Utilizing Radioisotope Power System Waste Heat for Spacecraft Thermal Management

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Abstract: One of the advantages of using a Radioisotope Power System (RPS) for deep space or planetary surface missions is the readily available waste heat, which can be used to maintain electronic components within a controlled temperature range, to warm propulsion tanks and mobility actuators, and to gasify liquid propellants. Previous missions using Radioisotope Thermoelectric Generators (RTGs) dissipated a very large quantity of waste heat due to the relatively low efficiency of the thermoelectric conversion technology. The next generation RPSs, such as the 110-watt Stirling Radioisotope Generator (SRG110) will have much higher conversion efficiencies than their predecessors and therefore may require alternate approaches to transferring waste heat to the spacecraft. RTGs, with efficiencies of ~6 to 7% and 200°C housing surface temperatures, would need to use large and heavy radiator heat exchangers to transfer the waste heat to the internal spacecraft components. At the same time, sensitive spacecraft instruments must be shielded from the thermal radiation by using the heat exchangers or additional shields. The SRG110, with an efficiency around 22% and 50°C nominal housing surface temperature, can use the available waste heat more efficiently by more direct heat transfer methods such as heat pipes, thermal straps, or fluid loops. The lower temperatures allow the SRG110 much more flexibility to the spacecraft designers in configuring the generator without concern of overheating nearby scientific instruments, thereby eliminating the need for thermal shields. This paper will investigate using a high-efficiency SRG110 for spacecraft thermal management and outline potential methods in several conceptual missions (Lunar Rover, Mars Rover, and Titan Lander) to illustrate the advantages with regard to ease of assembly, less complex interfaces, and overall mass savings.

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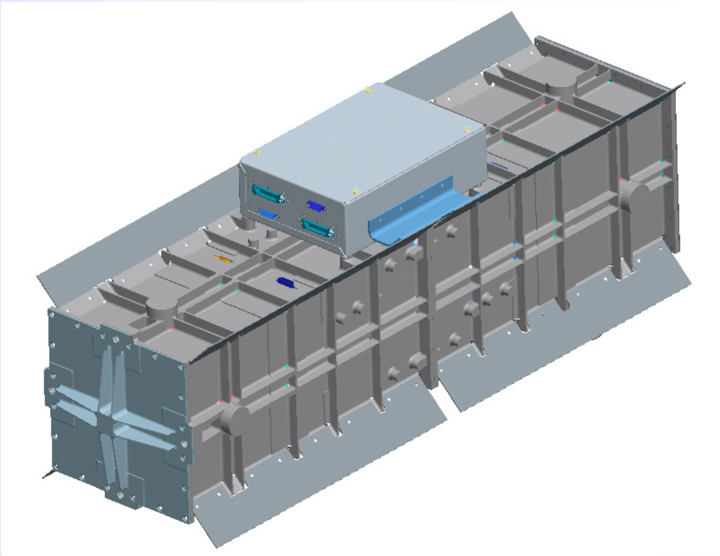
Introduction

Radioisotope Power Systems (RPS)

- Converts heat of Pu^{238} decay to electricity
- Pu heat source can last for decades
- Ideal power system for missions having weak or no solar flux
  - » Planetary Surface Missions
  - » Deep Space Missions
  - » Lunar Missions

Introduction
Radioisotope Power Systems (RPS) (cont.)

- Various technologies to convert heat to electricity
  - » Past missions used thermoelectrics
    - Radioisotope Thermoelectric Generators (RTG)
    - Relatively low-efficiency (>7%)
  - » Next generation RPS
    - Stirling Radioisotope Generator (SRG110)
      - – Uses 2 GPHS modules
        - » 250 W_t each
      - – Free-piston Stirling engine drives linear alternator
      - – High-efficiency (>22%)
      - – 110 W_e (pre-technology-insertion SRG110)



High-efficiency systems

- ***Four advantages of high-efficiency systems***
  1. Less fuel
     - » SRG110: four-fold reduction over present state-of-the-art RTGs
  2. Lower surface temperature
     - » Less waste heat enables lower rejection temperature
       - » 50+°C for SRG110

         vs.
       - » 200+°C for RTGs
  3. Lower surface temperature = greater flexibility
     - » Significantly less concern of overheating onboard science instruments
       - » More options for SRG placement on spacecraft
       - » Need for heat shield much less likely
     - » Can be mounted internally
       - » Maximize waste heat utilization

High-efficiency systems (cont.)

4. Less mass
   - » PuO_2 Fuel is heavy
     - » GPHS module: 1.6kg
     - » 2 GPHS for SRG110: 3.2 kg

       vs.
     - » 8 GPHS for MMRTG: 12.8 kg
     - » 9.6 kg mass savings
   - » Thermal shield mass minimized
   - » Waste heat recovery is via direct connection
     - » Heavy radiation heat exchanger not required

High-efficiency systems (cont.)

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- ***High-efficiency systems also have less waste heat available for S/C thermal management***

- ***Goal of this paper:***

  Determine whether the SRG110 can supply the waste heat required for multi-mission RPS S/C thermal management

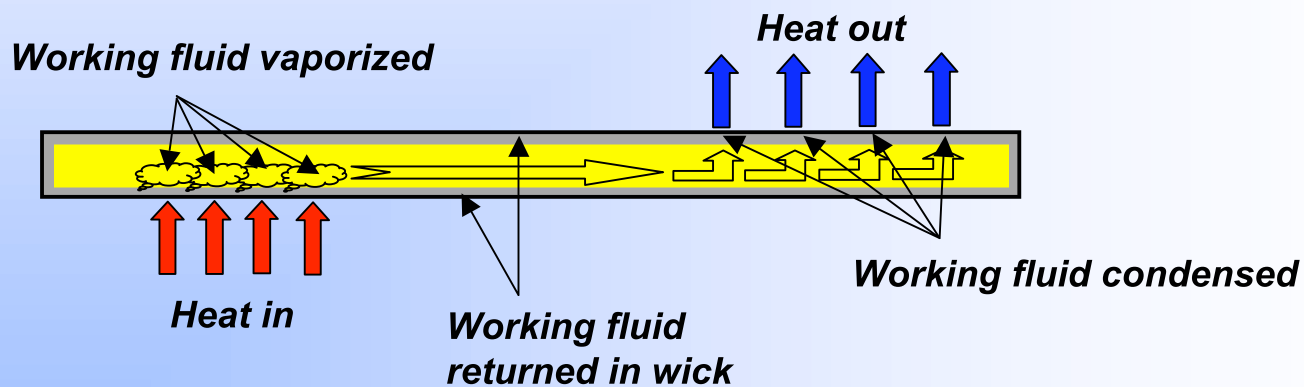
Spacecraft Thermal Management

- Sources of heat
  - » RPS waste heat
  - » RHUs (Radioisotope Heater Unit) $1W_t$
  - » Electric heaters
- Heater power required
  - » Cassini
    - 157 RHUs + 140 W_t from RTGs = 297 W_t (+electrical heaters)
  - » Galileo
    - 120 RHUs + 0 W_t from RTGs = 120 W_t (+electrical heaters)
  - » MSL
    - >500 W_t from RPSs (+electrical heaters)

$500W_t$ reasonable waste heat requirement for RPS missions

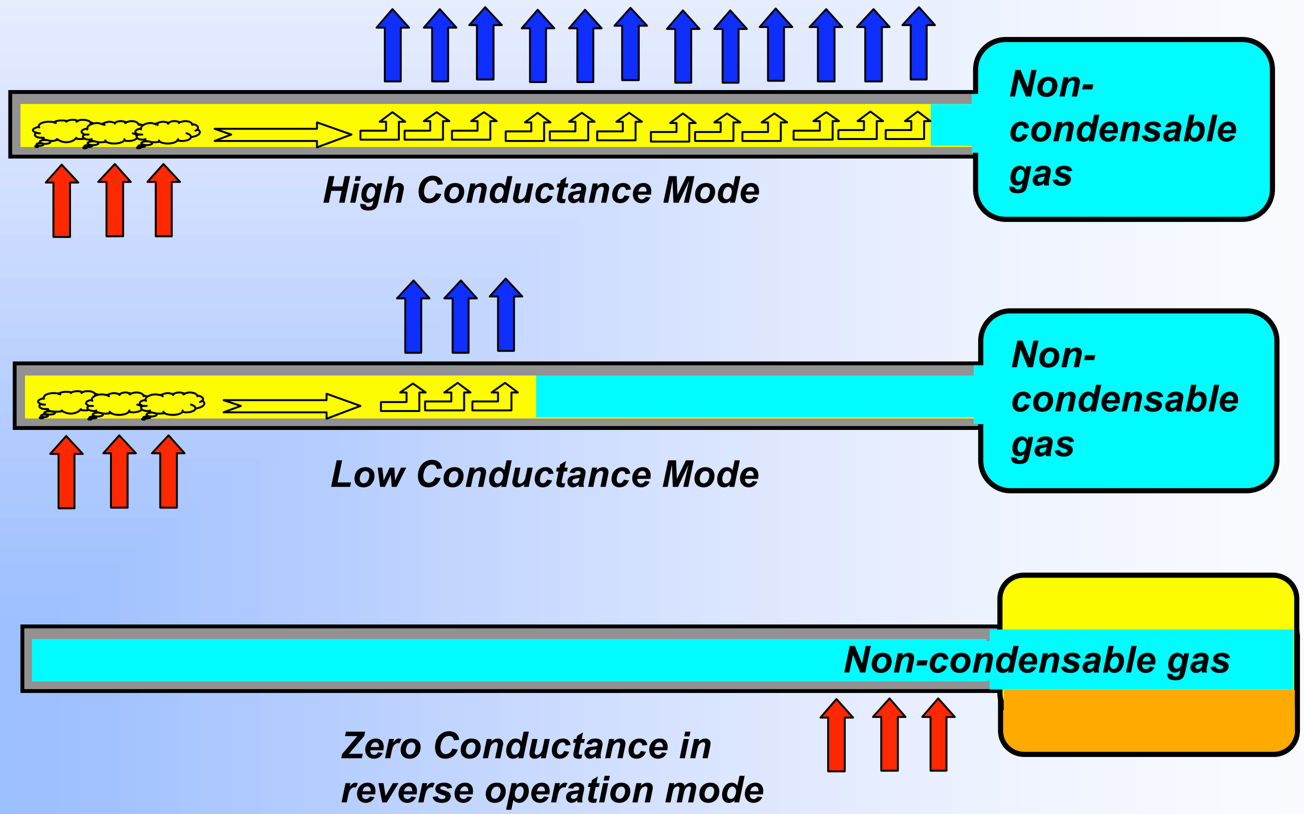
Spacecraft Thermal Management

- ***Transport methods for RPS waste-heat***
  - » Heat Pipes
    - Constant – conductance heat pipes (CCHPs)



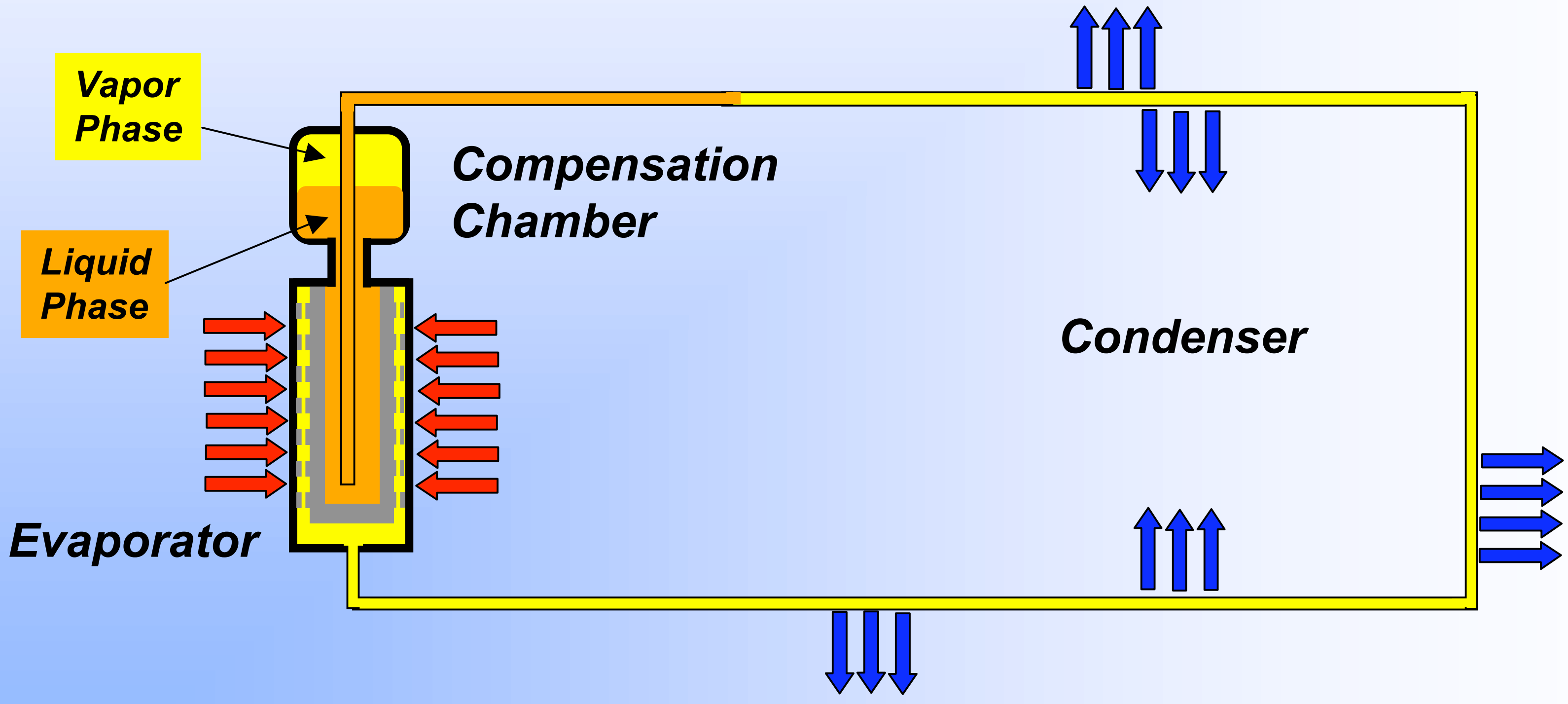
» Heat Pipes (cont.)

- Variable conductance heat pipes (VCHPs)



» Heat Pipes (cont.)

- Loop Heat Pipes (LHPs)



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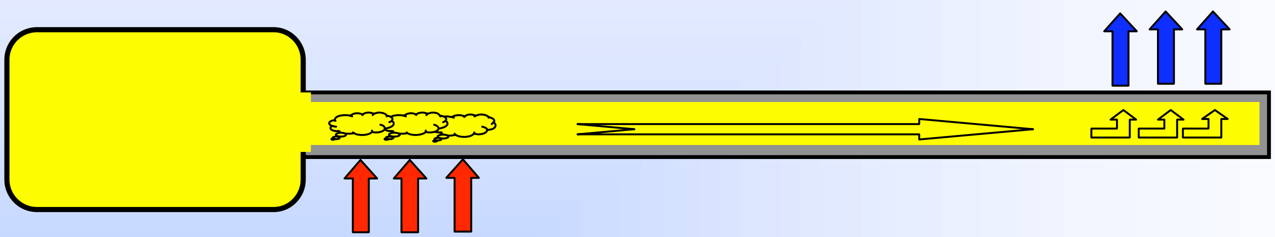
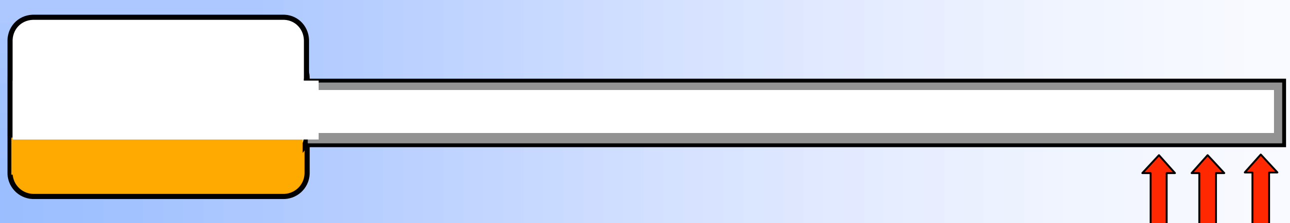
» Heat Pipes (cont.)

- Diode Heat Pipes
  - Normal Operation



  - Reverse Operation



Spacecraft Thermal Management
Waste-heat transport methods (cont.)

» Forced Fluid Loop

- Mechanically pumped fluid

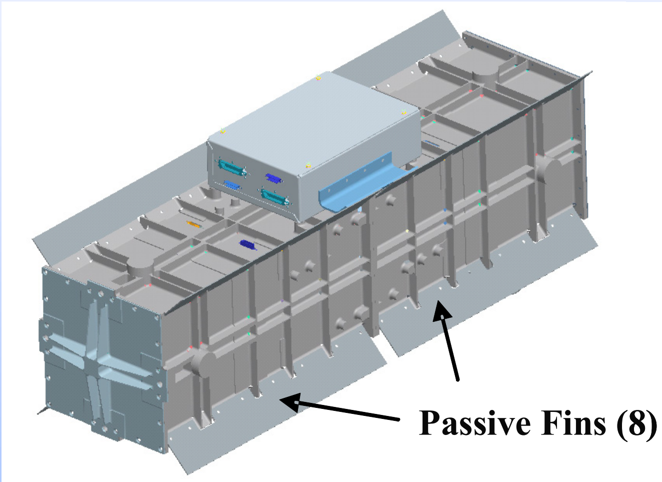
» Louvers

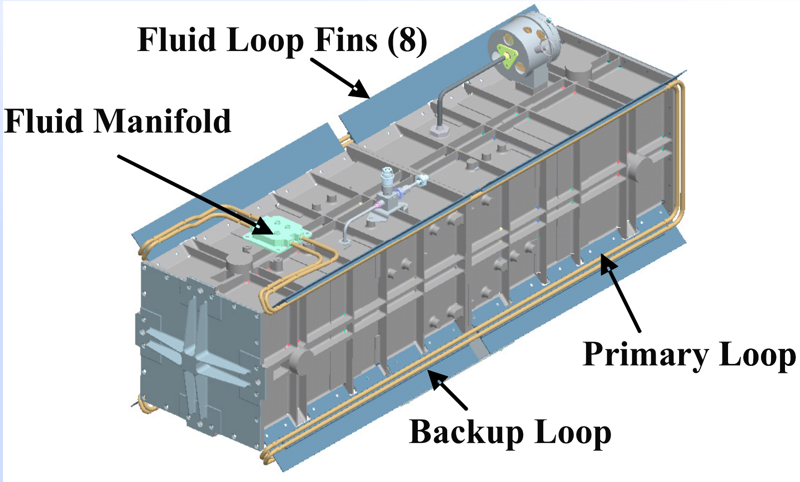
- Passive or active louvers

» Insulation

Heat-Transport Interfaces

- ***High-efficiency systems***
  - » Low surface temperatures allow for direct attachment
    - SRG110 has reconfigurable fins





- ***Low-efficiency systems***
  - » High surface temperatures require indirect interface
    - Radiation heat exchanger with embedded heat transport

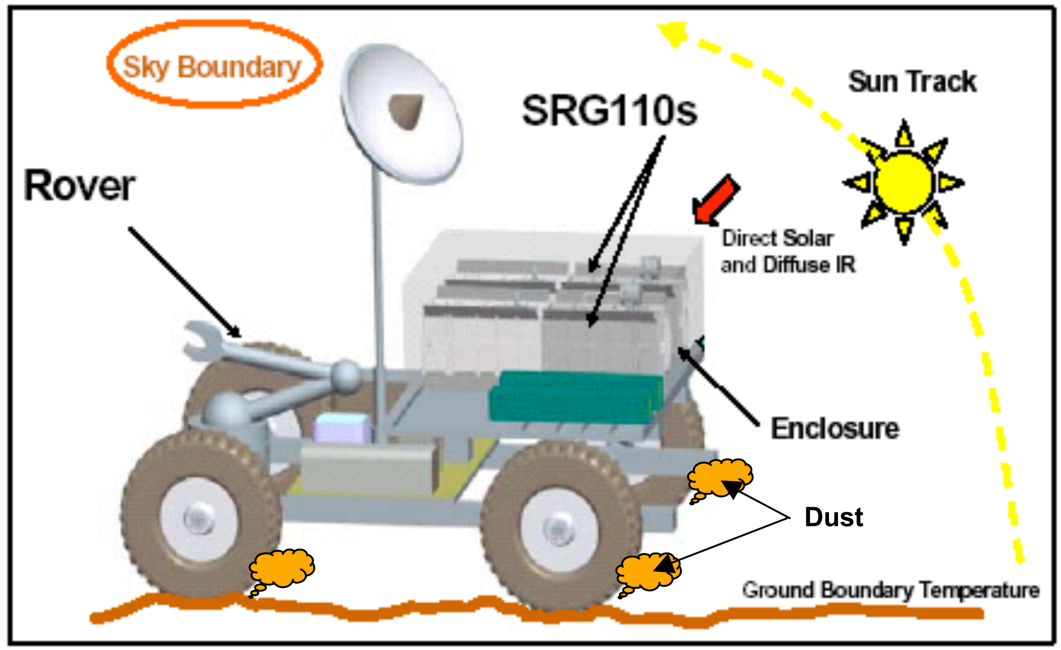
RPS Missions Analyzed

- ***Three potential missions analyzed to demonstrate capability of SRG110 to supply 500 W_t of thermal waste heat***

- ***Each mission based on JPL study of potential missions enabled by next-generation RPS***
  - » Lunar Rover
  - » Mars Rover
  - » Titan Lander

Analysis and Results:
Lunar Rover

- ***Lunar rover concept***
  - » 2 - SRG110s mounted internally
    - View to electronics
  - » Vertical radiators on sides (not shown)
  - » Variable heat transport mechanism needed to accommodate hot/cold
    - VCHPs selected
    - Send waste-heat to:
      - – Electronics in cold case
      - – Colder of the 2 radiators in hot case



Analysis and Results:
Lunar Rover

- ***Environments***
  - » Both Hot (direct sun) and Cold (no sun) conditions analyzed
  - » Some form of dust mitigation assumed (to reduce radiator **α** from 0.93 to 0.5)

Condition	Hot Case	Cold Case
Location	Lunar Surface – Direct Sun	Permanently Dark Crater
Incident Solar Flux (W/m^2)	1400	0
Surface Temperature (°C)	127	-190
Sky Sink Temperature (°C)	-269	-269
Surface Emissivity (ϵ) / Absorptivity (α)	0.9 / 0.5	0.9 /0.5
Required rover heat (W_t)	Little as possible	~500

Analysis and Results:
Lunar Rover

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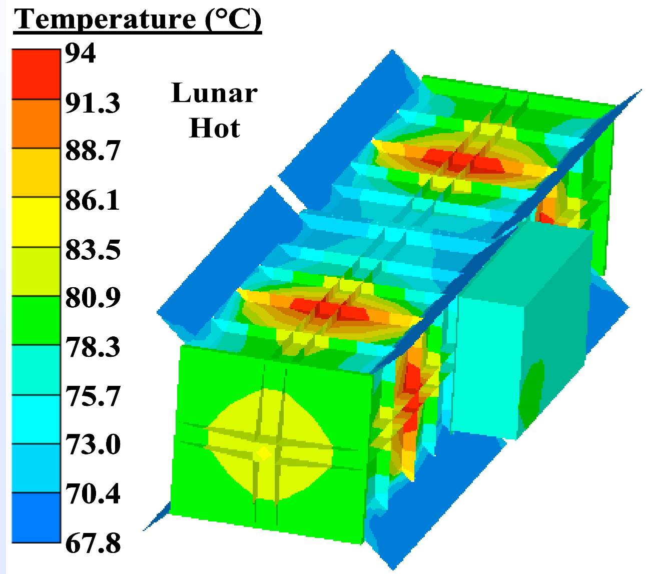
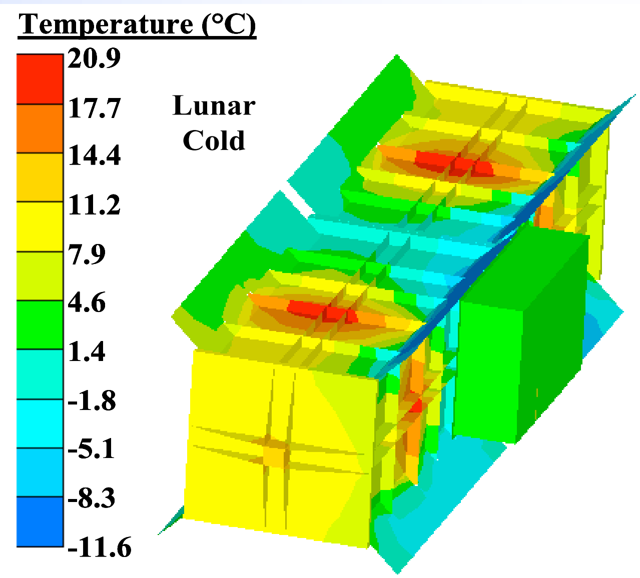
- Results

Condition	Hot Case	Cold Case
Total Electrical Power – 2 SRG110s BOM (W_{dc})	201	234
Waste Heat to Rover – 2 SRG110s BOM (W_t)	76*	610**
Average SRG110 Surface Temperature (°C)	77	5

Notes: * Includes radiation only (i.e., max)
** Includes heat transported by VCHPs only (i.e., min)





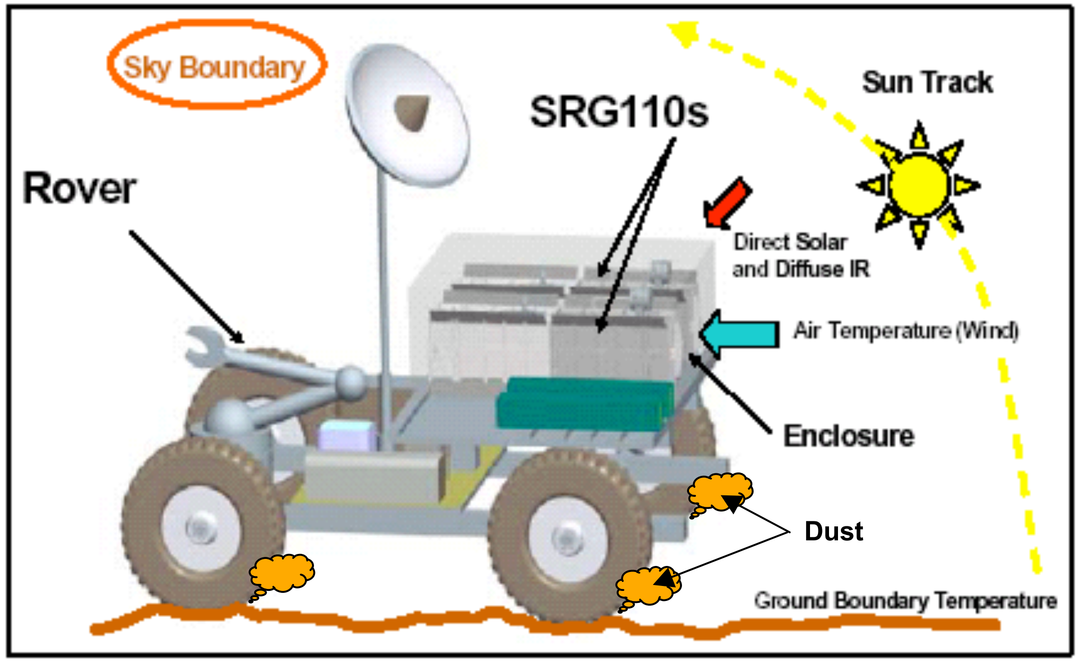
SRG110 provides more than required waste heat for lunar rover missions

Analysis and Results:
Mars Rover

- ***Mars rover concept***
  - » Based on JPL study and MSL
  - » 2 - SRG110s mounted internally
    - View to electronics
  - » Vertical radiators on sides (not shown)
  - » Variable heat transport mechanism needed to accommodate hot/cold
    - Pumped fluid loop selected
      - – Working fluid: H_2O at 100 psi, 0.65 L/min flow rate
      - – Transports heat to electronics and/or radiators

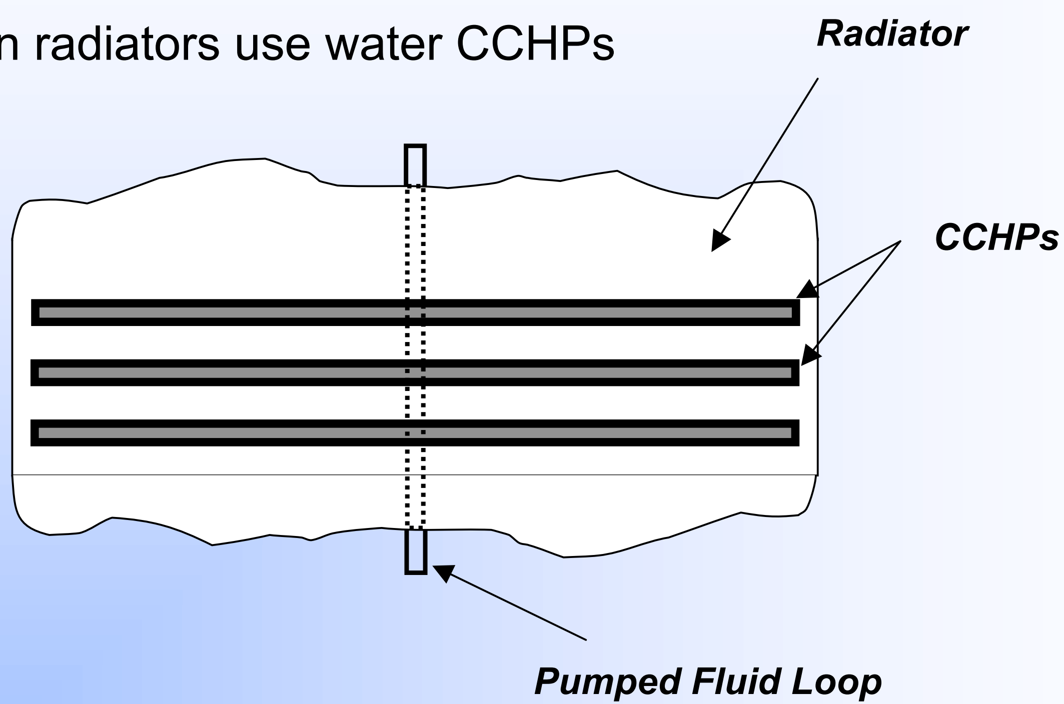
Similar to Lunar Rover

Similar to MSL



Analysis and Results:
Mars Rover

- ***Mars rover concept (cont.)***
  - » Heat rejection radiators use water CCHPs



  - » In cold case CCHPs freeze
    - Greatly reducing effective radiator area
    - Conserving waste heat for S/C thermal management

Analysis and Results:
Mars Rover

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- ***Environments***
  - » Both Hot (direct sun; no wind) and Cold (no sun; w/ wind) conditions
  - » No dust mitigation scheme needed

Condition	Hot Case	Cold Case
Location	15° South Latitude	60° North Latitude
Season	Martian Summer	Martian Winter
Direct Solar Flux (W/m^2)	580	0
Diffuse Solar Flux (W/m^2)	104	0
Surface Temperature (°C)	31	-123
Atmosphere Temperature (°C)	5	-123
Sky Sink Temperature (°C)	-101	-150
Atmospheric Pressure (kPa)	0.67	1.34
Surface Wind Speed (m/s)	0	30
Surface Emissivity (ϵ) / Absorptivity (α)	0.8 / 0.8	0.8 /0.8
Required rover heat (W_t)	Little as possible	~500

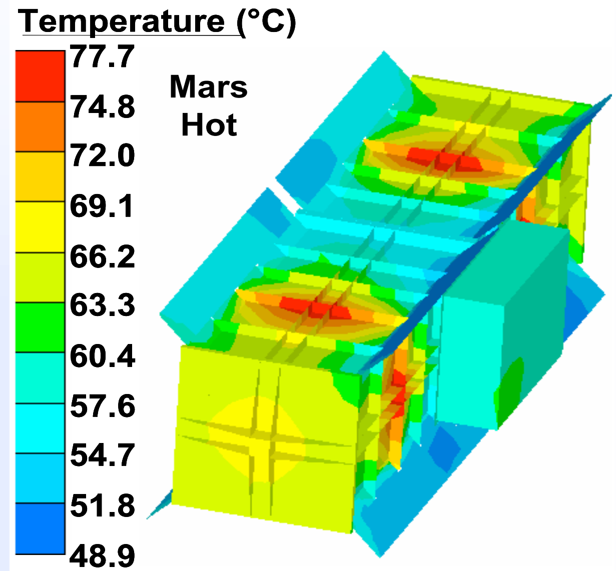
Analysis and Results:
Mars Rover

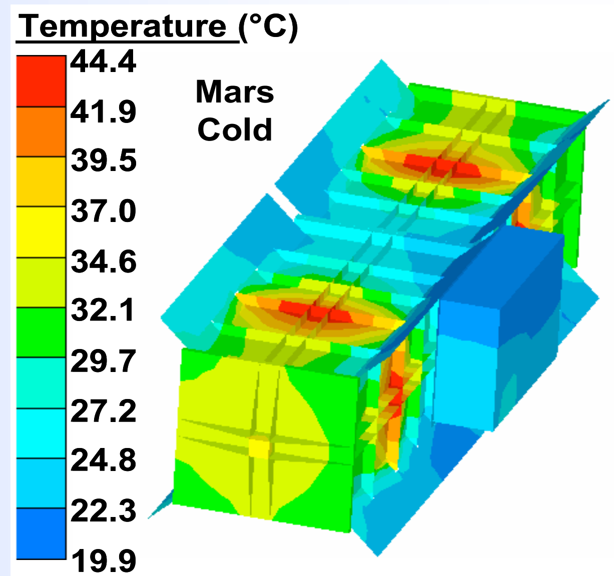
- Results

Condition	Hot Case	Cold Case
Total Electrical Power – 2 SRG110s BOM (W_{dc})	206	216
Waste Heat to Rover – 2 SRG110s BOM (W_t)	58*	512**
Average SRG110 Surface Temperature (°C)	62	30

Notes: * Includes radiation only (i.e., max)
** Includes heat transported by pumped fluid loop only (i.e., min)

SRG110 provides more than required waste heat for Mars rover missions





Analysis and Results:
Titan Lander

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- ***Titan Lander concept***
  - » 2 - SRG110s mounted internally
    - View to electronics
  - » Only Cold case considered
    - Variable heat transport mechanism <u>not</u> needed
    - Aluminum-Ammonia CCHPs selected to connect SRG fins to electronics

Analysis and Results:
Titan Lander

- ***Environments based on JPL and Huygens data***
  - » Only Cold case considered (no sun; w/ wind)

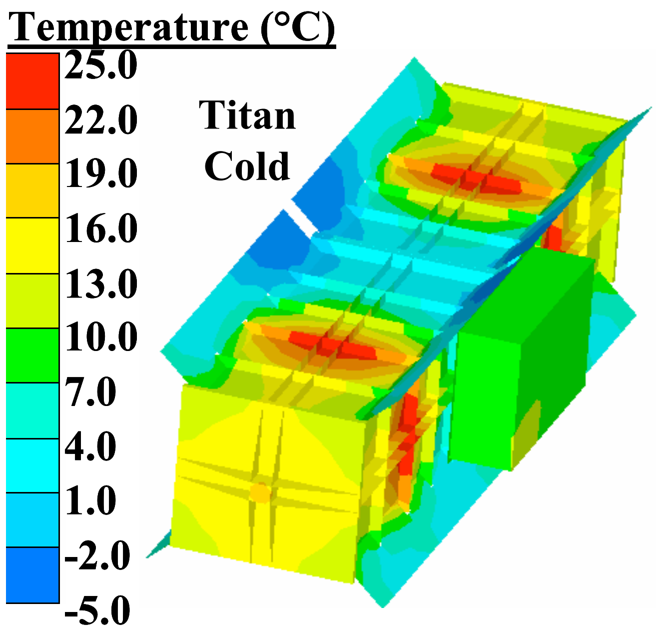
Condition	Cold Case
Location	Surface
Direct Solar Flux (W/m^2)	0
Diffuse Solar Flux (W/m^2)	0
Surface Temperature (°C)	-180
Atmosphere Temperature (°C)	-180
Sky Sink Temperature (°C)	-180
Atmospheric Pressure (kPa)	152
Surface Wind Speed (m/s)	12 (assumed)
Surface Emissivity (ε) / Absorptivity (α)	0.8 /0.8
Required rover heat (W$_t$)	~500

Analysis and Results:
Titan Lander

- Results

Condition	Cold Case
Total Electrical Power – 2 SRG110s BOM (W_{dc})	228
Waste Heat to Lander – 2 SRG110s BOM (W_t)	482**
Average SRG110 Surface Temperature (°C)	10

Notes: ** Includes heat transported by CCHPs only (i.e., min)



SRG110 provides adequate waste heat for Titan Lander missions

Conclusions

- High-efficiency systems offer substantial advantages:
  - » Greater design flexibility
    - Need for thermal shields is minimized
    - Internal mounting possible for maximum waste heat utilization
  - » Lower surface temperatures
  - » Reduced mass
- Analysis of 3 potential missions shows that SRG110 can meet waste heat requirements multi-mission applications:
  - » Lunar Rover = 610 W_t
  - » Mars Rover = 512 W_t
  - » Titan Lander = 482 W_t

SRG110 can provide required waste heat for multi-mission Spacecraft thermal management

Questions?

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