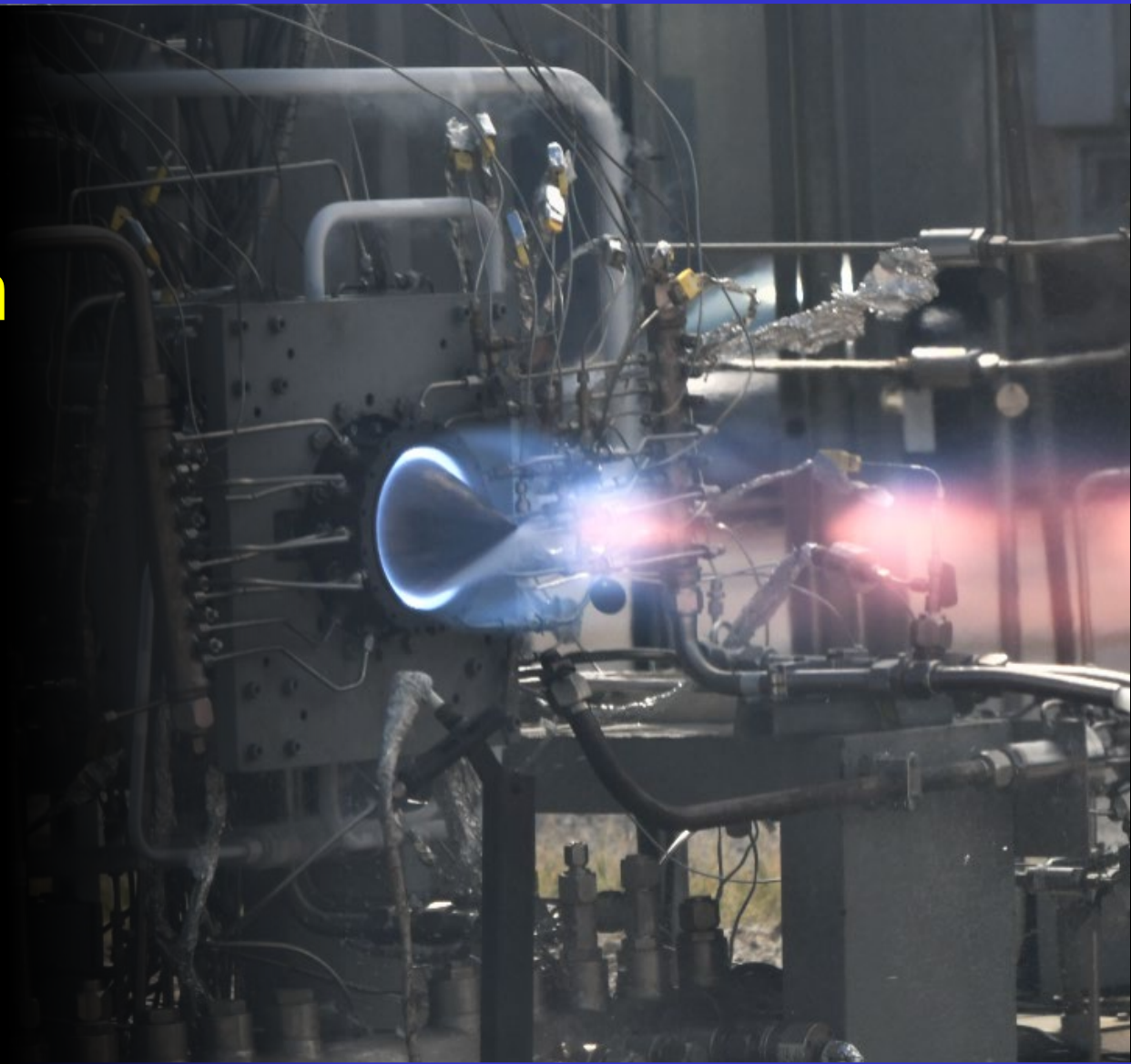




Analysis of Integrated Spacecraft Performance Using a Rotating Detonation Rocket Engine

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Motivation: RDRE Vehicle Studies

Chemical & Thermal Propulsion Systems

◆ Rotating Detonation Rocket Engines (RDREs) may yield system mass savings & performance gains at the vehicle level.

- Higher performance enabled by pressure-gain combustion
- Vehicle trade studies were performed to evaluate the gains and losses enacted by using an RDRE

◆ Vehicle trade studies presented in this work are intended to be the first of many

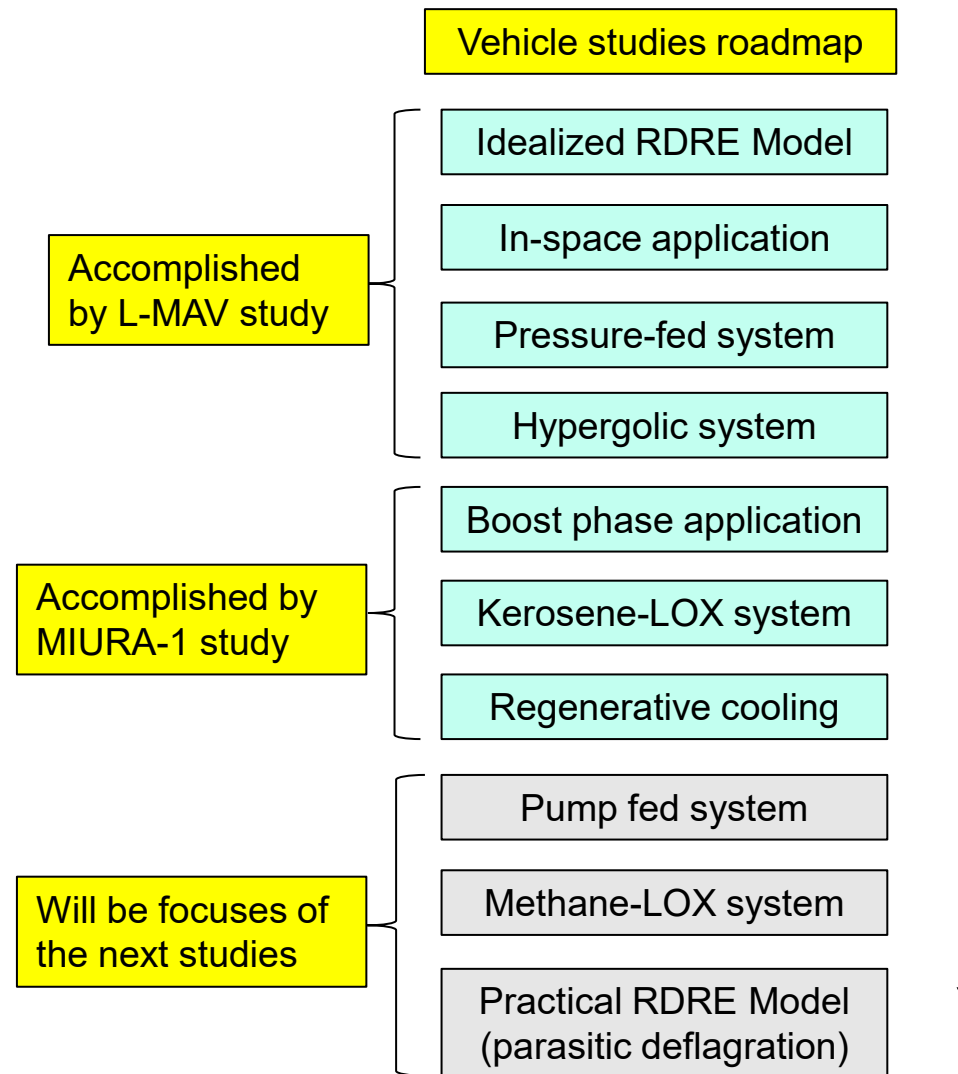
- Intent is to understand how RDREs fit into system design for a wide variety of vehicles
- Highlight use-cases that are worth pursuing
- Highlight vehicle-level impacts of RDRE, good and bad

◆ Study #1: Liquid Mars Ascent Vehicle (L-MAV)

- NASA design, not flown. In-space, pressure-fed, hypergolic
- Single use and mass constrained: provides opportunity to evaluate RDRE impact on system mass

◆ Study #2: MIURA-1 Sounding Rocket

- Developed by Payload Aerospace S.K. (PLD Space), Flown once (Oct 2023). Kerolox, pressure-fed
- Regeneratively cooled and reusable: provides opportunity to evaluate regenerative cooling impacts for RDREs





Liquid Mars Ascent Vehicle (L-MAV)

Liquid MAV RDRE Trade Study (1/4)

Chemical & Thermal Propulsion Systems

◆ First spacecraft assessed was the L-MAV

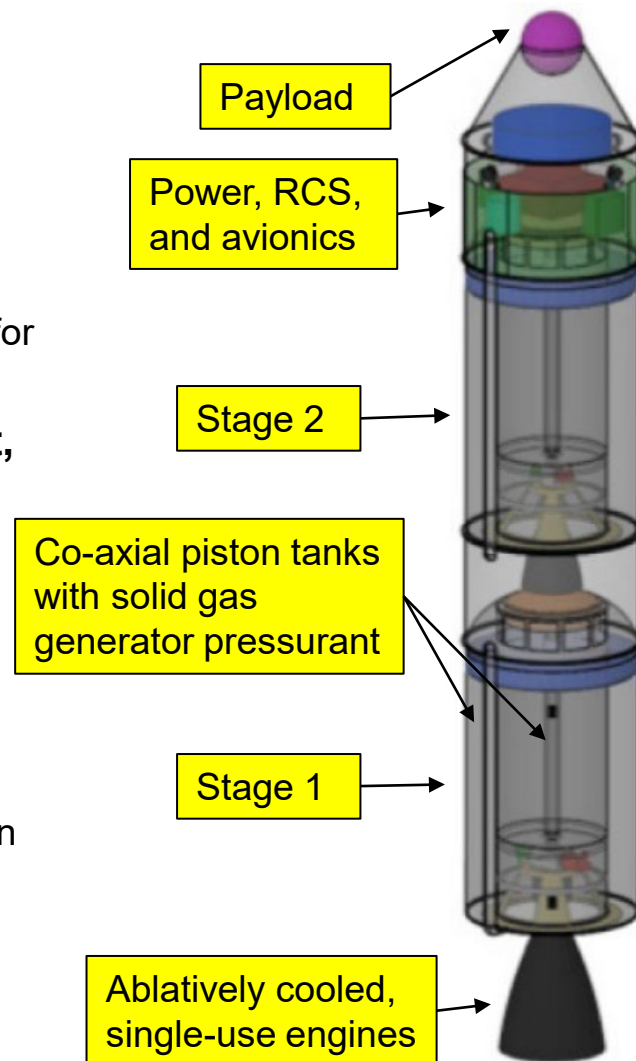
- Design dates to a 2011 study by Collaborative Modeling for Parametric Assessment of Space Systems (COMPASS) group at NASA
- Storable liquid propellants (MMH & MON-25) in coaxial piston tanks
- 1st and 2nd stage propellant tanks are identical, for cost-savings

◆ Baseline design was not selected for flight, in part due to being overweight

- Baseline design is 756 lbm, well over 637 lbm mission requirement

◆ L-MAV is an attractive candidate for an RDRE system trade

- Highly mass-constrained
- Pressure-fed design – pressure-gain combustion enables lower tank pressures, leading to mass savings
- Single-use conops reduces (but does not eliminate) the need to consider harsh operating environment of RDRE combustion chamber



Parameter	Stage 1	Stage 2
Thrust	900 lbf	300 lbf
Specific Impulse	325 sec	325 sec
Tank Pressure	1,300 psia	1,300 psia
Chamber Pressure	800 psia	800 psia

Mission Requirement	Value
Gross Liftoff Mass (GLOM)	637 lbm maximum
Payload Capsule Mass	11 lbm
Destination Orbit	45° inclination, 460 km to 580 km altitude



Workflow for L-MAV Trade Study

Liquid MAV RDRE Trade Study (2/4)

Chemical & Thermal Propulsion Systems

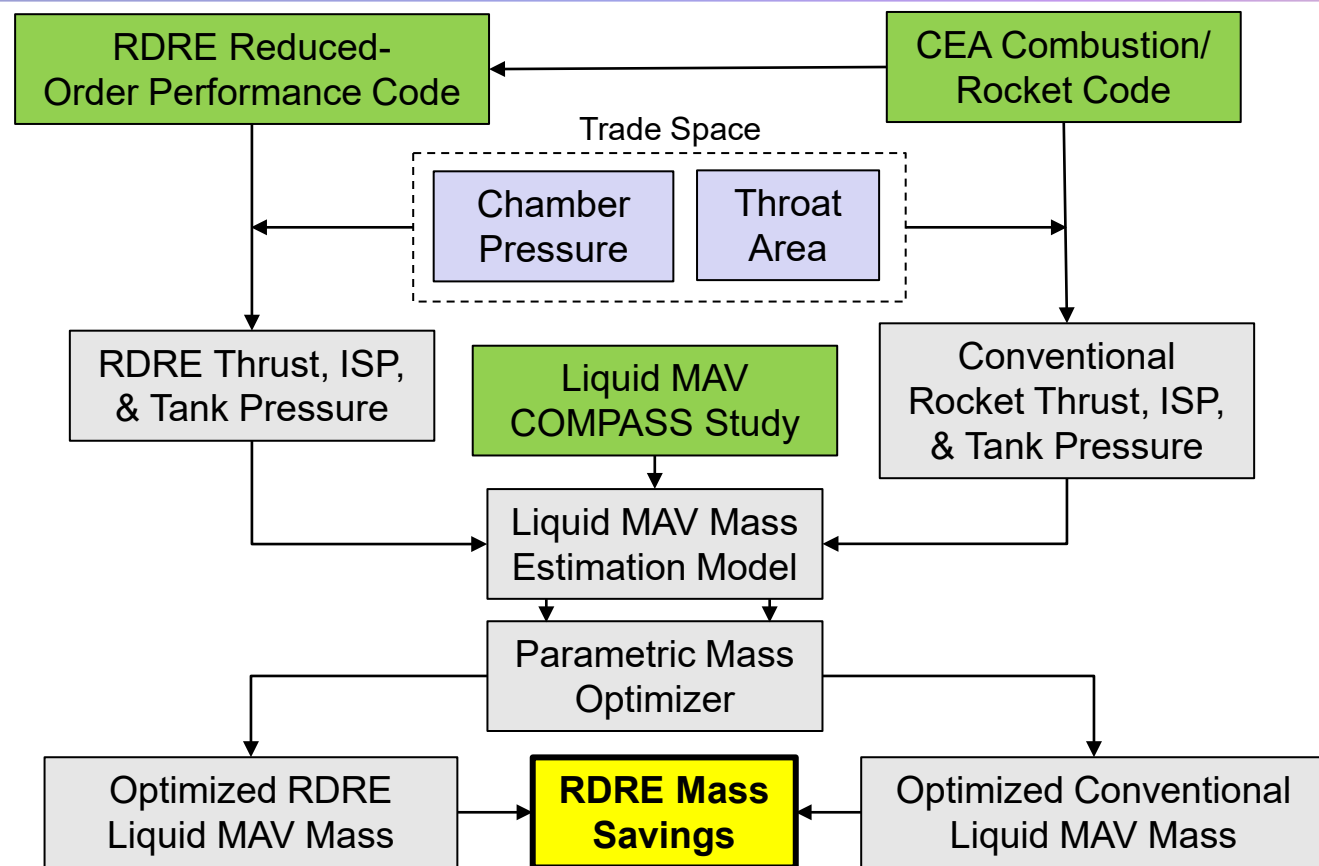
◆ The independent variables for the L-MAV trade study are chamber pressure and throat area

- Performance codes are used to calculate engine performance – namely thrust and specific impulse
- Codes account for heat losses to walls, non-ideal combustion efficiency
- RDRE performance code developed in-house at GRC, available here: <https://software.nasa.gov/software/LEW-20423-1>

◆ Mass estimation models calculate GLOM required to meet mission requirements

- Propellant tank and pressurant masses calculated as function of required propellant tank pressure and volume
- Delta-V required calculated as function of thrust-to-weight ratios for each stage
- Iterative solver converges on design parameters
- Component masses for avionics, power, feed system, etc. are held constant at baseline values
- Further details in paper

◆ Parametric sweep optimizes the design for minimum GLOM



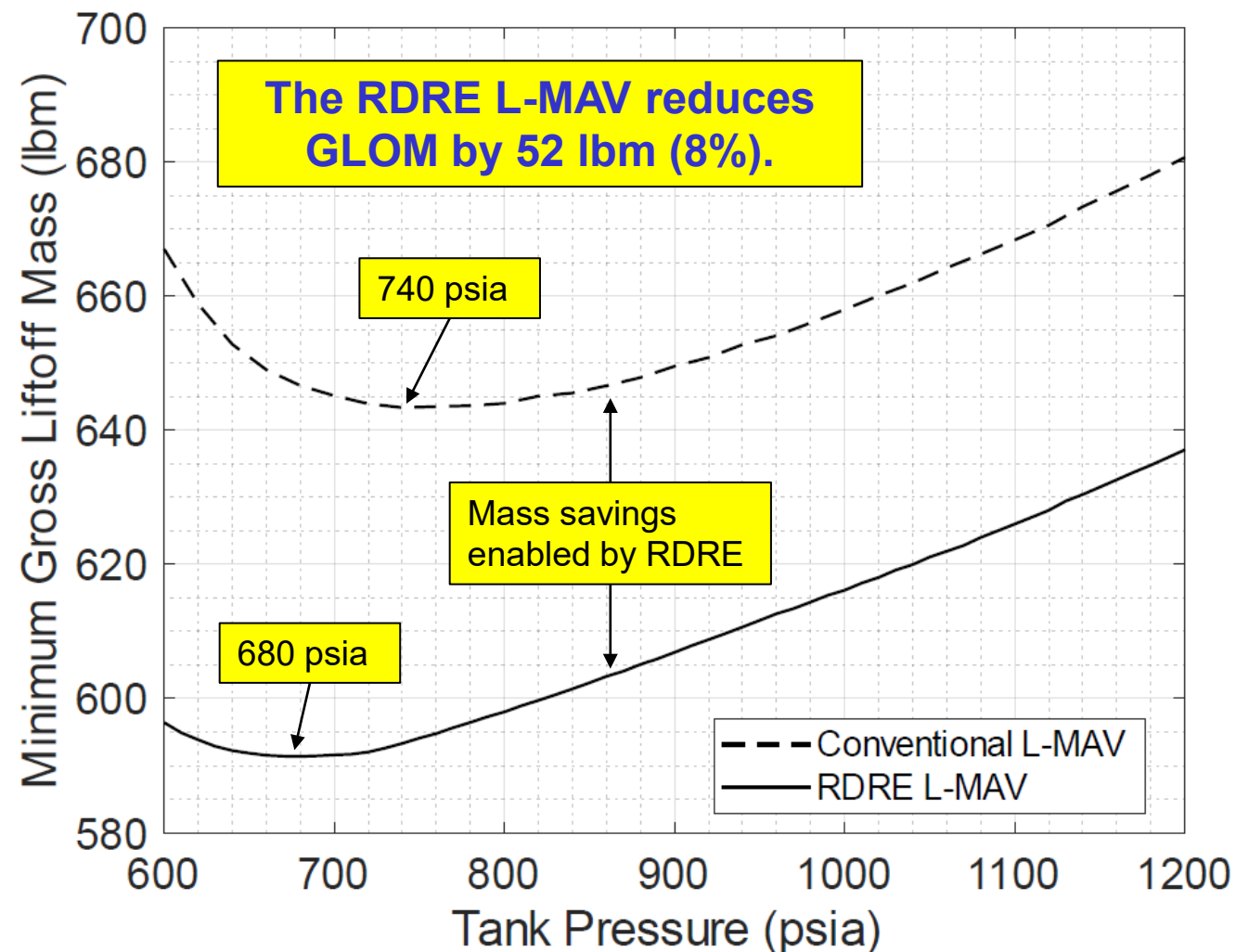
Repeating the optimization for a conventional L-MAV and an RDRE L-MAV tells us how much mass savings can be attributed to the RDRE.



Optimization Results

- ◆ The parametric sweep calculated the minimum GLOM as a function of propellant tank pressure
- ◆ Results show optimal tank pressures:
 - Conventional L-MAV: 740 psia
 - RDRE L-MAV: 680 psia
- ◆ Further performance data available in paper

Parameter	Optimized Conventional L-MAV	Optimized RDRE L-MAV
Required ΔV	12,692 ft/sec	12,678 ft/sec
Total prop load	479 lbm	389 lbm
Total tank mass (incl. pressurant)	44 lbm	37 lbm
Engine mass	22 lbm	20 lbm
GLOM	643 lbm	591 lbm

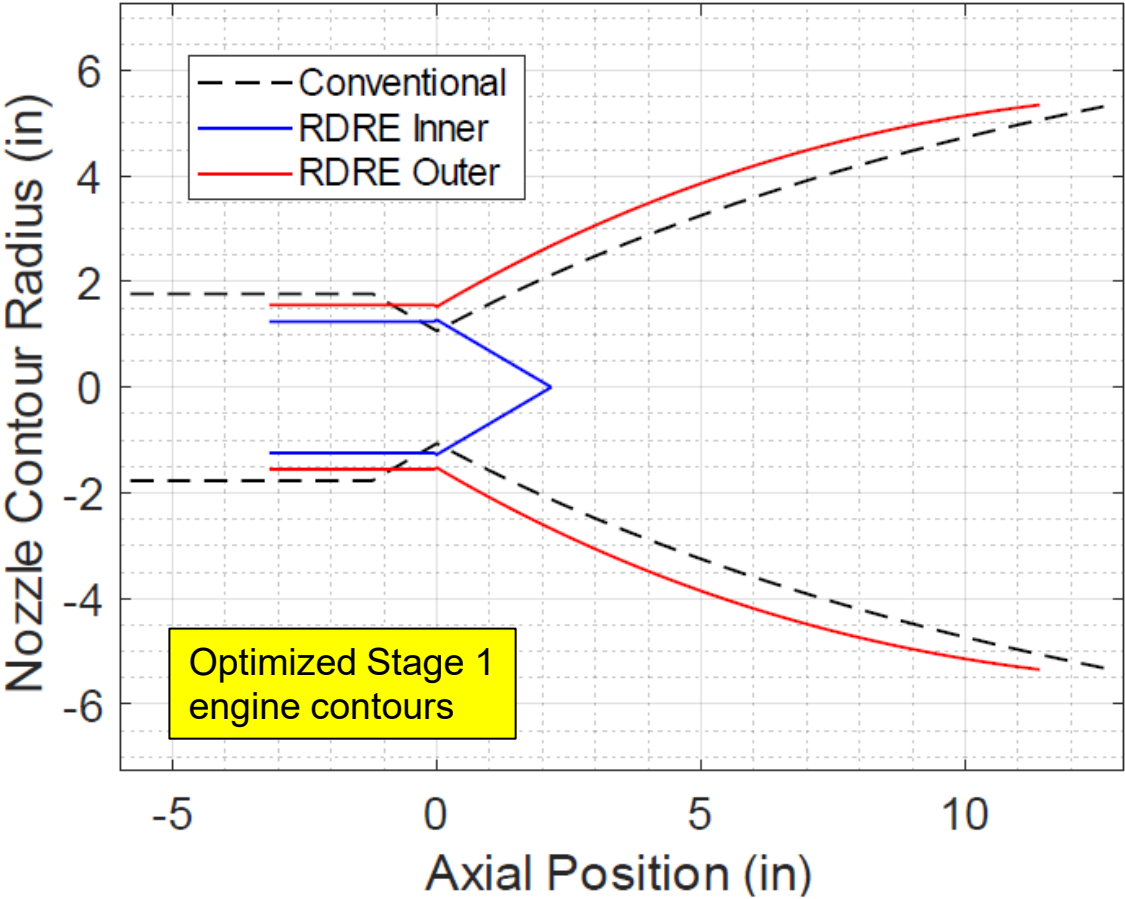




L-MAV Study Conclusions

- ◆ **L-MAV study highlights desirable characteristics of RDRES**
 - Pressure-gain combustion enables higher mass flow for a given throat area and tank pressure
 - Can reduce propellant tank pressure (to reduce weight) and accommodate a larger nozzle area ratio (to increase ISP)
 - Compounding effects – “tyranny of the rocket equation” result in large mass savings

Design	Mass	Mass Margin against 637 lbm req.
Baseline Liquid MAV	756 lbm	-119 lbm
Optimized Liquid MAV (Conventional)	643 lbm	-6 lbm
Optimized Liquid MAV (RDRE)	591 lbm	+46 lbm

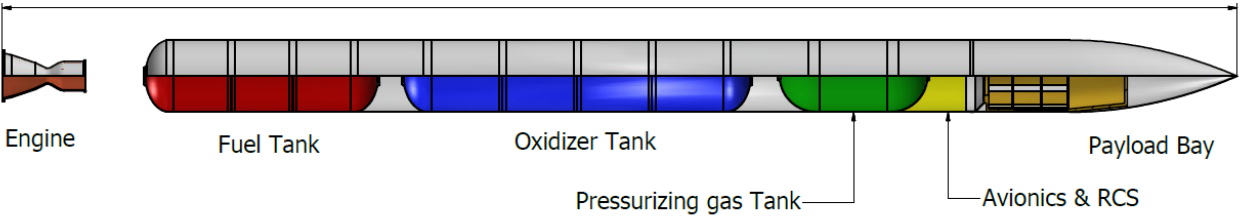


Results suggest that small-scale RDREs could enable missions which are not feasible with conventional propulsion.



MIURA-1 Sounding Rocket

- ◆ **Second spacecraft assessed was MIURA-1**
 - Developed by PLD Space; flown once in October 2023
 - Kerosene and liquid oxygen, single-stage, pressure fed
 - Regeneratively cooled
- ◆ **MIURA-1 is an attractive candidate for an RDRE system trade**
 - Similar thrust level to RDRE demonstrators ran to date
 - Can directly compare performance metrics like apogee and microgravity time
 - Can assess impact of regeneratively cooling a kerosene RDRE
 - Earth boost-phase application, provides opportunity to assess performance gains of RDRE under atmospheric conditions
 - PLD Space has publicly released enough vehicle data to allow for a worthwhile technical analysis



source: PLD space



source: PLD space

Publicly-available MIURA-1 information

Propulsion System Performance	Reported Value
Thrust (sea level)	6,800 lbf
Specific Impulse	240 sec
Tank Pressure	390 psia fuel, 520 psia oxid
Chamber Pressure	320 psia
Mixture Ratio (O/F)	2.35

Vehicle Performance	Reported Value
Payload Mass	Up to 200 lbm
Apogee (with 100 lbm payload)	95 miles
Microgravity Time (with 100 lbm payload)	250 seconds



Regenerative Cooling Model

◆ MIURA-1 assessment must include a regenerative cooling model

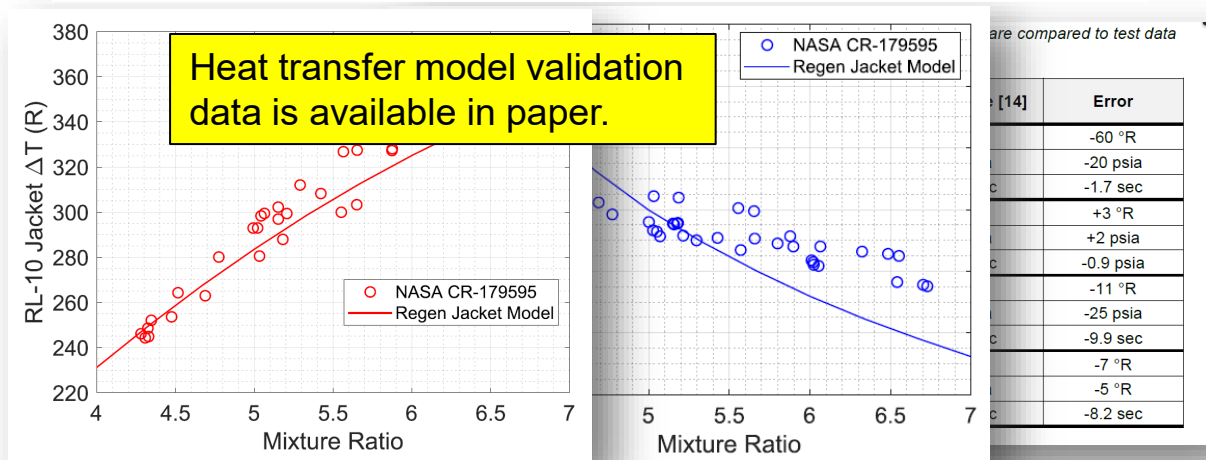
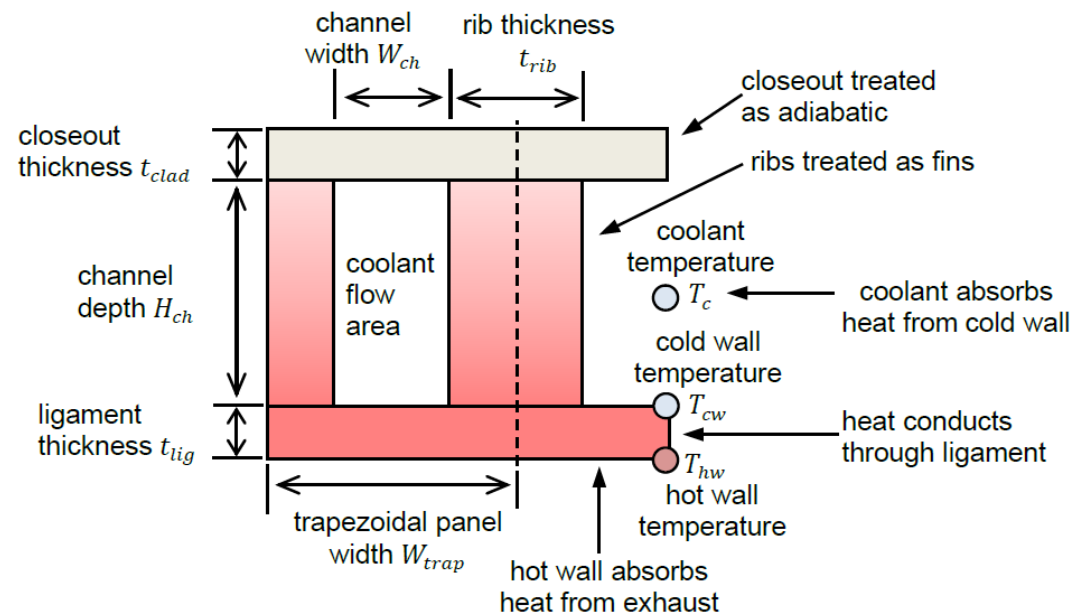
- The regenerative cooling jacket is modeled with 1-D, steady flow
- Channel dimensions are allowed to vary along flow path to minimize pressure drop while respecting user-input geometry limits and temperature limits
- Axially-varying temperature, pressure, and fluid properties are calculated for exhaust and coolant
- Bartz and Sieder-Tate correlations used

◆ Regenerative cooling model is used to calculate:

- Jacket ΔP , Jacket ΔT
- Performance loss due to exhaust heat losses
- Engine mass

◆ Regenerative cooling is a sensitive problem

- We validated our model using RL-10 test data, with excellent agreement for Jacket ΔP , Jacket ΔT , and performance loss. However, RL-10 is a conventional rocket engine.
- Sparse experimental data for RDRE heat transfer, so there is uncertainty in the RDRE heat transfer calculation





Regenerative Cooling Analysis

MIURA-1 Sounding Rocket RDRE Trade Study (3/6)

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◆ RDRE chamber pressure is described using term “initial pressure”

- This is the manifold pressure minus the injector pressure drop. It is the pressure that supplies the RDRE chamber.

◆ Engine thrust was held constant at 6,800 lbf

- Initial pressure swept across 160 psia – 320 psia
- For all cases, chamber diameter is set such that thrust is 6,800 lbf

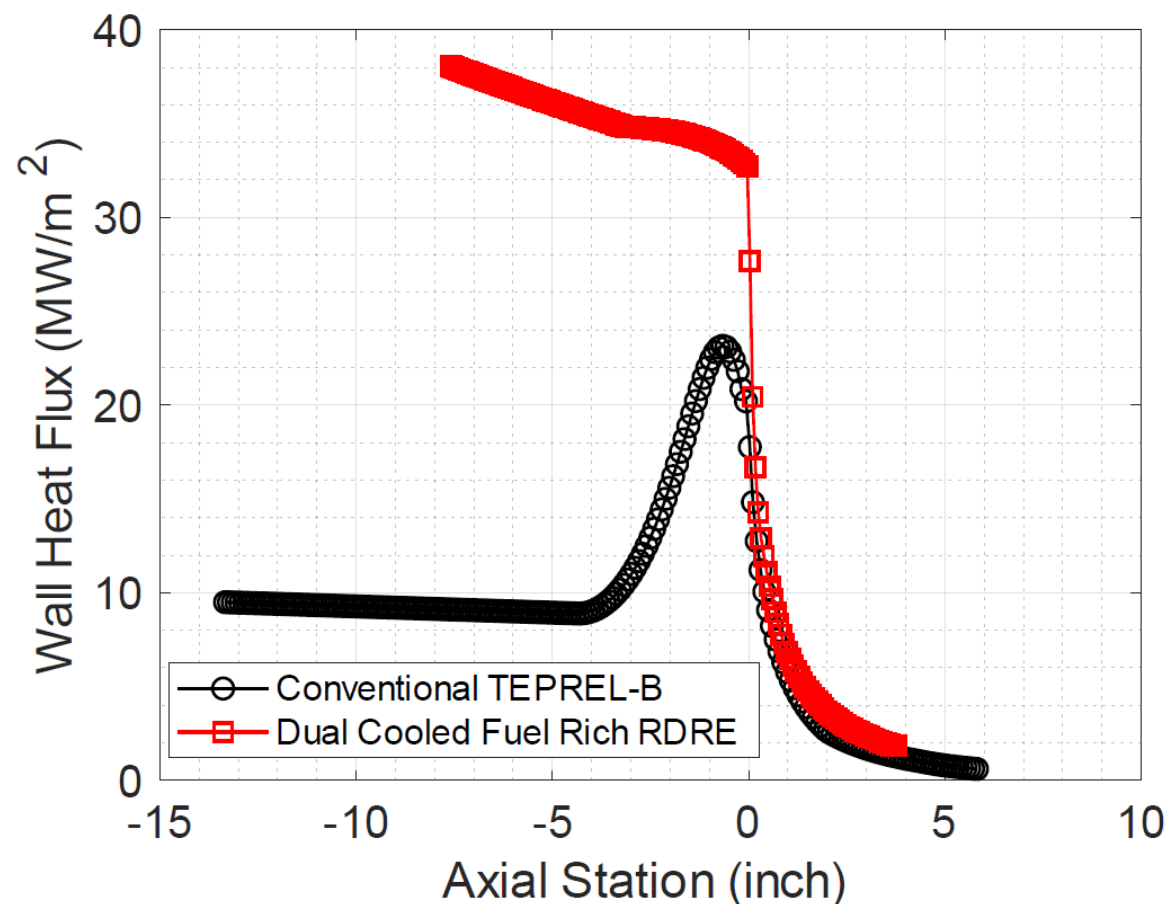
◆ Predicted RDRE wall heat loads are very high

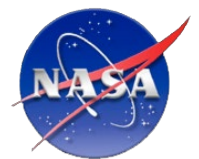
- In conventional combustion chambers, peak heat flux typically occurs where flow is near-sonic (i.e. near throat)
- In RDRE combustion chamber, entire flow field is near sonic, and there is more surface area available due to detonation channel geometry

◆ Uncertainty in required chamber length, so maximum possible chamber length (respecting kerosene coking limit) was used for three cases:

- Kerosene cooling only
- Dual commodity cooling: Kerosene cooled inner body, liquid oxygen cooled outer body
- Dual commodity cooling with mixture ratio reduced to 1.90

Predicted wall heat flux for one RDRE configuration, compared to MIURA-1's conventional rocket engine (TEPREL-B)

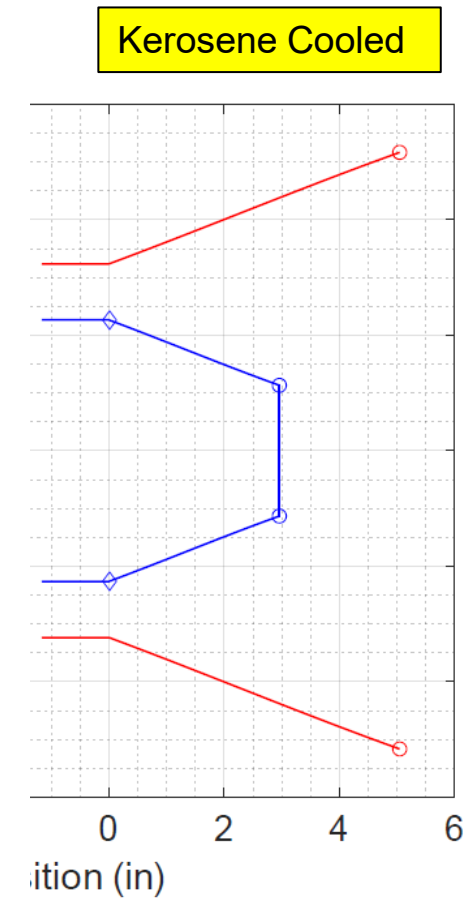
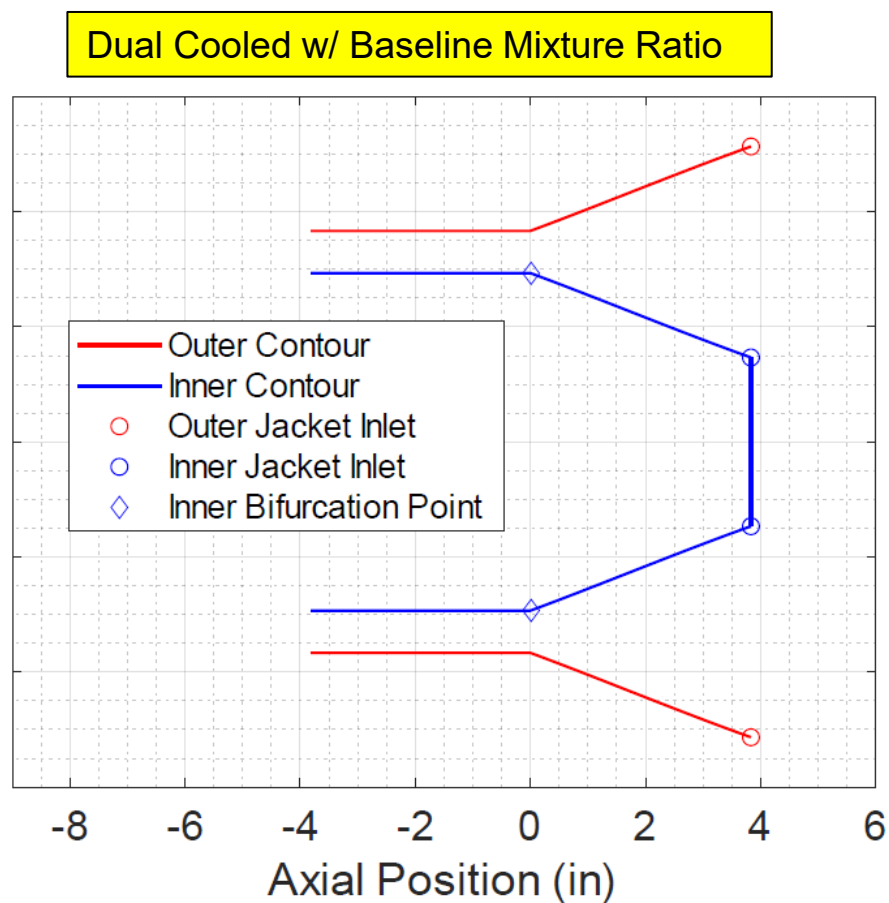
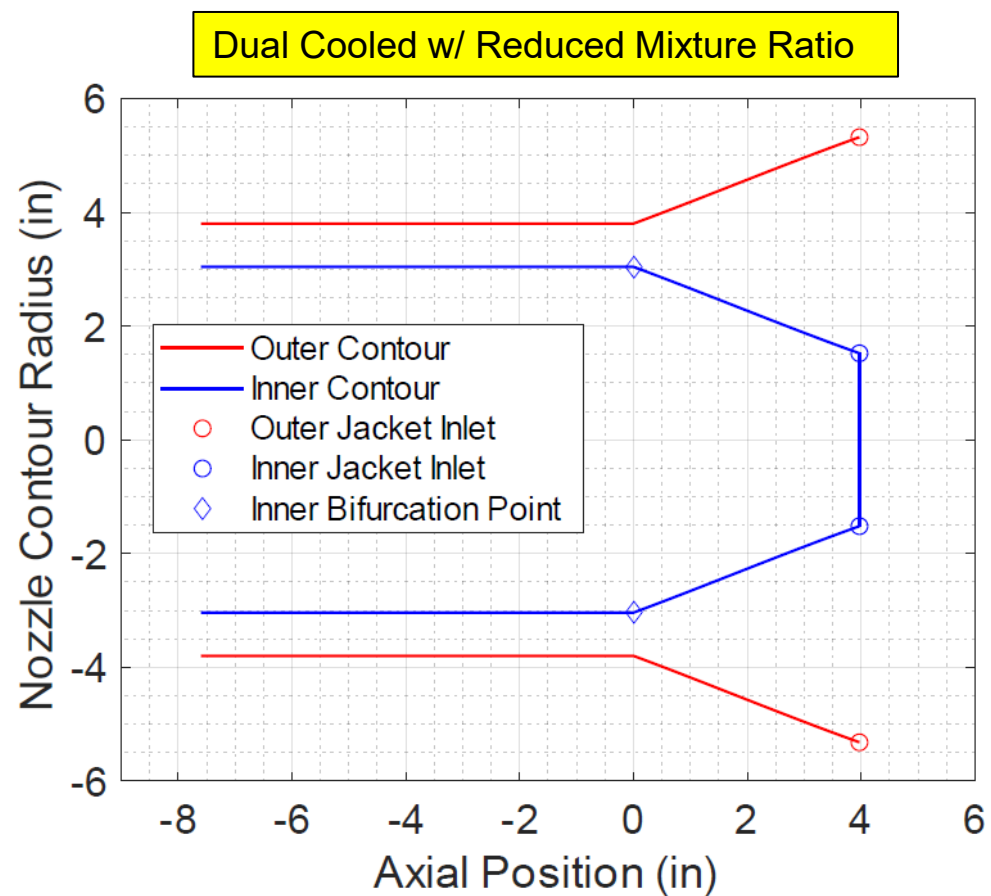




RDRE Geometry Used for MIURA-1 Trade Study

MIURA-1 Sounding Rocket RDRE Trade Study (4/6)

Chemical & Thermal Propulsion Systems





Summary of Calculated RDRE Performance

MIURA-1 Sounding Rocket RDRE Trade Study (5/6)

Chemical & Thermal Propulsion Systems

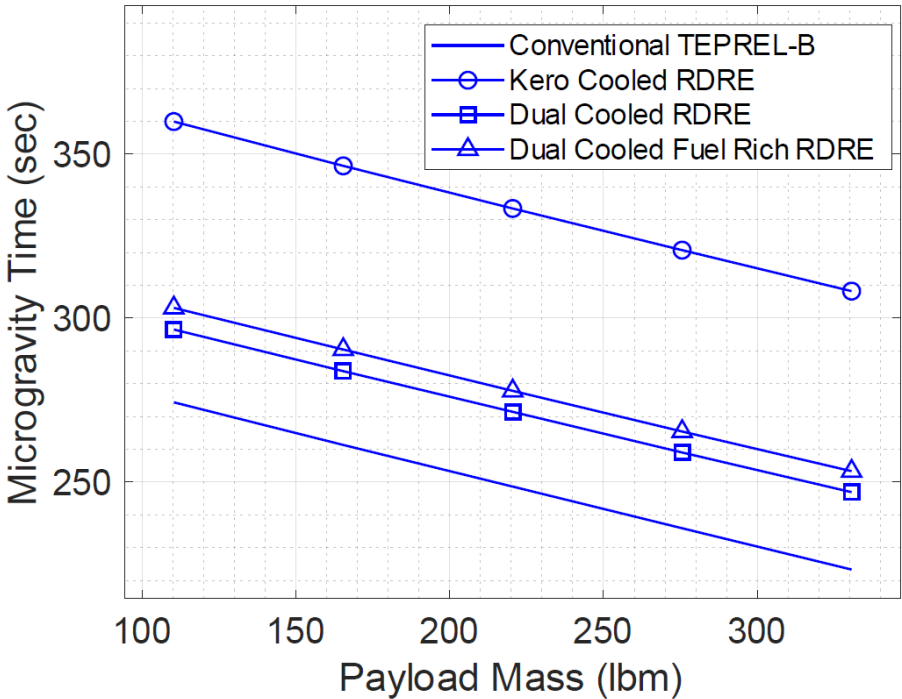
- ◆ **Kerosene-only cooling is limited by kerosene coking**
 - Requires short chamber & large channel to limit heat load
- ◆ **Dual cooling enables longer chambers, reduced jacket pressure drop**
- ◆ **Dual cooling requires high LOX jacket inlet pressures, to keep coolant from boiling in channels**
- ◆ **Even at reduced mixture ratio, RDRE still has higher specific impulse than conventional rocket**
 - 252 sec vs. 240 sec
 - Highlights benefit of using an RDRE for sea-level conditions

Engine Parameter	Kerosene Cooling Only		Dual Commodity Cooling		Dual Cooling w/ Reduced MR	
Initial Pressure	160 psia		220 psia		220 psia	
Mixture Ratio	2.35		2.35		1.90	
Specific Impulse (sea level)	270.7 sec		265.4 sec		252.4 sec	
Channel Width	0.97"		0.73"		0.76"	
Mean Chamber Diameter	5.50"		6.60"		6.84"	
Chamber Length	1.16"		3.80"		7.60"	
Wall Heat Loss (% Total Reaction Heat)	2.2%		6.5%		8.3%	
	Inner	Outer	Inner	Outer	Inner	Outer
Coolant	Kero	Kero	Kero	LOX	Kero	LOX
Jacket Inlet Pressure	780 psia	780 psia	358 psia	885 psia	306 psia	815 psia
Jacket ΔP	484 psid	550 psid	65 psid	147 psid	16 psid	80 psid



MIURA-1 RDRE Trade Results

- ◆ **Two trades were performed:**
 - Vehicle mass was held constant at 5,400 lbm (below)
 - Vehicle’s mission was held constant, delivering a 220 lbm payload to a 97.4 mile apogee (right)
- ◆ **Applied same methods used for L-MAV study**



Length & Mass Reductions	Conventional TEPREL-B	Kerosene Cooling Only	Dual Commodity Cooling	Dual Cooling w/ Reduced MR
Vehicle Length	500"	421"	466"	461"
Length Reduction	N/A	-16%	-7%	-8%
Vehicle Mass (excluding payload)	5,400 lbm	4,131 lbm	4,871 lbm	4,818 lbm
Mass Reduction	N/A	-24%	-10%	-11%

All RDRE configurations were predicted to out-perform the conventional system.



Conclusion

- ◆ **L-MAV trade study looked at an in-space RDRE application**
 - RDRE powered vehicle predicted to have 8% lower mass than conventionally powered vehicle
 - Suggests there is a use case for small, in-space RDREs in 300 to 1,500 lbf thrust class
 - Primary benefit identified: reduced propellant tank pressure & throat area for a given thrust level.

- ◆ **MIURA-1 trade study looked at a boost-phase regeneratively cooled RDRE application**
 - RDRE regenerative cooling jackets predicted to have high heat loads and high pressure drops compared to conventional engine, requiring higher propellant tank pressures
 - Even with impacts of regenerative cooling challenges, RDRE powered sounding rocket predicted to achieve 12% more microgravity time
 - For a reference mission, RDRE powered sounding rocket can be 8% shorter and 11% lighter
 - Suggests there is a use case for boost-phase RDREs in 6,800 lbf thrust class
 - Primary benefit identified: increased specific impulse from pressure-gain combustion

Thank You