9th IAASS Conference: Toulouse, France – *"Know Safety, No Pain"*

RISK MANAGEMENT FOR DYNAMIC RADIOISOTOPE POWER SYSTEMS

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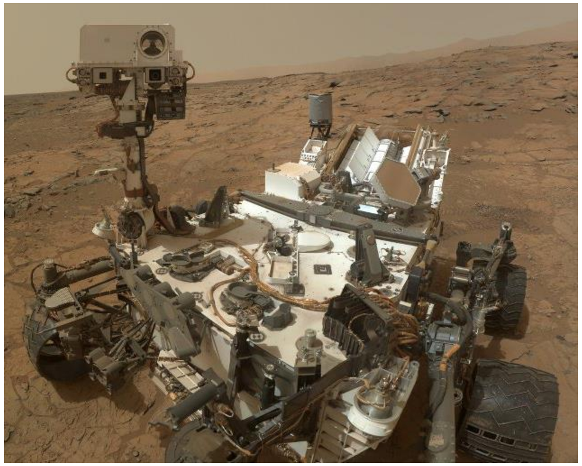
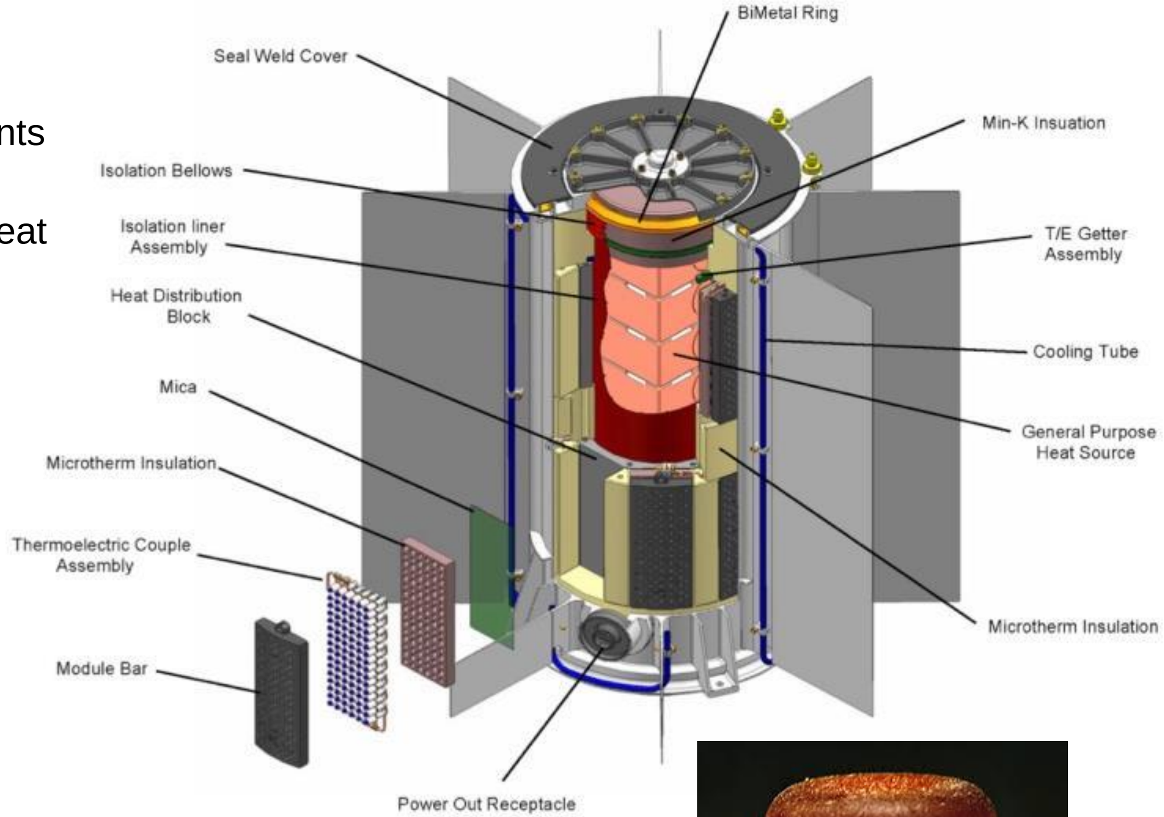
Agenda

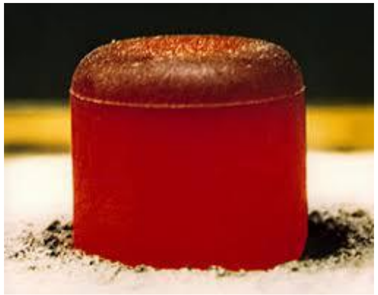
- What is an RPS?
  - DRPS concepts vs RTG
- System Concept Requirements
  - Design considerations
  - Operational Capabilities
- Risk Management Process
  - RIDM → CRM
- Risk Mitigation Procedure
  - NASA 5x5 Risk Matrix
- Plans & Conclusions

What is a Radioisotope Power System (RPS)?

- Provides electricity to missions in remote and challenging environments where solar power is unavailable
- Thermoelectric materials convert heat from a radioisotope into electricity
    - Heat is the natural byproduct of isotope decay
- Used by NASA missions of various types for over 50 years

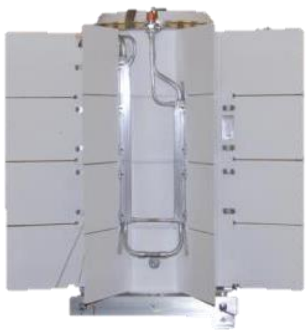






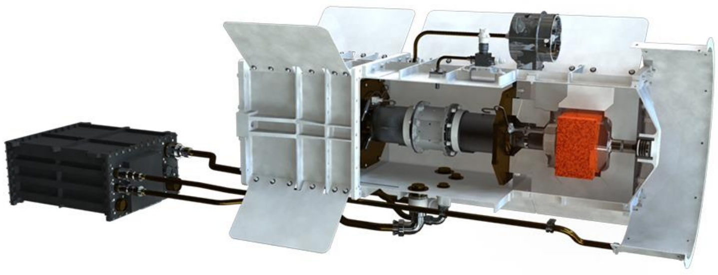
RTG vs DRPS

Radioisotope Thermoelectric Generator (RTG)



- Static thermoelectric (TE) design
  - No moving parts
- Stable, reliable
- Low conversion efficiency (<15%)
- Flight proven
  - Used by NASA for over 5 decades
- Wear mechanisms limited to TE degradation
  - Sublimation degrades conversion efficiency

Dynamic Radioisotope Power System Concept (DRPS)



- Heat engine produces electricity using a working fluid in this concept
  - Uses moving parts (pistons, dynamic seals, linear alternators)
- Advanced Stirling radioisotope generator (ASRG) concept
  - Flight project now terminated, was a NASA-DOE joint effort
- Could provide up to 4x efficiency of RTGs
  - Could provide equal power level with less fuel, or greater power per unit fuel
- **Never been flown**

Pre-decisional information for planning and discussion only

Potential Mission Risk Areas for DRPS Concepts

- Installation timing and accessibility
- Vibration effects
- G-loads
- Manufacturing for Flight
- Converter performance
- Efficiency Tradeoffs
- Design Requirements/Constraints
- Failure impacts to operations
- Power interruptions/failures
- Mass
- Communications
- Schedule/timeline
- Material composition
- Conversion
- Compatibility
- Heat transfer
- Integration
- Load tolerance
- Effects of waste heat
- Deviate from goals
- Mission objective tradeoff
- Environments

Other Risk Areas

- Unrealistic schedule estimates or allocation
- Unrealistic cost estimates or budget allocation
- Inadequate staffing or skills
- Uncertain or inadequate contractor capability
- Uncertain or inadequate vendor capability
- Insufficient production capacity
- Operational hazards
- Unprecedented efforts without estimates
- Poorly defined requirements
- No bidirectional traceability of requirements
- Infeasible design
- Inadequate configuration management
- Inadequate test planning
- Inadequate quality assurance
- Inconsistent or incomplete requirements
- Inadequate design
- Workmanship issues
- Inadequate accounting of environmental effects
- Software errors
- Inadequate analyses

System Concept Requirements

Design Considerations

- Multi-Mission Radioisotope Thermoelectric Generator (MMRTG) is a baseline for future RPS designs
    - Step 2 GPHS modules
    - 9904 shipping cask – size constraint
- Vibration/imbalance mitigation
    - Isolation, active dampening, pair convertors out of phase with one another
- Robust design
    - How to accommodate convertor failure
- Power output level of the generator
- Power level of individual convertors
- Quantity and configuration of GPHS modules
- Methods to utilize and reject heat
- Force balancing strategies
- System-level fault tolerance

Envisioned Operational Capabilities

- Lifetime of 10 yrs minimum, goal of 14 yrs
- Net electric power degradation <1.5%
    - Includes Pu-238 decay of 0.8%
- Power output of minimum 300 W, goal 500 W
- Conversion efficiency of at least 20%
- Fault-tolerant design
- Mission specific capabilities
- Able to withstand EDL conditions
    - Thermal transients and disturbance forces
    - Up to 20 g peak, and up to 5 g during spin-stabilization of the space vehicle
    - Parachute deployment, pyrotechnic actuation
- Space vehicle interface requirements
    - Communications architectures
- Minimize disturbances to host vehicle
    - Excessive thermal loads, vibrations

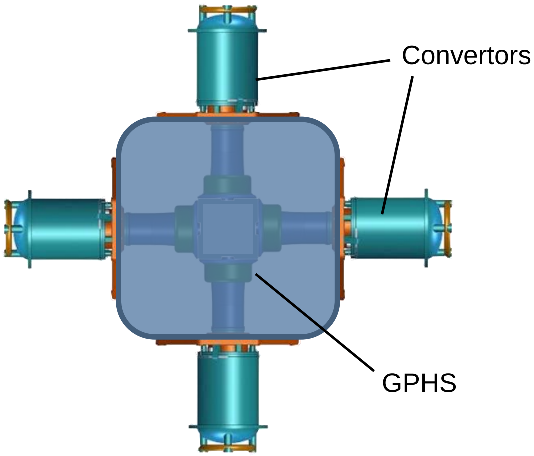
Reliability Considerations

- Wiring of a 4-convertor generator is critical to system reliability

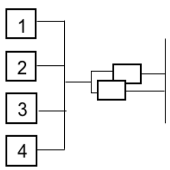
a) Parallel configuration with shared controller
  - Reliability significantly affected by controller reliability

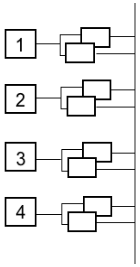
b) Parallel generators with individual controllers
  - Reduced effect of controller reliability

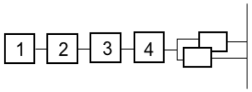
c) Series wiring
  - Convertor failure/degradation affects upstream converters



4-convertor DRPS Concept Drawing



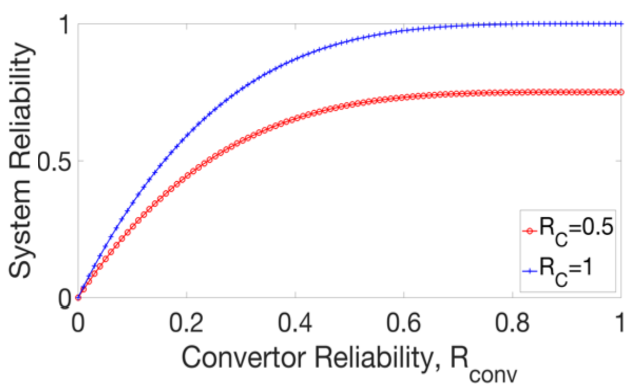


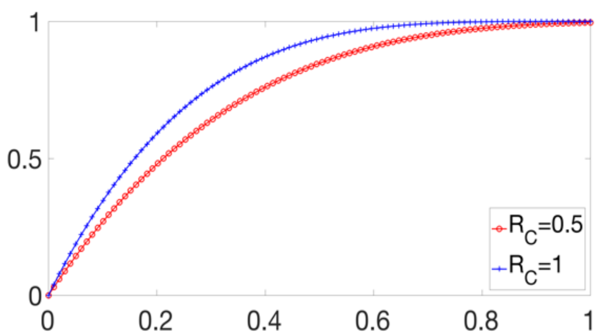


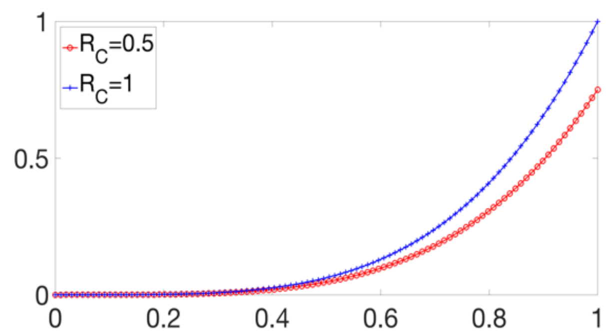
$$R_{(a)} = [1-(1-R_{conv})^4] \times [1-(1-R_C)^2]$$

$$R_{(b)} = 1-\{1-R_{conv} \times [1-(1-R_C)^2]\}^4$$

$$R_{(c)} = R_{conv}{}^4 \times [1-(1-R_C)^2]$$







Risk-Informed Decision Making (RIDM)

1. Identification of Alternatives

- Which options fit within the mission objectives?
- Performance measures are associated with each objective
- Example: convertor wiring options

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2. Risk Analysis of Alternatives

- Performance assessment paired with probabilistic modeling
- Assess alternative's effectiveness at achieving program objectives
- Example: using reliability model with cost, weight considerations

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3. Risk-Informed Alternative Selection

- Alternatives are assessed within consistent levels of risk tolerance
- May be iterative, require additional analysis
- Example: wiring option 2 provides best balance of reliability and cost

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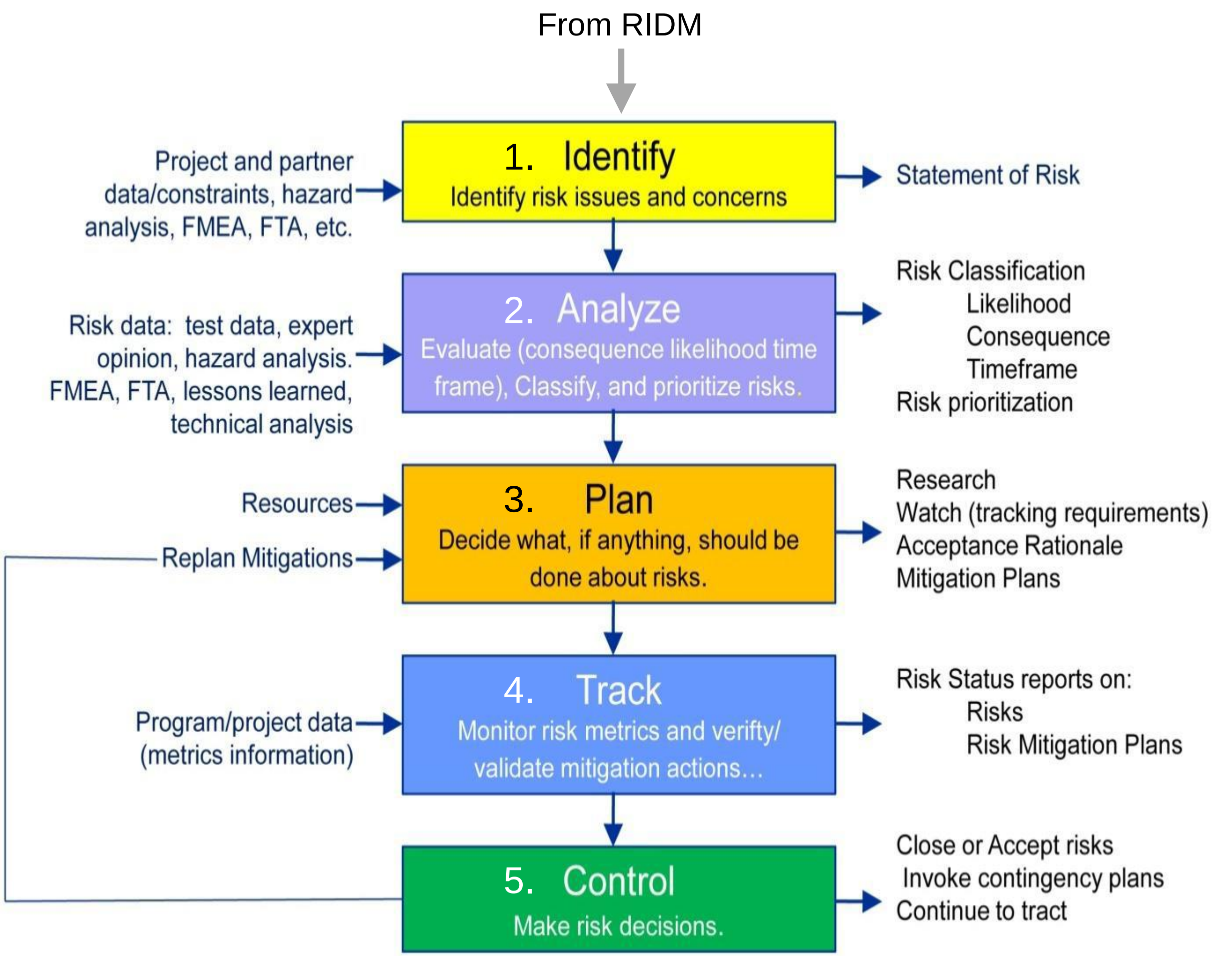
Selected alternative fed into CRM process

Continuous Risk Management (CRM)



Example: Employ DRPS concept modularity to optimize power system output and size for each specific mission

1. Higher complexity, number of interfaces contribute to risk
2. Reliability model applied to each interface
3. Impose design constraints to minimize interfaces
4. Testing power levels across mating assemblies
5. Assess whether constraint lowers risk to acceptable level

Risk Analysis Ratings

Consequence vs. Likelihood

Rating	Consequence	Implementation Risk	Mission Risk
5	Very High	Cannot achieve flight readiness with remaining resources	Mission Failure
4	High	Consume all (100%) of remaining resources	Significant reduction in return
3	Moderate	Consume significant (26-99%) remaining resources	Moderate reduction in return
2	Low	Consume little (10-25%) of remaining resources	Small reduction in return
1	Very Low	Consume minimal (<10%) remaining resources	Minimal reduction in return

Rating	Likelihood	Definition
5	Very High	Almost Certain (> 90%)
4	High	More Likely than Not (75 < P < 90%)
3	Moderate	Significant but Not Assured (30 < P < 75%)
2	Low	Unlikely (10 < P < 30%)
1	Very Low	Very Unlikely (< 10%)

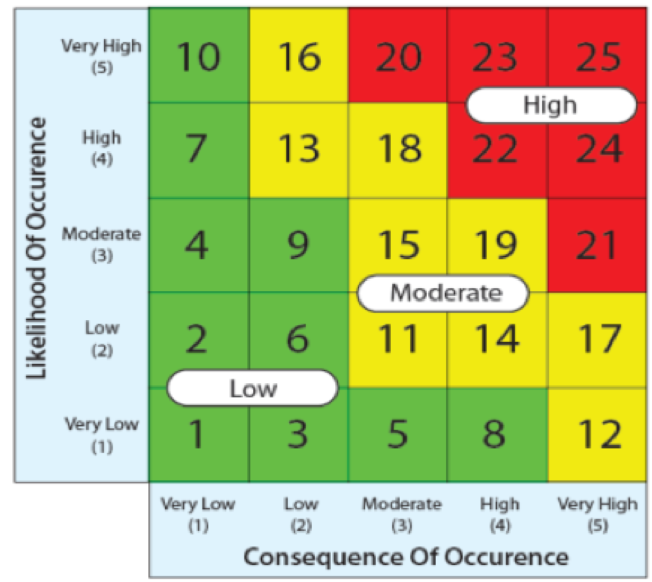


Figure 5. NASA 5x5 Risk Matrix

Risk Mitigation Example

Risk Title: DRPS Reliability Risk Due to Convertor Failure				Risk Owner: C. Matthes	
Risk Statement: In a DRPS composed of one or more convertor units, there exists a possibility that any of these units may become inoperable, resulting in a loss of power and excess unused thermal energy input from the GPHS.					
Context: The power system must meet power output and thermal dissipation requirements over the entire mission. In the event of a single convertor failure in a multi-convertor configuration, the generator needs to meet these minimum requirements while operating with one less converter. A fault-tolerant design must be adopted such that no single credible fault condition renders the entire system inoperable.					
Time Frame: Near		**Performance: 5**	**Consequence: 5**	**Date Initiated:** 11/02/16	
Approach: Mitigate	**Trigger:** Gate Review #1			**Cost if Occurs: $5M—$20M**	**Mitigation Cost: $500k**
Status:	11/02/16 – DRPS RCB validated this candidate risk as DRPS-M-05 . 12/07/16 – RCB review – No update 12/14/16 – RPSP Program CB – Updated Risk presented with the Lien request for $500K. Detailed mitigation tasks were included in the task description table mapping out the required work. The PCB approved the Lien and the 7 additional mitigation plan tasks. 4/24/17 – Updated risk retirement schedule with achievements and a delay. 5/31/16 – RCB – Agreed to updated task date. 8/22/17 – Updated risk retirement schedule. All remaining milestones slipped one month. Entire task set to complete in November now.				

	Task Description	ECD	L	C	Rating	Success Criteria
-	**Initial Rating**	-	**5**	**5**	**25**	-
1	Initiate plan as described in lien.	Aug, 17	**5**	**5**	**25**	Documented characterization of convertor reliability.
1c	Complete assessment of wiring for improved system reliability rating	Aug, 17	**2**	**5**	**17**	Results provide reliability quantifications to be balanced with cost and weight considerations.
1d	Complete viability assessment for initially operating convertors below peak power output	Sep, 17	**2**	**2**	**6**	Provides information on the resources necessary to accommodate this option.
1e	Complete reliability tests to improve component reliability rating	Oct, 17	**1**	**2**	**3**	Testing complete and results demonstrate robustness.
1f	Monitors, Controls, and Requirements finalized	Oct, 17	**1**	**1**	**1**	Convertor reliability understood and manageable.

Plans & Conclusions

- DRPS concepts offer great potential for **revolutionizing** the way future NASA planetary missions could be powered
- **Requirements** and **constraints** influenced by past RPS
- Effective **risk management** is critical to mission success
  - NASA's RIDM and CRM processes help maximize **reliability** and **viability** of new technology
- **Risk management** is critical to a number of areas throughout the technology development process
  - Convertor technologies, configuration and design
  - Component layout
  - Mission concept needs
  - Budget and schedule

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