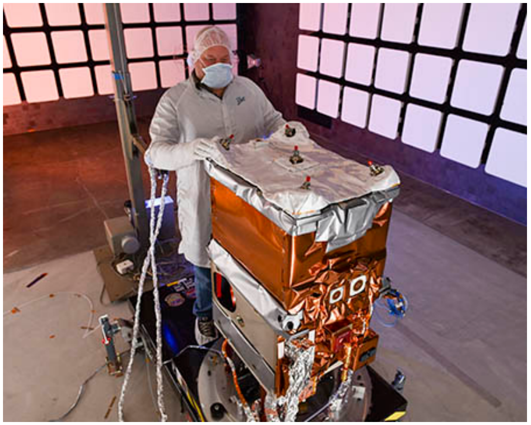

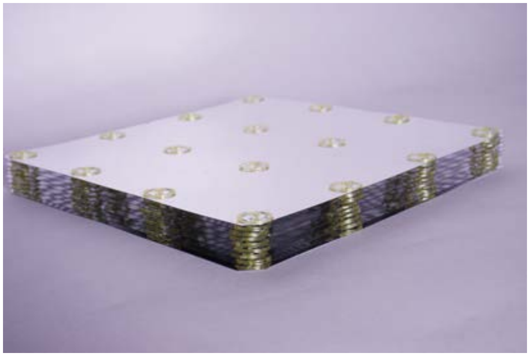

Highly Variable Radiators for Improved Spacecraft Thermal Control

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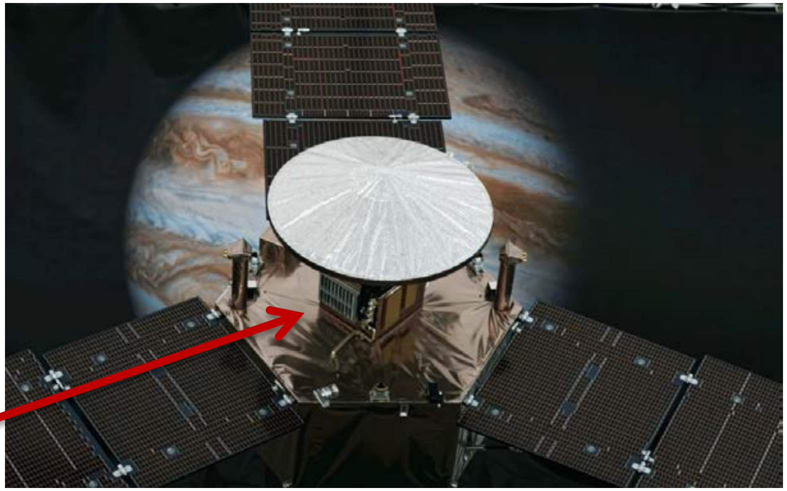
NSMMS/CRASTE 2019

Spacecraft thermal control

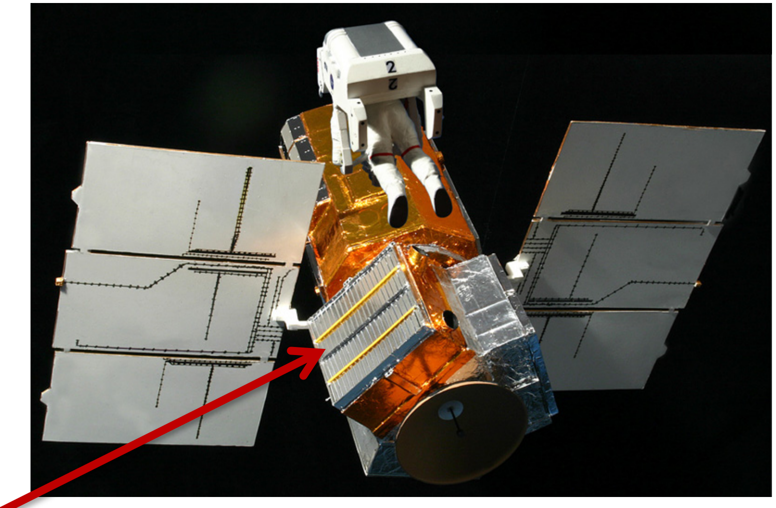
- Spacecraft (SC) must be kept within proper temperatures
- High power SC in Earth orbit need to reject waste heat
- Deep space exploration missions need to both reject excess heat and conserve heat in different mission phases
- Variable radiators provide this capability.



Variable louver radiator on Juno.

Spacecraft thermal control

- Variable heat rejection is an enabling technology to reliably vary heat rejection during human and robotic spaceflight missions with wide variation in thermal environments and vehicle heat loads
- Technology advancements needed include variable heat rejection radiators, with low mass and high energy efficiency



SMM4 with louver radiators.

Spacecraft thermal control

- Spacecraft waste heat is rejected to space by radiators
- Heat leaves the SC and radiator via blackbody radiation

$$Q = A \cdot \varepsilon \cdot \sigma \cdot (T_{hot}^4 - T_{cold}^4)$$

- SC internal heat is currently brought to radiator surface via heat doublers, heat pipes or pumped coolant loops
- Variable radiators use variable emissivity coatings or surfaces, variable surface area, or pumped loops.

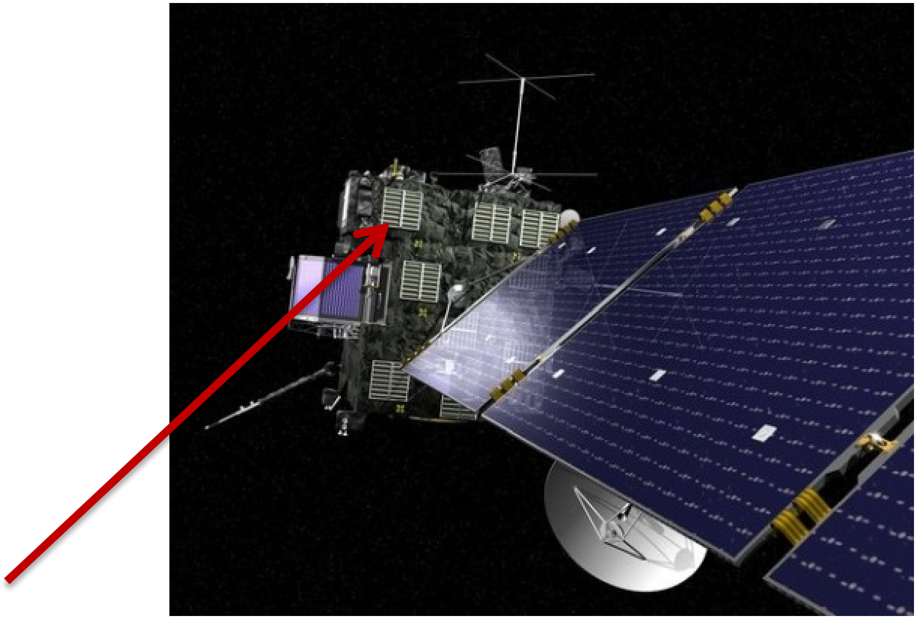
High power deployed radiators on ISS use pumped NH_3 loops.

Spacecraft thermal control

- Current state-of-the-art variable radiators are louver design
- Movable louvers cover/uncover a high ε surface with metal vanes of low ε
- Effective ε varies from 0.14 to 0.7, for a 5:1 *turndown* ratio
- NASA has requested new technology able to provide 6:1 to 12:1 *turndown* ratios

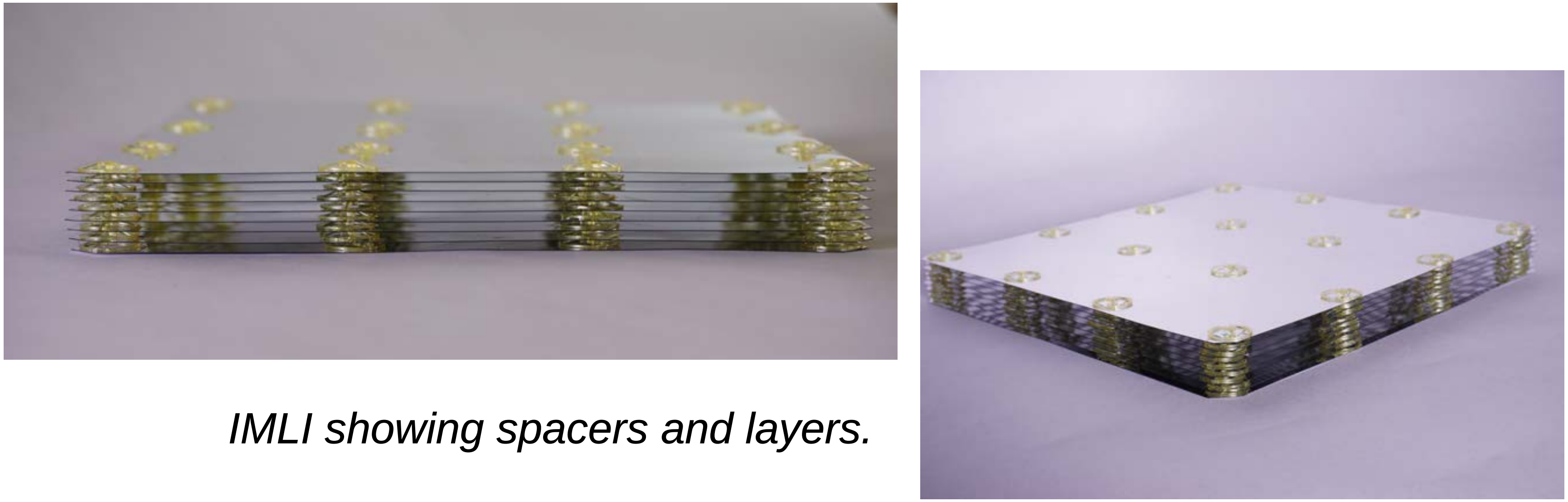
Louver radiator design.

Multiple louver radiators on Rosetta.



Integrated Multilayer Insulation (IMLI)

- Ball Aerospace and Quest Thermal Group have been developing advanced thermal insulation systems since 2007
- IMLI is an advanced next generation MLI
- Uses discrete polymer spacers instead of netting
- IMLI has half the heat flux per layer of netting MLI
- IMLI has predictable thermal performance
- IMLI and variants provide structural support up to 90 psi



IMLI showing spacers and layers.

IMLI flight on GPIM & RRM3

- Green Propellant Infusion Mission (GPIM)
  - NASA and Ball Aerospace & Technologies Corp. are collaborating on GPIM
  - Will demonstrate the capabilities of a Hydroxyl Ammonium Nitrate fuel/ oxidizer
  - Flight scheduled for June 2019

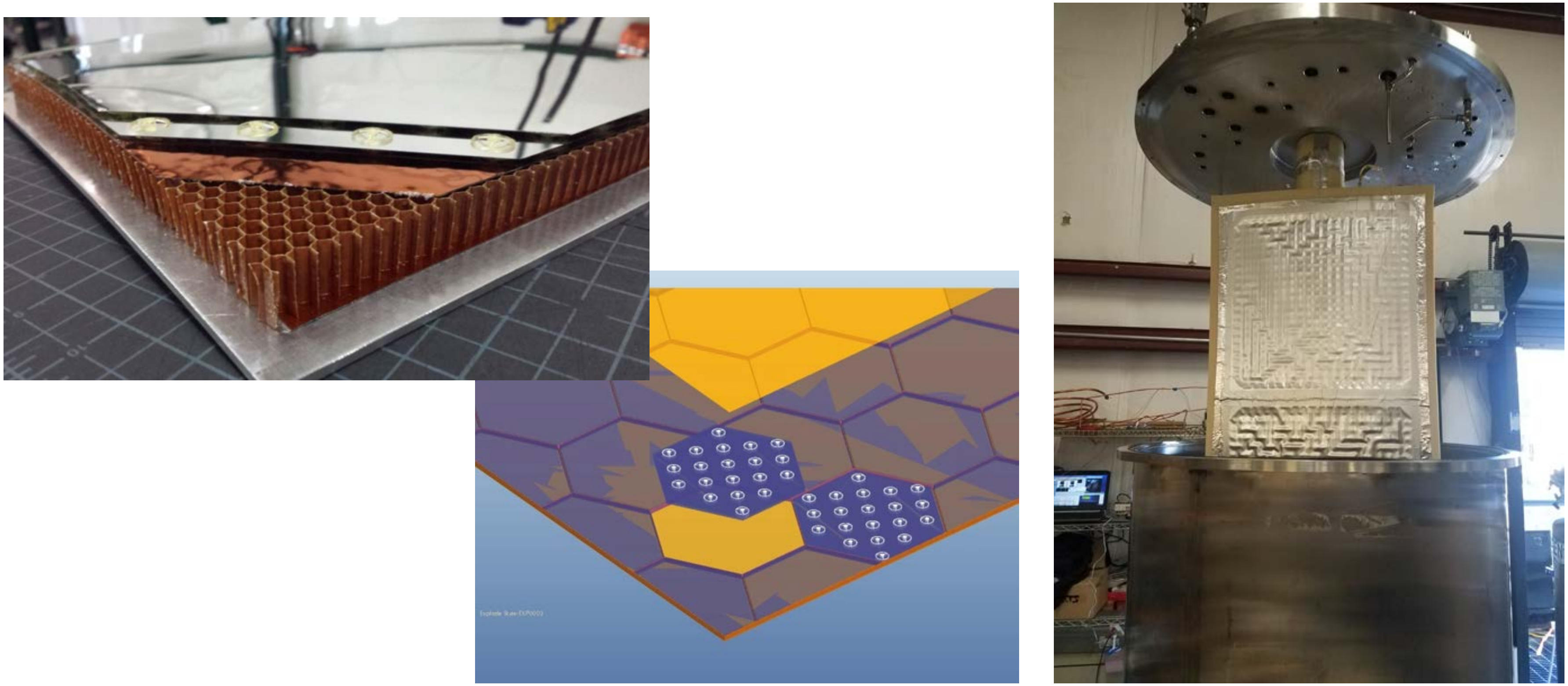
- Remote Refueling Mission 3 (RRM3)
  - NASA RRM3 flight experiment on cryogenic storage and transfer
  - IMLI insulates a cryocooled flight dewar
  - IMLI flew on CRS-16, is currently on the ISS, and is at TRL9

A family of insulation systems have evolved based on Discrete Spacer Technology

	Application	Development Status	TRL
Integrated Multilayer Insulation (IMLI)	In space and high vacuum	Phase 3 SBIR completed, 1st spaceflight 2018	9
Load Bearing Multilayer Insulation (LBMLI)	Supports thermal shields for active cooled systems	Phase 3 SBIR completed	5
Vapor Cooled Structure MLI (VCSMLI)	Vapor cools tank support elements	Phase II SBIR complete	5
Cellular Load Responsive MLI (CLRMLI)	Replaces SOFI on launch vehicle cryotanks	Phase II SBIR complete	4
Vacuum Cell Multilayer Insulation (VCMLI)	Replaces SOFI on launch vehicle cryotanks	Phase I CRAD complete	4
Multi-Environment MLI (MEMLI)	Operates in environments from space to on-Mars	Phase II SBIR in progress	4
Micrometeorite and Orbital Debris MLI (MMOD MLI)	Thermal insulation and MMOD protection	Phase I SBIR complete	3
Variable Conductance Radiator Variable Gas Radiator	Spacecraft thermal control	Phase II SBIR in progress	4

Control over internal pressures

- Quest Thermal and Ball have developed systems that control internal gas pressures or internal vacuum - useful for *Variable Gas Radiators*.
- Cellular Load Responsive MLI and Vacuum Cell MLI use a cellular core that cryopumps internal gas species, has internal or external IMLI layers, and performs both in-air and in-space.

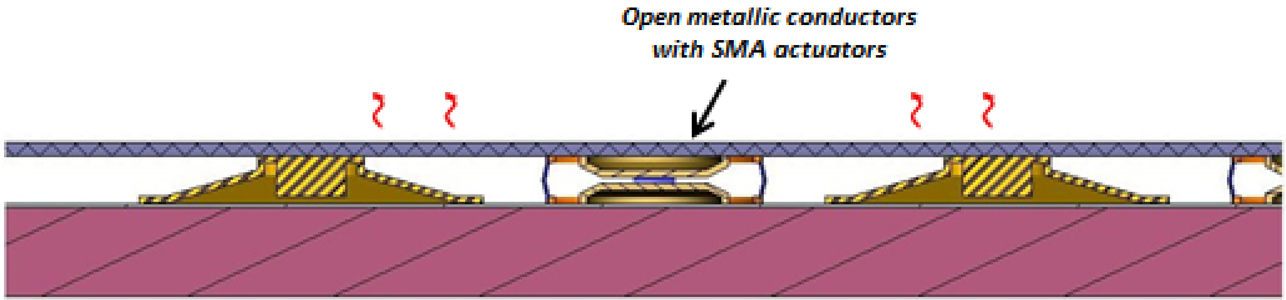


VCMLI left, CLRMLI concept (middle); CLRMLI prototype (right)

Variable Conductor Radiator (VCR)

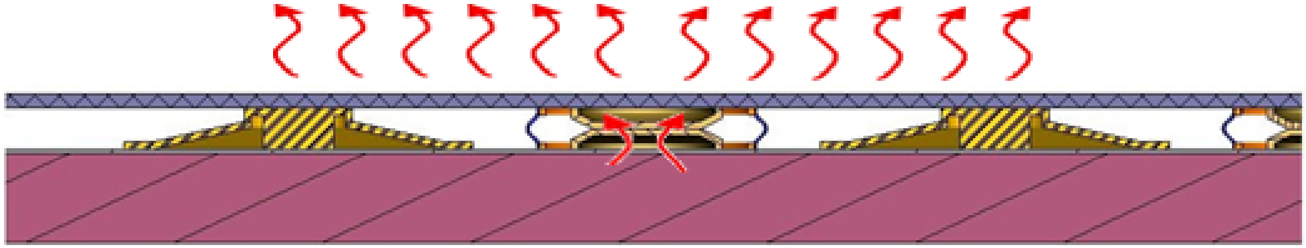
- *Variable Conductor Radiator* uses variable heat actuators embedded in IMLI insulation
- Heat conductors are SMA actuators that open/close thermal paths
- VCR is capable of acting as either high performance insulation or an effective radiator

VCR 'off'



VCR concept: spacers (yellow tripods) provide low thermal conductance; Solid conductors shown held open by SMA actuators. ***Open conductors provide low heat transfer to the radiator surface.***

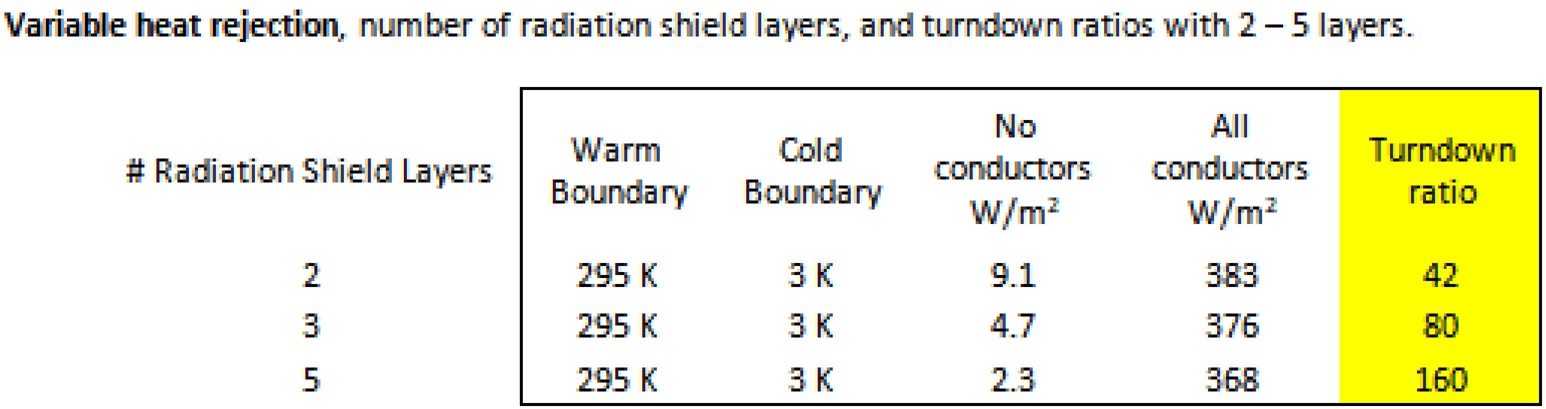
VCR 'on'



SMA actuators compress the conductive pillars, forming high heat conductive paths through the VCR. ***Closed conductors provide high heat transfer to the radiator outer surface.***

Variable Conductor Radiator (VCR)

- VCR can be engineered for specific heat rejection values
- Number of IMLI layers affects minimum and maximum heat radiated
- Heat actuators can be varied for size, number and interface conductance
- Thermal modeling estimates high turndown ratios are possible.



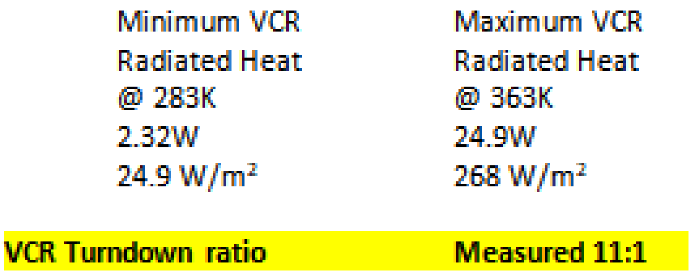
Variable heat rejection, number of radiation shield layers, and turndown ratios with 2 – 5 layers.

# Radiation Shield Layers	Warm Boundary	Cold Boundary	No conductors W/m^2	All conductors W/m^2	Turndown ratio
2	295 K	3 K	9.1	383	42
3	295 K	3 K	4.7	376	80
5	295 K	3 K	2.3	368	160

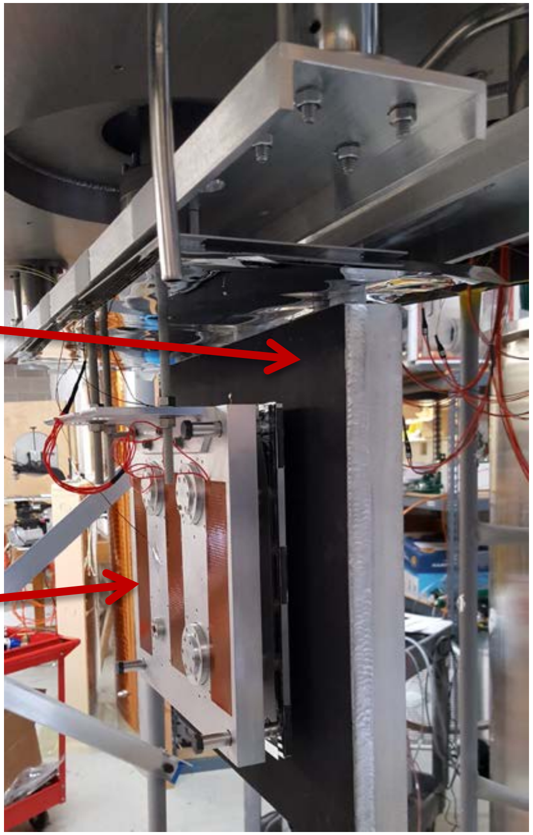
Modeled maximum and minimum heat rejection.

Variable Conductor Radiator (VCR)

- A VCR prototype was modeled, analyzed, designed, built and tested in an SBIR Phase I
- Heat actuators were designed and demonstrated to work (SMA and bimetallic passive actuators).
- Heat radiated varied from 24.9 W/m^2 to 268 W/m^2, achieving a turndown ratio of 11:1



	Minimum VCR Radiated Heat @ 283K	Maximum VCR Radiated Heat @ 363K
	2.32W	24.9W
	24.9 W/m^2	268 W/m^2
VCR Turndown ratio		Measured 11:1



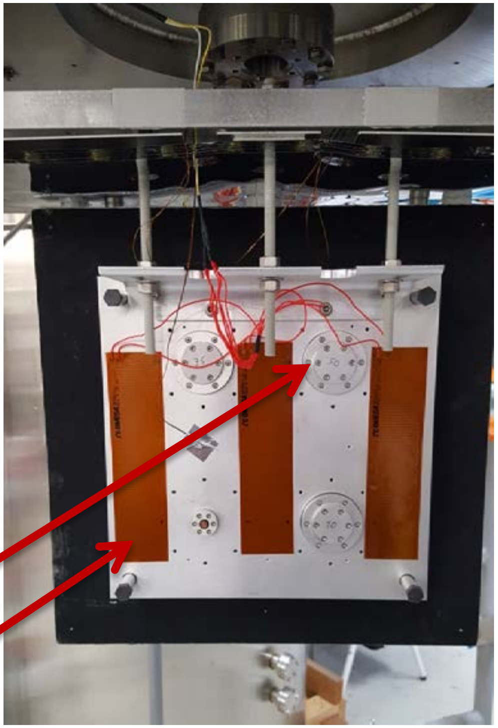
Cold target

VCR prototype

Variable Conductor Radiator (VCR)

- Variable Conductor Radiator technology was proven feasible and achieved TRL4
- Heat flows were analyzed; next generation actuator design should improve maximum and minimum heat radiated
- A 31:1 or greater turndown ratio is modeled and believed achievable

	Minimum VCR Radiated Heat @ 283K	Maximum VCR Radiated Heat @ 363K	Maximum Modeled Radiated Heat @ 363K
	2.32W	24.9W	
	24.9 W/m^2	268 W/m^2	788 W/m^2
VCR Turndown ratio		**Measured 11:1**	**Modeled 31:1**



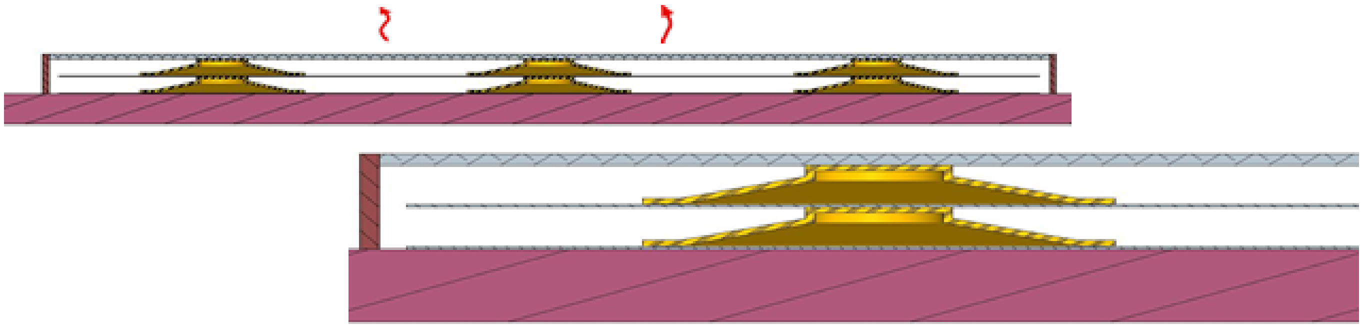
VCR heat actuators

backplane film heaters.

Variable Gas Radiator (VGR)

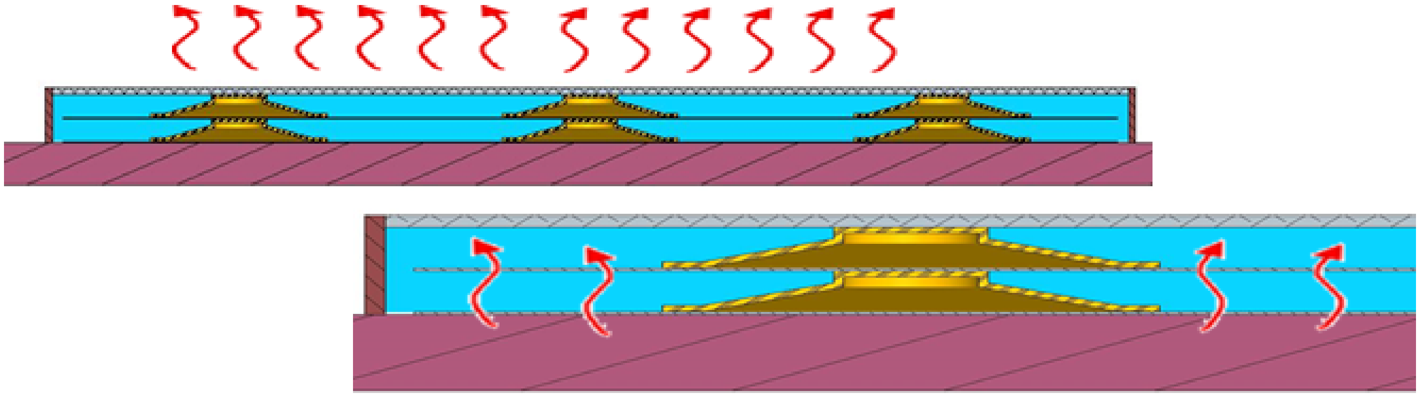
- VGR uses variable gas conductance within an IMLI insulation stack
- VGR can also act as either a good insulator or a good radiator

VGR 'off'



VGR shown with 2 layers, spacers (yellow) support robust IMLI insulation layers. ***With no gas present there is very low heat transfer to the outer radiator surface.***

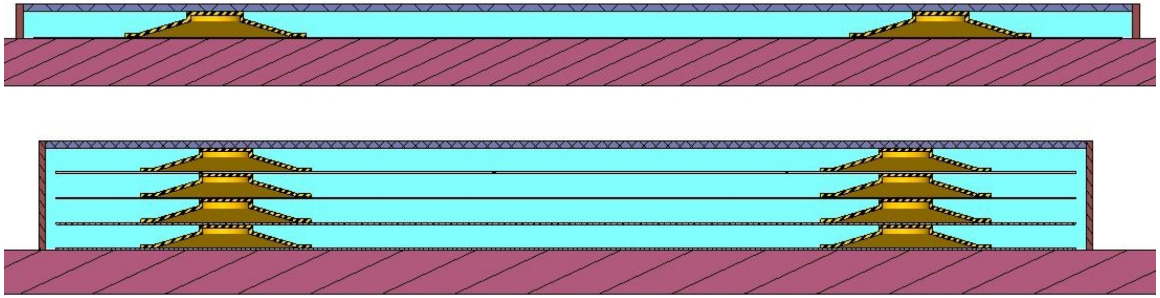
VGR 'on'



VGR with internal gas. Low pressure He or H_2 gas is an excellent heat conductor to the radiator surface.

Variable Gas Radiator

- VGR heat conduction through the Variable Radiator is controlled by the number of IMLI layers, gas species, gas pressure, emissivity of outer radiator surface, and parasitic heat leak
- Modeled max and min heat rejection shown below
- VGR should be capable of high turndown ratios



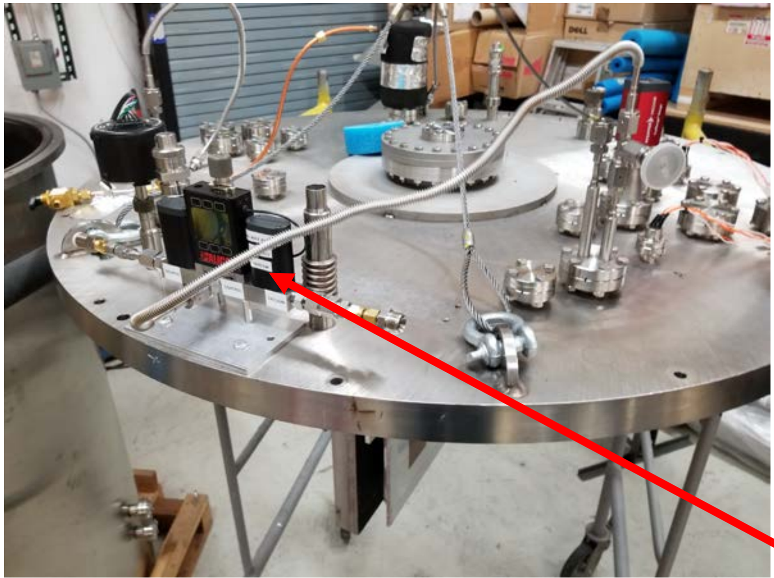
IMLI layers can be varied to control max/min heat flow

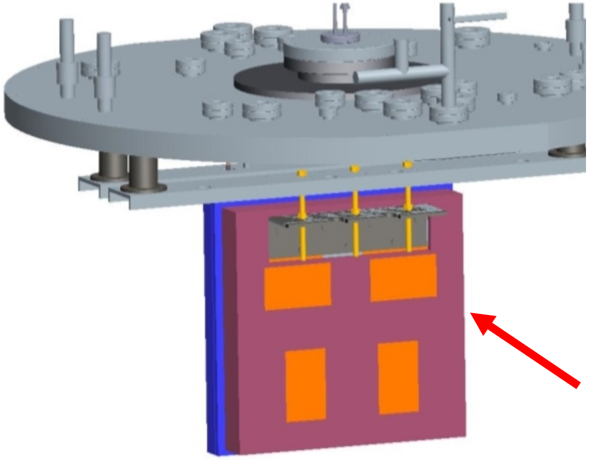
Modeled VGR Heat Rejection					
# IMLI radiation shields	Warm Boundary	Cold Boundary	Internal Vacuum W/m^2	He Gas Filled W/m^2	Turndown ratio
2	295 K	3 K	9.1	378	41
3	295 K	3 K	4.7	358	76
5	295 K	3 K	2.4	325	136
10	295 K	3 K	1.1	267	248

Variable Gas Radiator

- Heat conduction through radiator controlled by gas pressure
- Pressures in the range 0.1millitorr to 1 torr allow full heat control
- Low level precision gas pressure controller was developed

Helium gas pressure torr	Vacuum	0.0001	0.001	0.01	0.1	1	10
Modeled Radiated heat (W)	9.11W	10.1W	17.9W	66.1W	218W	377W	377W
%Max Heat Flux	2%	3%	5%	18%	58%	100%	100%
Radiator Surface Temp, K	114	117	135	187	252	289	289
BaseplateTemp, K	294	294	294	294	294	294	294



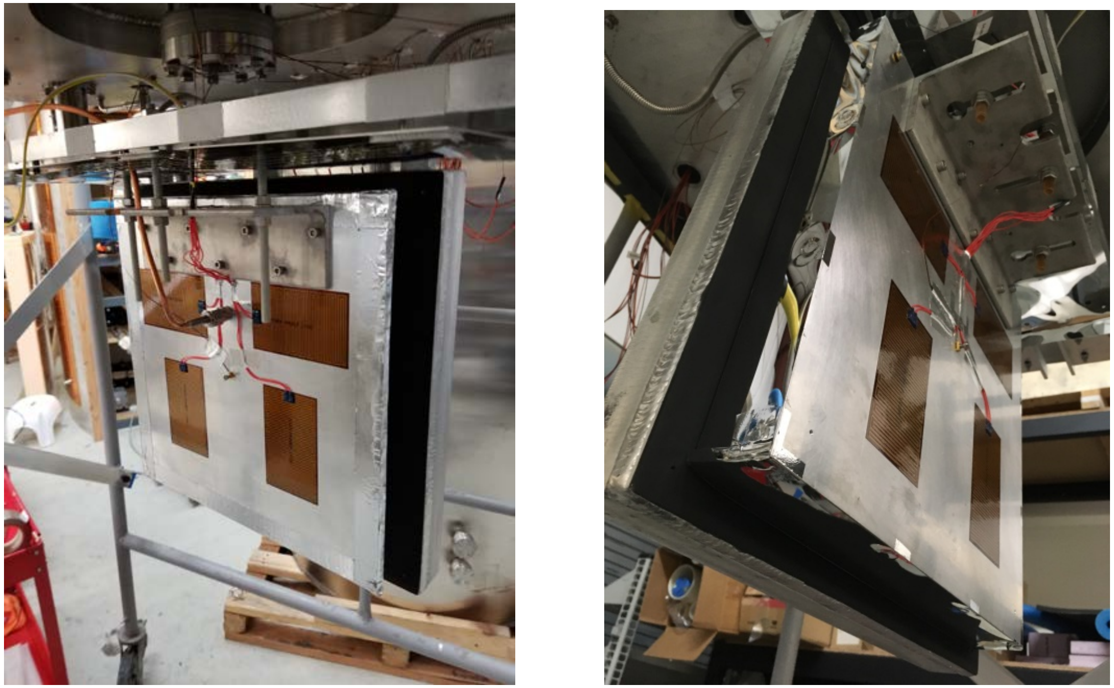


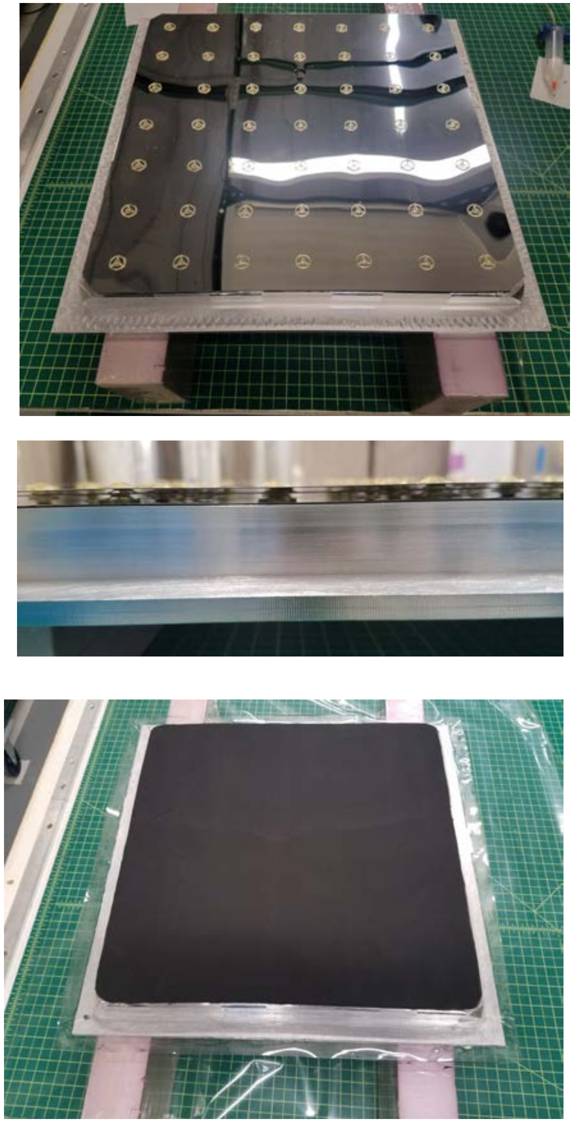
Gas pressure controller

VGR test platform, with VGR and cold target shown

Variable Gas Conductor Radiator

- A VGR prototype was designed, built and tested
- A gas enclosure was designed and fabricated
- Radiator test platform was designed and built





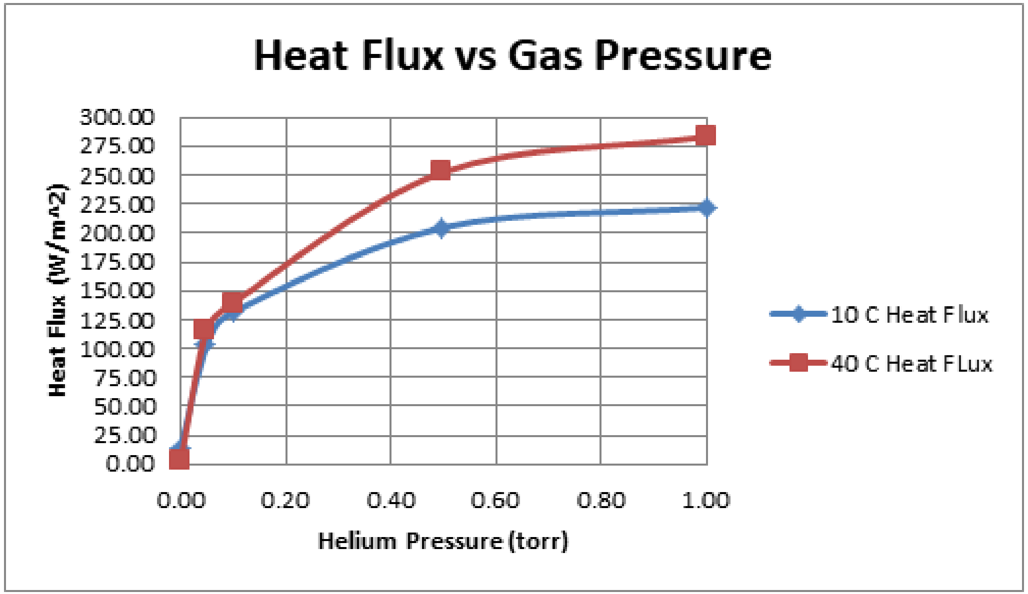
VGR prototype ready for test; left two images show prototype mounted and facing cold target; right images show VGR outer radiator surface fabrication

Variable Gas Conductor Radiator

- Radiated heat was controlled by gas pressure and baseplate temperature

VGR Measured Radiated Heat

Baseplate temperature °C	Gas pressure torr	Radiated Heat Flux W/m^2
10 °C	0.000	7.86
10 °C	0.050	97.05
10 °C	0.100	125.7
10 °C	0.500	199.0
10 °C	1.000	216.2
40 °C	0.050	116.6
40 °C	0.100	139.5
40 °C	0.500	252.6
40 °C	1.000	283.2



Heat Flux Values vs gas pressure at 10C and 40C

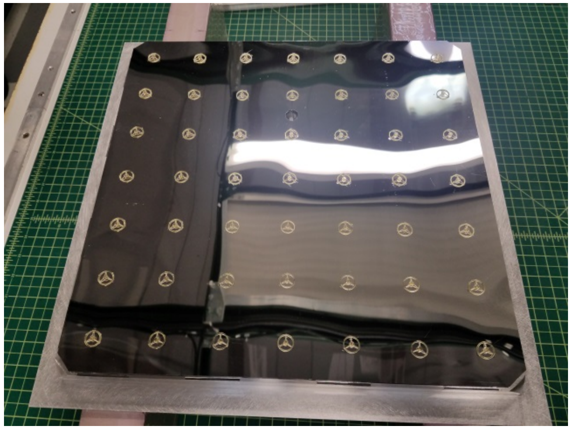
VGR radiated heat flux	**'off'**	**283K**	**7.86 W/m^2**
	'on'	**313K**	**283 W/m^2**

Turndown ratio: 36:1

Variable Gas Conductor Radiator

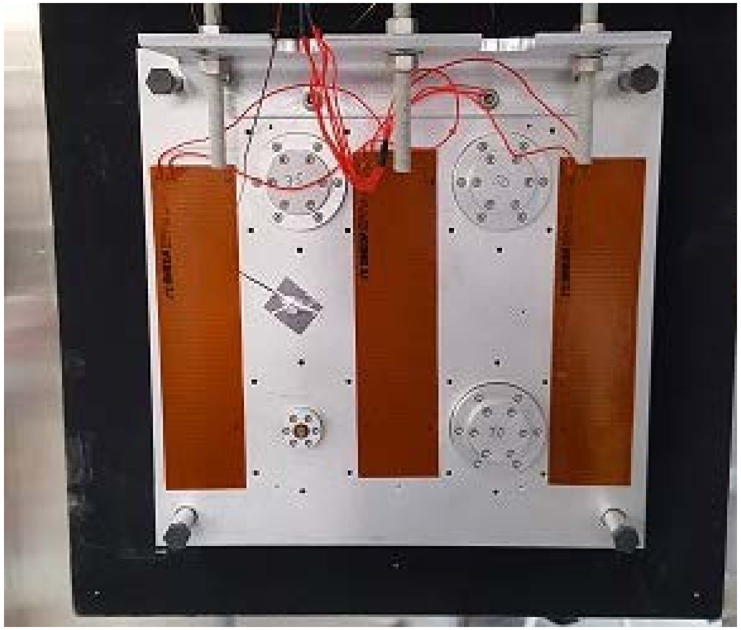
- Variable Gas Radiator technology was proven feasible, reached TRL4
- A first prototype achieved a 36:1 turndown ratio
- Good agreement between thermal model and test data
- Lightweight system at 0.69 kg/m^2 (louvers are ~5 kg/m^2)
- NASA SBIR Phase II R&D program in progress
- 2nd generation VGR has improved enclosure, gas control, and larger expected turndown ratio
- Current R&D is to mature and improve Variable Radiator technologies

	Turned off	*Turned fully on*	*Turndown ratio*
VGR modeled heat flux	**9.1 W/m^2**	**377W/m^2**	**41:1**
VGR measured heat flux	**7.9 W/m^2**	**283W/m^2**	**36:1**



Variable Radiator technologies

- Variable Radiator technology, using either variable heat actuators or variable gas controllers, was proven feasible, and are at TRL4
- First prototypes achieved 11:1 to 36:1 turndown ratios
- Thermal model and prototype test data suggest much higher turndown ratios can be achieved
- R&D work is in progress, funded by NASA SBIR program
- R&D goals are to mature and improve Variable Radiator technologies, and prepare for commercial availability



VGR left, VCR right.