 250

Power (kWe)
MSR Mission Statement

• Nuclear Power for the Martian Surface
  – Test on Lunar Surface

• Design Criteria
  – 100kWe
  – 5 EFPY
  – Works on the Moon and Mars
Organizational Chart

Project Management

- Core Task Manager
  - Core Group
- PCU Task Manager
  - PCU Group
- Radiator Task Manager
  - Radiator Group
- Shielding Task Manager
  - Shielding Group
Decision Goals

- **Litmus Test**
  - Works on Moon and Mars
  - 100 kWe
  - 5 EFPY
  - Obeys Environmental Regulations

- **Extent-To-Which Test**
  - Small Mass and Size
  - Controllable
  - Launchable/Accident Safe
  - High Reliability and Limited Maintenance

- **Other**
  - Scalability
  - Uses Proven Technology
MSR System Overview

- Core
  - Fast, UN, Zr$_3$Si$_2$ reflector w/ drums, Hf vessel
- Power Conversion Unit
  - Cs Thermionics, Heat Pipes, D-to-A
- Radiator
  - Heat Pipe/Fin, 950K
- Shielding
  - 2mrem/hr, Neutron/Gamma
- Total Mass ~8MT
CORE
Core – Challenges

• Fit on one rocket
• Autonomous control for 5 EFPY
• High reliability
• Safe in worst-case accident scenario
• Provide 1.2 MW\text{th}
## Core - Design Choices Overview

<table>
<thead>
<tr>
<th>Design Choice</th>
<th>Reason</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast Spectrum, High Temp</td>
<td>High Power Density</td>
</tr>
<tr>
<td>Uranium Nitride</td>
<td>Material Characteristics</td>
</tr>
<tr>
<td>33.1% Enrichment</td>
<td>Breeding</td>
</tr>
<tr>
<td>Heatpipe with Li coolant</td>
<td>Power Conversion</td>
</tr>
<tr>
<td>Hafnium Core Vessel</td>
<td>Accident Scenario</td>
</tr>
<tr>
<td>Tantalum Neutron Absorber</td>
<td>Lower BOL $k_{eff}$ for accidents</td>
</tr>
<tr>
<td>Rotating Drums</td>
<td>Autonomous Control</td>
</tr>
<tr>
<td>$\text{Zr}_3\text{Si}_2$ Reflector</td>
<td>Less Thermalization</td>
</tr>
<tr>
<td>Fuel Pins in Tricusp</td>
<td>Heat Transfer</td>
</tr>
</tbody>
</table>
Core - Pin Geometry

- Fuel pins are the same size as the heat pipes and arranged in tricusp design.
- Highest centerline fuel pin temperature at steady state is 1890K.
Core – Design Advantages

- UN fuel, Ta absorber, Re Clad/Structure performance at high temperatures, heat transfer, effect on neutron economy, and limited corrosion
- Heat pipes no pumps required, excellent heat transfer, small system mass
- Li working fluid operates at high temperatures necessary for power conversion unit
Core – Dimensions and Control

Small core, total mass ~4.3 MT

Isometric View

Top-Down View

Fuel Pin
Control Drum
Neutron Absorber
### Core – Isotopic Composition

<table>
<thead>
<tr>
<th>Material</th>
<th>Purpose</th>
<th>Volume Fraction</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^7\text{Li}$</td>
<td>Coolant</td>
<td>0.073</td>
</tr>
<tr>
<td>$^{15}\text{N}$</td>
<td>Fuel Compound</td>
<td>0.353</td>
</tr>
<tr>
<td>$\text{Nat}^{91}\text{Nb}$</td>
<td>Heatpipe</td>
<td>0.076</td>
</tr>
<tr>
<td>$^{181}\text{Ta}$</td>
<td>Neutron Absorber</td>
<td>0.038</td>
</tr>
<tr>
<td>$\text{Nat}^{186}\text{Re}$</td>
<td>Cladding/Structure</td>
<td>0.110</td>
</tr>
<tr>
<td>$^{235}\text{U}$</td>
<td>Fissile Fuel</td>
<td>0.117</td>
</tr>
<tr>
<td>$^{238}\text{U}$</td>
<td>Fertile Fuel</td>
<td>0.233</td>
</tr>
</tbody>
</table>
Core - Power Peaking

\[ RPPR_{\text{Drums In}} = 1.31 \quad \text{and} \quad RPPF_{\text{Drums Out}} = 1.24 \]
Operation over Lifetime

BOL $k_{\text{eff}}$: 0.975 – 1.027

$\Delta k_{\text{eff}} = 0.052$

EOL $k_{\text{eff}}$: 0.989 – 1.044

$\Delta k_{\text{eff}} = 0.055$
Launch Accident Analysis

- Worst Case Scenario
  - Oceanic splashdown assuming
    - Non-deformed core
    - All heat pipes breached and flooded
- Problem: Large gap between BOL $k_{eff}$ and accident scenario
Accident Scenario: $^{\text{Nat}}\text{Hf}$ Vessel

- Introduce absorbing vessel
  - High thermal cross-section
  - Low fast cross-section

![Graph showing vessel flux versus energy](image-url)
Launch Accident Results

<table>
<thead>
<tr>
<th>Reflector Position</th>
<th>Stowed</th>
<th>Detached</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>$K_{\text{eff}} = 0.970$</td>
<td>$K_{\text{eff}} = 0.953$</td>
</tr>
<tr>
<td>Wet Sand</td>
<td>$K_{\text{eff}} = 0.974$</td>
<td>$K_{\text{eff}} = 0.965$</td>
</tr>
</tbody>
</table>

- Inadvertent criticality will not occur in conceivable splashdown scenarios
Accident Scenario Design Constraint

- NASA requires reactor to be subcritical in **all** launch accident scenarios
- Improvements
  - Higher enrichment
  - Flatten $k_{\text{eff}}$ vs. lifetime plots
  - Less mass
- Design freedom increases if this constraint is eased
Core Summary

• Core has UN fuel, Re clad/tricusp, Ta absorber, Hf vessel, Zr$_3$Si$_2$ reflector and TaB$_2$ control material

• Relatively flat fuel pin temperature profile

• 5+ EFPY at 1.2 MW$_{th}$, ~100 kW$_e$,

• Autonomous control by rotating drums over entire lifetime

• Subcritical for worst-case accident scenario
PCU
PCU – Mission Statement

Goals:

- Remove thermal energy from the core
- Produce at least 100kWe
- Deliver remaining thermal energy to the radiator
- Convert electricity to a transmittable form

Components:

- Heat Removal from Core
- Power Conversion/Transmission System
- Heat Exchanger/Interface with Radiator
PCU – Design Choices

- Heat Transfer from Core
  - Heat Pipes
- Power Conversion System
  - Cesium Thermionics
- Power Transmission
  - DC-to-AC conversion
  - 22 AWG Cu wire transmission bus
- Heat Exchanger to Radiator
  - Annular Heat Pipes
PCU – Heat Extraction from Core

- How Heat Pipes Work
  - Isothermal heat transfer
  - Capillary action
  - Self-contained system
- Heat Pipes from Core:
  - 127 heat pipes
  - 1 meter long
  - 1 cm diameter
  - Niobium wall & wick
  - Pressurized Li working fluid, 1800K
PCU – Heat Pipes (2)

- Possible Limits to Flow
  - Entrainment
  - Sonic Limit
  - Boiling
  - Freezing
  - Capillary

- Capillary force limits flow:

\[
Q_{\text{max}} = \frac{\rho_l \sigma_l L K A_w \left( 2 \frac{1}{r_e} - \frac{\rho_l g l \sin(\phi)}{\sigma_l} \right)}{\mu_l l}
\]
PCU - Thermionics

• Thermionic Power Conversion Unit
  – Mass: 240 kg
  – Efficiency: 10%+
    • 1.2MWt -> 125kWe
  – Power density: 10W/cm²
  – Surface area per heat pipe: 100 cm²
PCU - Thermionics Issues & Solutions

- Creep at high temp
  - Set spacing at 0.13 mm
  - Used ceramic spacers
- Cs -> Ba conversion due to fast neutron flux
  \[ Cs^{133}(n, \gamma) \rightarrow Cs^{134} \rightarrow Ba^{134} + \beta \]
  - 0.01% conversion expected over lifetime
- Collector back current
  - \( T_E = 1800K, T_C = 950K \)
PCU – Thermionics Design
PCU – Power Transmission

- D-to-A converter:
  - 25 x 5kVA units
  - 360kg total
  - Small
- Transmission Lines:
  - AC transmission
  - 25 x 22 AWG Cu wire bus
  - 500kg/km total
  - Transformers increase voltage to 10,000V
- ~1.4MT total for conversion/transmission system
PCU – Heat Exchanger to Radiator

- Heat Pipe Heat Exchanger
PCU – Failure Analysis

- Very robust system
  - Large design margins in all components
  - Failure of multiple parts still allows for ~90% power generation & full heat extraction from core
- No possibility of single-point failure
  - Each component has at least 25 separate, redundant pieces
- Maximum power loss due to one failure: 3%
- Maximum cooling loss due to one failure: 1%
Radiator
Objective

• Dissipate excess heat from a power plant located on the surface of the Moon or Mars.

\[ \dot{Q} = \sigma \varepsilon A \left( T_s^4 - T_\infty^4 \right) \]
Environment

• Moon
  – 1/6 Earth gravity
  – No atmosphere
  – 1360 W/m² solar flux

• Mars
  – 1/3 Earth gravity
  – 1% atmospheric pressure
  – 590 W/m² solar flux
Radiator – Design Choices

• Evolved from previous designs for space fission systems:
  – SNAP-2/10A
  – SAFE-400
  – SP-100

• Radiates thermal energy into space via finned heat pipes
Concept Choices

- Heat pipes
- Continuous panel
- Carbon-Carbon composites
- One-sided operation
Component Design

- Heat pipes
  - Carbon-Carbon shell
  - Nb-1Zr wick
  - Potassium fluid

- Panel
  - Carbon-Carbon composite
  - SiC coating
Component Design (2)

- Supports
  - Titanium beams
    - 8 radial beams
    - 1 spreader bar per radial beam
  - 3 rectangular strips form circles inside the cone
Structural Design

- **Dimensions**
  - Conical shell around the core
  - Height 3.34 m
  - Diameter 4.8 m
  - Area 41.5 m²

- **Mass**
  - Panel 360 kg
  - Heat pipes 155 kg
  - Supports 50 kg
  - Total 565 kg
Analysis: Models

- Models
  - Isothermal
  - Linear Condenser

- Variables
  - Power
  - Sky temperature
  - Emissivity
  - Panel width

![Graph showing Radiating Area needed to Reject 900 kW]

- Radiator Temperature (K): 940 K
- Radiator Area (m²): 25 m²
Analysis (2): Temperature

• Condenser model
  – Calculate sensible and latent heat loss
  – Length dependent on flow rate
Analysis (3): Dust

• Dust Buildup
  – SiO$_2$ dust has small effect on Carbon-Carbon emissivity
  – 5% emissivity loss predicted for 5 yrs
  – Emissivity loss increases required area by 2 m$^2$
Shielding - Design Concept

• Natural dose rate on Moon & Mars is ~14 times higher than on Earth

• Goal:
  – Reduce dose rate due to reactor to between 0.6 - 5.6 mrem/hr
    • 2mrem/hr
  – ALARA

• Neutrons and gamma rays emitted, requiring two different modes of attenuation
Shielding - Constraints

- Weight limited by landing module (~2 MT)
- Temperature limited by material properties (1800K)
Shielding - Design Choices

Neutron shielding
boron carbide ($B_4C$) shell (yellow)
40 cm

Gamma shielding
Tungsten (W) shell (gray)
12 cm

- Total mass is 1.97 MT
- Separate reactor from habitat
  - Dose rate decreases as $1/r^2$ for $r >> 50$ cm
  - For $r \sim 50$ cm, dose rate decreases as $1/r$
Shielding - Dose w/o shielding

- Near core, dose rates can be very high
- Most important components are gamma and neutron radiation

![Dose vs Distance Graph](image)

Dose (mrem/hr)

Distance (m)
Shielding - Neutrons

- Boron Carbide (B₄C) was chosen as the neutron shielding material after ruling out several options.

<table>
<thead>
<tr>
<th>Material</th>
<th>Reason for Rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂O</td>
<td>Too heavy</td>
</tr>
<tr>
<td>Li</td>
<td>Too reactive</td>
</tr>
<tr>
<td>LiH</td>
<td>Melting point of 953 K</td>
</tr>
<tr>
<td>B</td>
<td>Brittle; would not tolerate launch well</td>
</tr>
<tr>
<td>B₄CAl</td>
<td>Possible; heavy, needs comparison w/ other options</td>
</tr>
</tbody>
</table>
Shielding - Neutrons (3)

- Boron burnup is a resolvable issue
Shielding - Gammas

- Tungsten (W) was chosen as the gamma shielding material after ruling out several options

<table>
<thead>
<tr>
<th>Material</th>
<th>Reason for Rejection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z &lt; 72</td>
<td>Too small density and/or mass attenuation coefficient</td>
</tr>
<tr>
<td>Z &gt; 83</td>
<td>Unstable nuclei</td>
</tr>
<tr>
<td>Pb, Bi</td>
<td>Not as good as tungsten, and have low melting points</td>
</tr>
<tr>
<td>Re, Ir</td>
<td>Difficult to obtain in large quantities</td>
</tr>
<tr>
<td>Os</td>
<td>Reactive</td>
</tr>
<tr>
<td>Hf, Ta</td>
<td>Smaller mass attenuation coefficients than alternatives</td>
</tr>
</tbody>
</table>
Shielding - Design

- Two pieces, each covering 40° of reactor radial surface
- Two layers: 40 cm B$_4$C (yellow) on inside, 12 cm W (gray) outside
- Scalable
  - at 200 kW(e) mass is 2.19 metric tons
  - at 50 kW(e), mass is 1.78 metric tons
Shielding - Design (2)

- For mission parameters, pieces of shield will move
  - Moves once to align shield with habitat
  - May move again to protect crew who need to enter otherwise unshielded zones
Shielding - Design (3)

- Using a shadow shield requires implementation of exclusion zones:

- Unshielded Side:
  - 32 rem/hr - 14 m
  - 2.0 mrem/hr - 1008 m
  - 0.6 mrem/hr - 1841 m

- Shielded Side:
  - 32 rem/hr - inside shield
  - 400 mrem/hr – at shield boundary
  - 2.0 mrem/hr - 11 m
  - 0.6 mrem/hr - 20 m
Shielding – Future Extensions

- Three layer shield
  - W (thick layer) inside, B₄C middle, W (thin layer) outside
  - Thin W layer will stop secondary radiation in B₄C shield
  - Putting thick W layer inside reduces overall mass
Shielding – Future Extensions (2)

- The Moon and Mars have very similar attenuation coefficients for surface material.
- Would require moving 32 metric tons of rock before reactor is started.
Summary
MSR Assembly Sketches
MSR Assembly Sketches (2)
# MSR Mass

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>4310</td>
</tr>
<tr>
<td>PCU</td>
<td>1385</td>
</tr>
<tr>
<td>Radiator</td>
<td>565</td>
</tr>
<tr>
<td>Shielding</td>
<td>1975</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>8235</strong></td>
</tr>
</tbody>
</table>

**Bottom Line:** ~82g/We
Mass Reduction and Power Gain

• Move reactor 2km away from people
  – Gain 500kg from extra transmission lines
  – Lose almost 2MT of shielding

  Bottom Line: ~67 g/We

• Use ISRU plant as a thermal sink
  – Gain potentially 900kWth
  – Gain mass of heat pipes to transport heat to ISRU (depends on the distance of reactor from plant)
  – Lose 565kg of Radiator Mass
MSR Mission Plan

• Build and Launch
  – Prove Technology on Earth
• Earth Orbit Testing
  – Ensure the system will function for \( \geq 5 \text{ EFPY} \)
• Lunar / Martian Landing and Testing
  – Post Landing Diagnostics
• Startup
• Shutdown
MSR Group

Expanding Frontiers with Nuclear Technology

“The fascination generated by further exploration will inspire…and create a new generation of innovators and pioneers.”

~President George W. Bush
Additional Slides
Future Work – Core

- Investigate further the feasibility of plate fuel element design
- Optimize tricusp core configuration
- Examine long-term effects of high radiation environment on chosen materials
MSR Fuel Pin Sketch
$^{180}$Hf Cross Section
NatHf Cross Section
Radiological Hazard Mitigation

<table>
<thead>
<tr>
<th>Hazard During</th>
<th>Mitigation Strategy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Launch and Launch</td>
<td>Operational Procedures, Appropriate facilities and equipment</td>
</tr>
<tr>
<td>Orbital Diagnostic Testing</td>
<td>Use of Nuclear Safe Orbit</td>
</tr>
<tr>
<td>Reentry Dispersal of Inventory</td>
<td>Inventory Reactivity Contribution Was Determined to be Negligible</td>
</tr>
<tr>
<td>Splashdown Inadvertent Criticality</td>
<td>Hafnium Core Vessel</td>
</tr>
</tbody>
</table>

Radiological Hazards need not limit utilization of nuclear power in space!
PCU – Future Work

• Improving Thermionic Efficiency
• Material studies in high radiation environment
• Scalability to 200kWe and up
• Using ISRU as thermal heat sink
## PCU – Decision Methodology

<table>
<thead>
<tr>
<th></th>
<th>Brayton</th>
<th>Sterling</th>
<th>Thermionics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Small Mass and Size (Cost) - 1.35</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Actual PCU</td>
<td>2</td>
<td>1</td>
<td>3</td>
</tr>
<tr>
<td>Outlet Temperature</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Peripheral Systems (i.e. Heat Exchangers, A to D converter)</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td><strong>Launchable/Accident Safe - 1.13</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Robust to forces of launch</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Fits in rocket</td>
<td>3</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td><strong>Controllable - 1.14</strong></td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td><strong>High Reliability and Limited Maintenance - 1.00</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Moving Parts</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Radiation Resistant</td>
<td>2</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Single Point Failure</td>
<td>1</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>Proven System</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Inlet Temperature</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>23.77</strong></td>
<td><strong>26.55</strong></td>
<td><strong>28.51</strong></td>
</tr>
</tbody>
</table>
Solid-State vs. Dynamic PCU

• Stirling Assumptions:
  – At 100kWe, operating at 10% efficiency
  – 4MT net gain in PCU
    • Heat exchanger
    • 4x 800kg engines
  – 1MT gain in radiator
  – Scales with gain in efficiency, also gains radiator mass.
## Solid State v. Dynamic (2)

<table>
<thead>
<tr>
<th></th>
<th>Thermionics</th>
<th>Sterling</th>
</tr>
</thead>
<tbody>
<tr>
<td>100 kWe</td>
<td>8.2</td>
<td>13.2</td>
</tr>
<tr>
<td>200 kWe</td>
<td>14.4</td>
<td>14.2</td>
</tr>
<tr>
<td>300 kWe</td>
<td>21</td>
<td>16.2</td>
</tr>
<tr>
<td>400 kWe</td>
<td>28.8</td>
<td>20.2</td>
</tr>
<tr>
<td>1 MWe</td>
<td>70.8</td>
<td>54.2</td>
</tr>
</tbody>
</table>
Radiator Future Work

- Analysis of transients
- Model heat pipe operation
- Conditions at landing site
- Manufacturing
Analysis (3): Location

• Environment
  – Moon closer to sun, but has no atmosphere

• Comparative Area
  – Moon 39.5 m²
  – Mars 39 m²

![Radiator Area for Three Power Levels](image)
Shielding - Future Work

- Shielding using extraterrestrial surface material:
  - On moon, select craters that are navigable and of appropriate size
  - Incorporate precision landing capability
  - On Mars, specify a burial technique as craters are less prevalent
- Specify geometry dependent upon mission parameters
  - Shielding modularity, adaptability, etc.
Radiation Interactions with Matter

- Charged Particles ($\alpha$, $\beta$)
  - Easily attenuated
  - Will not get past core reflector
- Neutrons
  - Most biologically hazardous
  - Interacts with target nuclei
  - Low Z material needed
- Gamma Rays (Photons)
  - High Energy (2MeV)
  - Hardest to attenuate
  - Interacts with orbital electrons and nuclei
  - High Z materials needed
Shielding - Dose Modeling

- Dose distance dependence is modeled as:
  - \( \frac{r_0}{r} \) for \( r < 2r_0 \)
  - \( A \frac{r_0}{r} + B \left( \frac{r_0}{r} \right)^2 \) for \( 2r_0 < r < 10r_0 \)
  - \( \left( \frac{r}{r_0} \right)^2 \) for \( r > 10r_0 \)

where \( r_0 = \) core radius,
\( A = -\frac{1}{8} \) and \( B = \frac{9}{4} \)
### Shielding - Neutrons (2)

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum thickness for 1 MT shield (cm)</th>
<th>Dose Rate at shielding edge (mrem/hr)</th>
<th>Dose rate at 10 m (mrem/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshielded</td>
<td>N/A</td>
<td>2.40*10^7</td>
<td>10.29</td>
</tr>
<tr>
<td>Boral (B₄CAI)</td>
<td>20.3</td>
<td>1.24*10^5</td>
<td>0.1242</td>
</tr>
<tr>
<td>Borated Graphite (BC)</td>
<td>22.7</td>
<td>4.28*10^4</td>
<td>0.0427</td>
</tr>
<tr>
<td>Boron Carbide (B₄C)</td>
<td>21.1</td>
<td>3.57*10^4</td>
<td>0.0357</td>
</tr>
</tbody>
</table>
## Shielding - Gammas (2)

<table>
<thead>
<tr>
<th>Material</th>
<th>Maximum thickness for 3 MT shield (cm)</th>
<th>Dose rate at 90 cm (mrem/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Unshielded</td>
<td>N/A</td>
<td>2.51*10^6</td>
</tr>
<tr>
<td>Pb</td>
<td>17.1</td>
<td>594.66</td>
</tr>
<tr>
<td>Bi</td>
<td>19.4</td>
<td>599.88</td>
</tr>
<tr>
<td>W</td>
<td>10.6</td>
<td>480.00</td>
</tr>
</tbody>
</table>
MSR Cost

- Rhenium Procurement and Manufacture
- Nitrogen-15 Enrichment
- Hafnium Procurement
## Mass Comparison

<table>
<thead>
<tr>
<th></th>
<th>MSR (100kWe)</th>
<th>SNAP-10A (650We)</th>
<th>SP-100 (100kWe)</th>
<th>SAFE-400 (100kWe)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Mass (g/We)</td>
<td>82</td>
<td>670</td>
<td>54</td>
<td>25</td>
</tr>
</tbody>
</table>
Motivation for Mars

• “We need to see and examine and touch for ourselves”

• “…and create a new generation of innovators and pioneers.”