

Parameterized Study of Heat Load Trends in a Subscale Rotating Detonation Rocket Engine

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NASA has developed a subscale rotating detonation rocket engine platform, enabling rapid parameterization of components and their associated performances. A major performance metric of interest for RDREs is the total heat absorbed at a given operating condition and wave mode operation. To investigate this, several sets of hardware were produced to have variation of the contraction ratio, injector geometry, and length. A wide range of total mass flow rates and mixture ratios were also explored using gaseous methane/oxygen. All hardware was produced using laser powder bed fusion GRCo-42, GRX-810, or C-103 alloys depending on the component cooling requirements. Outer and inner body hardware were made from GRCo-42 where heat fluxes were expected to be high and were water cooled through integrated coolant channels. Nozzles were made from C-103 which are radiatively cooled. Finally, the injectors were produced using GRCo-42 or GRX-810 as passive cooling via propellant injection has previously found to be sufficient given the small gap width of exposed injection surface. Total heat load and bulk heat flux measurements to the hot walls are reported. Trends in heat load and heat flux are shown with relation to parameters such as chamber pressure, area ratio, and wave mode. Heat loads between the inner and outer bodies and the chamber and shroud section are compared.

I. Nomenclature

AM	=	additive manufacturing
AR	=	area ratio
CAD	=	computer aided design
CP	=	constant pressure
CTAP	=	capillary tube attenuated pressure
GH ₂	=	gaseous hydrogen
HIP	=	hot isostatic pressing
L-PBF	=	laser powder bed fusion
GO _x	=	gaseous oxygen
GCH ₄	=	gaseous methane
L'	=	distance from injector face to throat proper.
MSFC	=	Marshall Space Flight Center

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MR	=	mixture ratio
NASA	=	National Aeronautics and Space Administration
Pc	=	chamber pressure
RDRE	=	rotating detonation rocket engine
ROV	=	remote operated valve
TCA	=	thrust chamber assembly

II. Introduction

NASA has developed and tested rotating detonation rocket engines (RDREs) in the 1000, 5K, and 10K lbf thrust classes. This has been the primary range of interest mainly due to cost effectiveness of hardware production and test position availability. A major goal of NASA is to ultimately assess scaling relations for RDREs so that any thrust class engine can be developed [1]. As combustors are demonstrated at higher thrust classes, confidence in scalability increases and uncertainty reduces. NASAs subscale RDRE is limited to the 1000 lbf class using GOX/GCH₄ and water-cooled hardware, shown in Figure 1. This subscale hardware design is referred to as “MARLEN”. First tested in summer 2023, the smaller thrust class proved beneficial for testing at a lower cost and faster schedule. It serves as an efficient way to investigate various design parameters, and then incorporate those findings into a full-scale design. This work built upon the MARLEN platform, increasing the thrust class from 200 lbf to 1000 lbf as well as increasing the coolant pressure to survive more extreme conditions. Hot fire testing was completed in summer 2024, achieving a maximum time-averaged chamber pressure of 744 psia. Images of both the MARLEN V1 hardware and the new MARLEN V3 hardware are shown below in Figure 1.

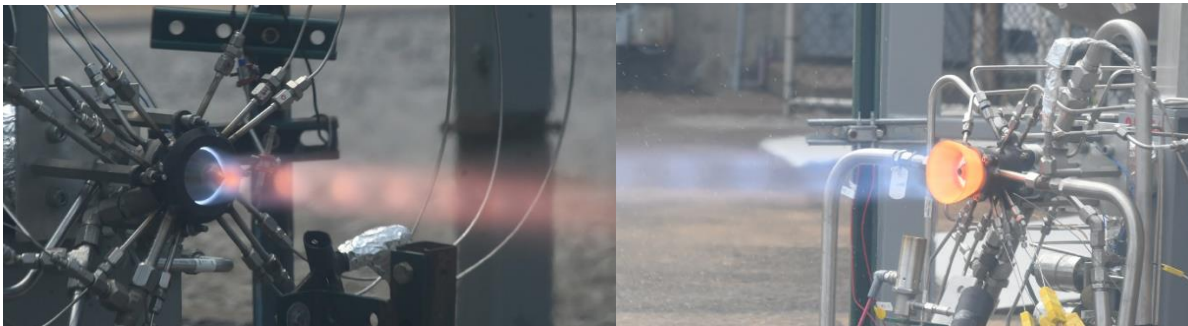


Figure 1. MARLEN V1 hot fire at the Test Stand 115 test position (left) and MARLEN V3 hot fire at the upgraded Test Cell 105 position (right).

A. Chamber and Injector Hardware

Several injectors, inner bodies, and outer bodies were manufactured and tested to evaluate a wide range of geometries. Some of the key parameters of interest for this study were combustor chamber length, L^* , contraction or subsonic area ratio (AR), and injector stiffness ratio. The stiffness ratio is the ratio of the fuel-side injector pressure drop to the oxidizer-side pressure drop. All chamber, injector, and nozzle hardware were printed using laser powder bed fusion (L-PBF). The inner and outer bodies were made from GRCo-42 (Cu-4Cr-2Nb) powder [2], the injectors were made with either GRCo-42 or GRX-810 powder, and the 3 radiatively cooled nozzles were made from C-103. GRX-810 excels at withstanding high temperatures and has been used for full-scale injectors, both RDRE and constant pressure (CP) [3]. A computer aided design (CAD) representation of the assembly is shown below in Figure 2, along with the finished assembly. To fit all the required fluid and instrumentation ports in such a small real-estate, all ports were made by welding flared tubes onto the AM part.

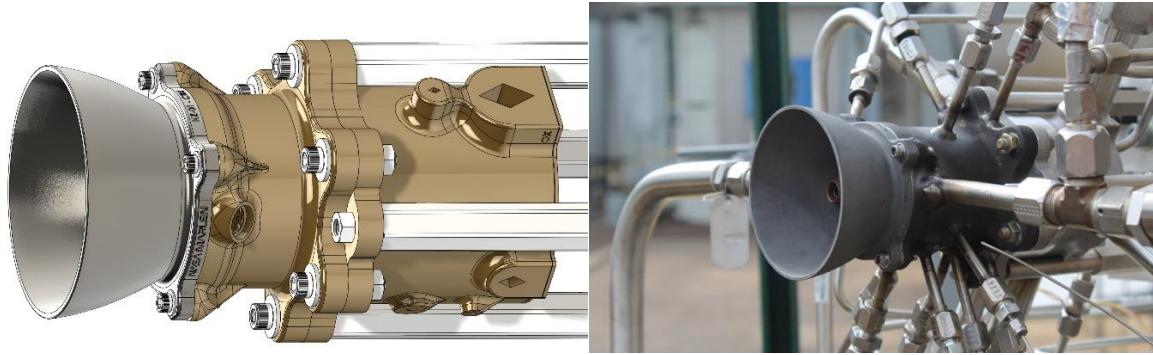


Figure 2. MARLEN V3 thrust chamber assembly (TCA), tubing not shown (left) and built up assembly (right).

A total of nine inner bodies were manufactured, each with a different L' and AR. Inner bodies featured lengths of 1.0, 1.5", 2.0", 2.5", and 3.0" and ARs of 1.0, 1.25, and 1.5. The subsonic AR was created by tapering the gap gradually to the desired diameter at the throat. Each inner body also had a 30° plug nozzle after the throat. Dimensions of each inner body is shown below in Table 1. Chamber surface area is called out in addition to total surface area as it has been observed that the heat flux to the plug nozzle is so low that the chamber surface area may be a better parameter for bulk heat flux calculations, which will be investigated in the following sections. All inner bodies had integrated coolant channels for water cooling. The inlet and exit water manifolds were located inside the injector to simplify the design and reduce the size of the inner bodies.

Table 1. Comparison of inner body throat areas and characteristic lengths.

Inner body	Actual Subsonic AR	Total Length (in)	Chamber Surface Area (in ²)	Total Surface Area (in ²)
1.0 L', 1.25 AR	1.19	2.14	8.13	11.98
1.5 L' 1.0 AR	1.00	2.56	10.15	14.26
1.5 L' 1.25 AR	1.23	2.64	10.55	14.43
1.5 L' 1.5 AR	1.47	2.69	10.92	15.72
2.0 L' 1.0 AR	1.01	3.06	12.43	16.52
2.0 L' 1.25 AR	1.25	3.14	12.95	16.78
2.0 L' 1.5 AR	1.48	3.19	13.17	16.86
2.5L', 1.25 AR	1.25	3.66	15.18	19.02
3.0 L' 1.0 AR	1.01	4.05	16.89	21.00

After printing, the inner and outer bodies undergo a hot isostatic pressing (HIP) process to improve ductility and remove any voids and residual stresses that may be present in the part [4]. Then they were machined, and the hot wall was polished prior to the ports and instrumentation tubing being welded on. After this, all parts were flow tested to find their channel resistance to improve cooling predictions prior to hot fire. Lastly, they were hydrostatic proof tested up to 1500 psi prior to testing to ensure all parts could withstand pressure and to check for any porosity in the hot walls.



Figure 3. MARLEN inner bodies before HIP (left) and after machining (center) and outer bodies after machining (right).

The GRX-810 parts did not undergo a HIP process. After printing the injectors were machined and then the stainless-steel flared tubes were welded on. The injectors were flowed with water to visualize the spray field and to check for flow uniformity and orifices that could be blocked with powder. The injectors were then flowed with nitrogen to calculate the flow area of the oxygen and fuel sides to compare to design values and use in hot fire test predictions. With additive manufacturing of small orifices, it is not uncommon to get actual flow areas that are less than the design due to factors such as shrinkage, surface roughness of the hole, and warping/non-circularity of the hole [5]. These variations from the design can greatly change the designed hot fire pressure drop and available pressure budget.

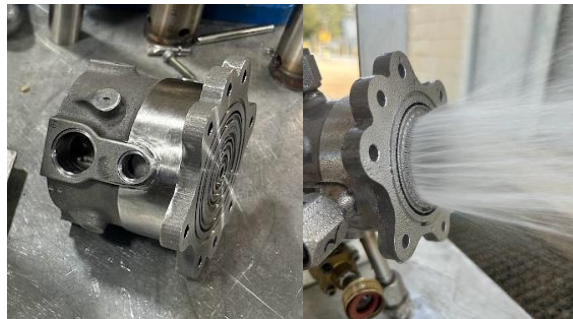


Figure 4. GRX-810 injector after machining and during flow testing.

The C-103 nozzles were printed using powder bed fusion and then polished using chemical-mechanical polishing. These nozzles all have the same exit diameter but vary length, from 1.4", 2.0", to 3.0" as well as a nozzle exit angle. The shortest nozzle has an exit angle of 15 degrees and the two longer nozzles have an exit angle of 7 degrees. A thermal coating was then applied to them and lastly, they were machined at the forward end sealing surface. A graphite gasket sits in between the nozzle and outer body to contain chamber pressure as well as reduce the heat load into outer body from the nozzle.



Figure 5. C-103 radiatively cooled nozzles post print (left) and post processed (right).

B. Igniter Hardware

A simple augmented spark igniter was developed to help ignite the main chamber using fittings and laser drilled micro-orifices. A small flowrate (less than 0.01 lbm/s) was flown through the igniter at oxygen-rich conditions where they were ignited by the spark plug and then flown through a tube that connected to the outer body. The igniter combustion products then passed through the ribs of the coolant channels and were injected into the annulus. The igniter assembly and injection scheme is shown below in Figure 6. Ultimately it was found that with these flowrates the combustion products were cooling down too much to reliably ignite as they passed in between the coolant channels. Instead, a hydrogen exhaust flare was used to reliably ignite via backlighting. In this setup, the fuel leg was filled with hydrogen to initially ignite before chasing with methane, a method also used in NASA's full scale testing [6]. Reliable internal ignition without hydrogen remains a goal for future RDRE designs and test campaigns.

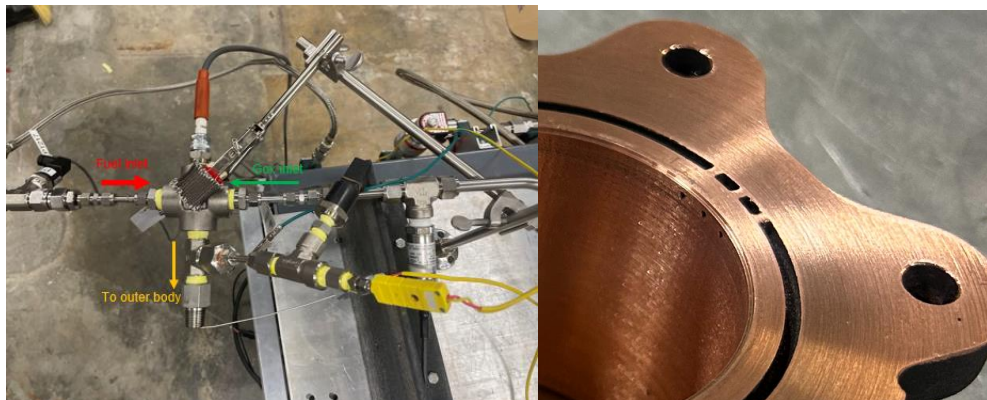


Figure 6. Igniter assembly (left) and outer body igniter products orifices (right).

III. Experimental Design

This test program took place at NASA's Test Cell 105 at Marshall's Space Flight Center (MSFC). This position was capable of supplying gaseous oxygen up to ~2k psi and was upgraded for this program to feed high-pressure gaseous methane up to 2k psi as well. It was also upgraded to have a high-pressure water supply, capable of 1400 psi tank pressure and flow rates up to 10 lbm/s. Both of the main propellant lines had GN2 purges that can be supplied up to 1500 psi. Additionally, the igniter feed lines tapped off the main lines with their own remote operated valve (ROV) to control the igniter flows. A schematic of the test facility is shown below in Figure 7.

Also shown in the schematic is instrumentation for the TCA. Gox and fuel plenum pressure were measured using a singular pressure transducer for each, while temperature of the incoming propellants were taken upstream in the supply line. The chamber had 6 chamber pressure measurements, spread out over the axial length of the outer body. In addition, the outer body also had 5 thermocouple ports to measure the temperature of the water in the coolant channels, but those ended up not giving accurate data presumably due to the probe touching the metal of the cold wall. Two microphones were used in addition to two high speed cameras, one positioned upstream and the second positioned at a side angle. These were primarily used to measure the number of waves, although the angle of the downstream camera made it difficult to visualize the whole annulus and accurately count the number of waves when several waves (5+) were present. A triaxial accelerometer was mounted to the hardware as well but that data is not evaluated in this work.

Additionally, regardless of inner body length most inner bodies showed almost no heat staining in the first inch and consistent staining from about 1" downstream the injector face all the way to the throat. This is an indication that the heat flux downstream of the first inch just continues when the annulus is made longer.



Figure 9. Heat staining on the inner body inside the annulus for the 1.5", 2", and 2.5" L' inner bodies.

The radiatively cooled nozzles saw 6 starts and a single test duration as long as 16.82 seconds (the 2" nozzle). All of them successfully survived a single start for a full duration, but all the three nozzles failed on their second start although the second start was at a much higher chamber pressure and flow rate condition than the first. The 3" nozzle's second start was cut short in duration when ablation of the nozzle started to occur, and thus remained intact except for erosion in the throat region, as seen below. The other two nozzles failed much more catastrophically and lost significant pieces of the nozzle. In addition to pushing the nozzles way past their design point, the flow rates also exceeded the injector design 1.5x-2x, which lead to propellant maldistribution that contributed to the failure. As shown below, all three nozzles started to erode and fail in the 11 o'clock position, which is 180 degrees from the GOX inlet and signifies a locally high MR region. Additionally, a small increase in heat load to the outer body was observed when testing with nozzles so those data are not included in the heat load trends below. Overall, the nozzles were extremely successful when tested in their design condition. Future programs will test more radiatively cooled nozzle extensions with different contour geometries.



Figure 10. Radiatively cooled nozzle failure modes of 1.4" (left), 2" (center), and 3" (right).

Over the course of the 39 tests, the hardware saw a wide range of chamber pressure and mixture ratio conditions. The mixture ratio was baselined at 3.5 but saw excursions anywhere from a 2.9-4.3. Chamber pressure was varied anywhere from ~160-700 psia, with most tests being between ~200-400 psia. In addition to multiple operating conditions, this campaign tested several inner body geometries. Figure 11 below shows both the map of conditions as well as what chamber pressures were tested with each inner body length. For most tests, with the exception of the high-pressure ones, a low, medium, and high flow rate were tested on the various inner bodies. The various contraction ratios from 1.0-1.5 allowed for a range of Pcs at the same flow rates, as well as the same Pcs at different flow rates. This flexibility is extremely useful in isolating driving performance parameters while keeping others constant.

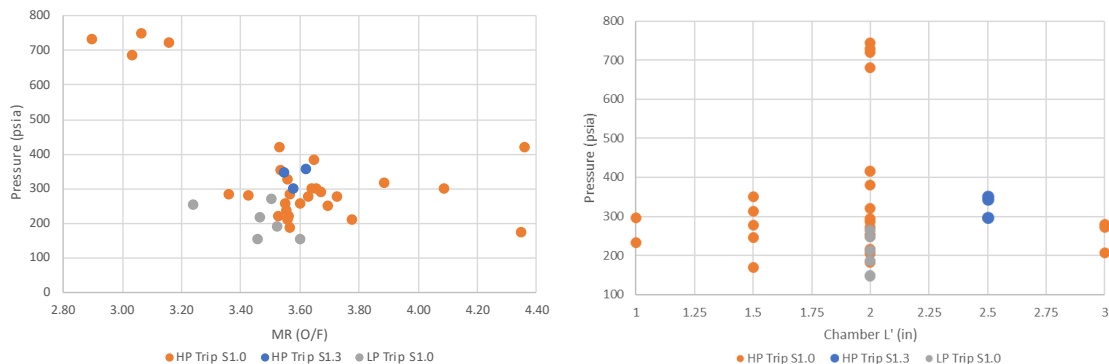


Figure 11. Map of operating conditions (left) and inner bodies tested (right).

B. Heat Load and Bulk Heat Flux Data

For all tests the heat load data was collected by measuring the change in enthalpy from a pressure transducer and thermocouple at the inlet and exit of both the inner and outer body. The mass flow through each body was measured with orifices that were characterized prior to testing to determine their discharge coefficient. The bulk heat flux was found by dividing the heat load by the hot wall surface area of each component. Multiple variables were compared to see their impact on heat load, such as chamber length, contraction area ratio, and shroud length, and are presented below. The differences in heat load between the inner and outer body are also compared.

Figure 12 shows the heat load and heat fluxes for each of the different chamber lengths tested. For each data set, a power trendline was used to relate the heat load to chamber pressure (Pc). The heat load plot is as expected; the heat load increases with chamber length since there is more surface area to cool. The heat flux graph is more interesting, as even after normalizing with respect to surface area there is still a ~40% difference in bulk heat flux between the 1" inner body and 3" inner body. Multiple factors could be influencing this, one being potential incomplete combustion in the 1" inner body lowering the bulk heat release of the detonation waves. Additionally, it has been observed in other RDRE testing that the plug nozzle sees significantly less heat flux than the annulus, thus the ratio of annulus surface area to plug nozzle surface area for a given inner body could be staggering them such that the bulk heat flux is higher for the longer L'. The estimated portion of the heat load going to the plug nozzle will be investigated below.

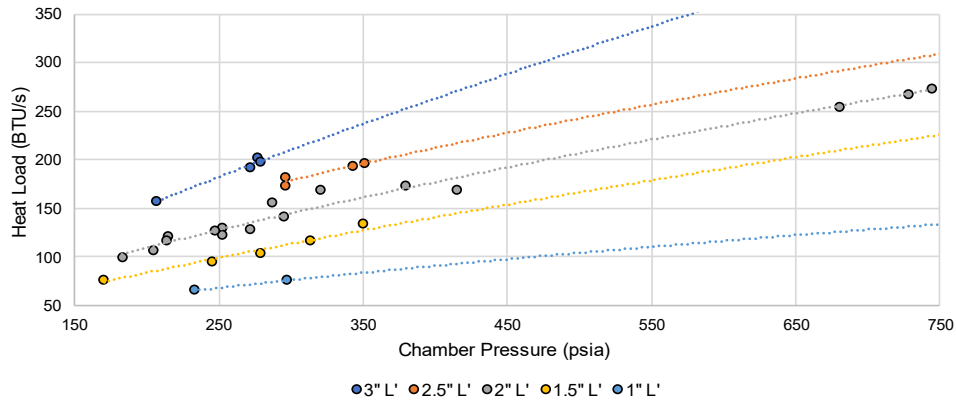
If the bulk heat flux is calculated with only the chamber surface area up to the throat, the spread of heat flux becomes much narrower as seen in the lower right plot of Figure 12. These values are likely much closer to what the annulus chamber heat fluxes are. These graphs show that for increasing chamber length, heat load increases but bulk heat flux remains about the same (for the same Pc). In addition to the heat staining pictures above, this also indicates that the heat flux in the annulus does not change with longer lengths but just "continues" until the throat. Additionally, another significant takeaway from the below heat load and heat flux graphs is that for the same injector and chamber configuration, there is no significant effect from mixture ratio (MR). MRs anywhere from 2.9 to 4.3 were tested and yet all curves are primarily dependent on chamber pressure.

The trendline equations for the inner body are shown in Table 2. The heat loads of CP rocket engines usually scale well to the 0.80 power in relation to Pc and to the 0.9 power with subsonic AR, as described in the Bartz heat transfer correlation. However, the scaling relations below don't agree with that and range from ~0.59-0.78. These scaling discrepancies are likely a result of the heat release of the detonation wave not scaling with Bartz and have been seen in full scale data as well. R² values are included below to give the reader an idea of how well the trendline fits the data points, but due to limited tests some inner bodies such as the 1.0" L' only have two data points and are inherently less accurate than the data sets with more points.

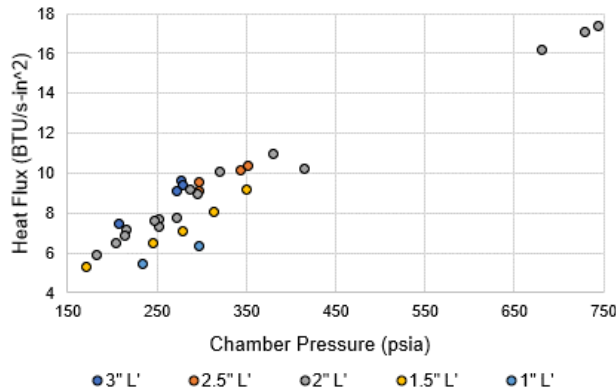
Table 2. Inner body heat load power trend equations.

Inner Body L'	Heat Load Power Trendline	R ² Value
3.0"	$y = 2.4539x^{0.7802}$	0.9779
2.5"	$y = 5.9139x^{0.5975}$	0.9012
2.0"	$y = 2.7657x^{0.694}$	0.9833
1.5"	$y = 1.5685x^{0.7505}$	0.9651
1.0"	$y = 2.2985x^{0.6136}$	1.0000

Inner Body Heat Loads for Various Lengths



Inner Body Heat Flux with Total SA



Inner Body Heat Flux with Chamber SA

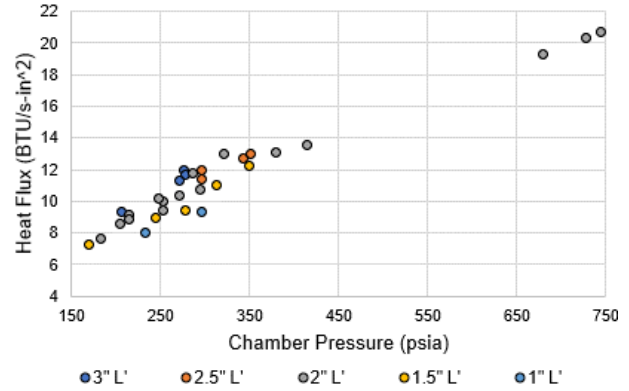


Figure 12. Heat load (top) and bulk heat flux (bottom) vs. Pc for different inner body chamber lengths.

For the same tests as above, the outer body heat loads and bulk heat flux were compared in a similar way to the inner body. Figure 13 below shows heat load and bulk heat flux measured against chamber pressure, with power function trendlines going through the data points. The data points are organized by chamber L' along with nozzle shroud length, and each adds up to either 2" or 3" depending on which outer body was being used. Unlike the inner bodies, these show a distinct difference between the 3" outer body and the 2" outer body. The 3" outer body increases heat load at a rate much faster than the 2" length outer body. When normalizing for differences in surface area and calculating bulk heat flux, most of the data points do collapse into a band of about +/- 15% except for the 1" inner body.

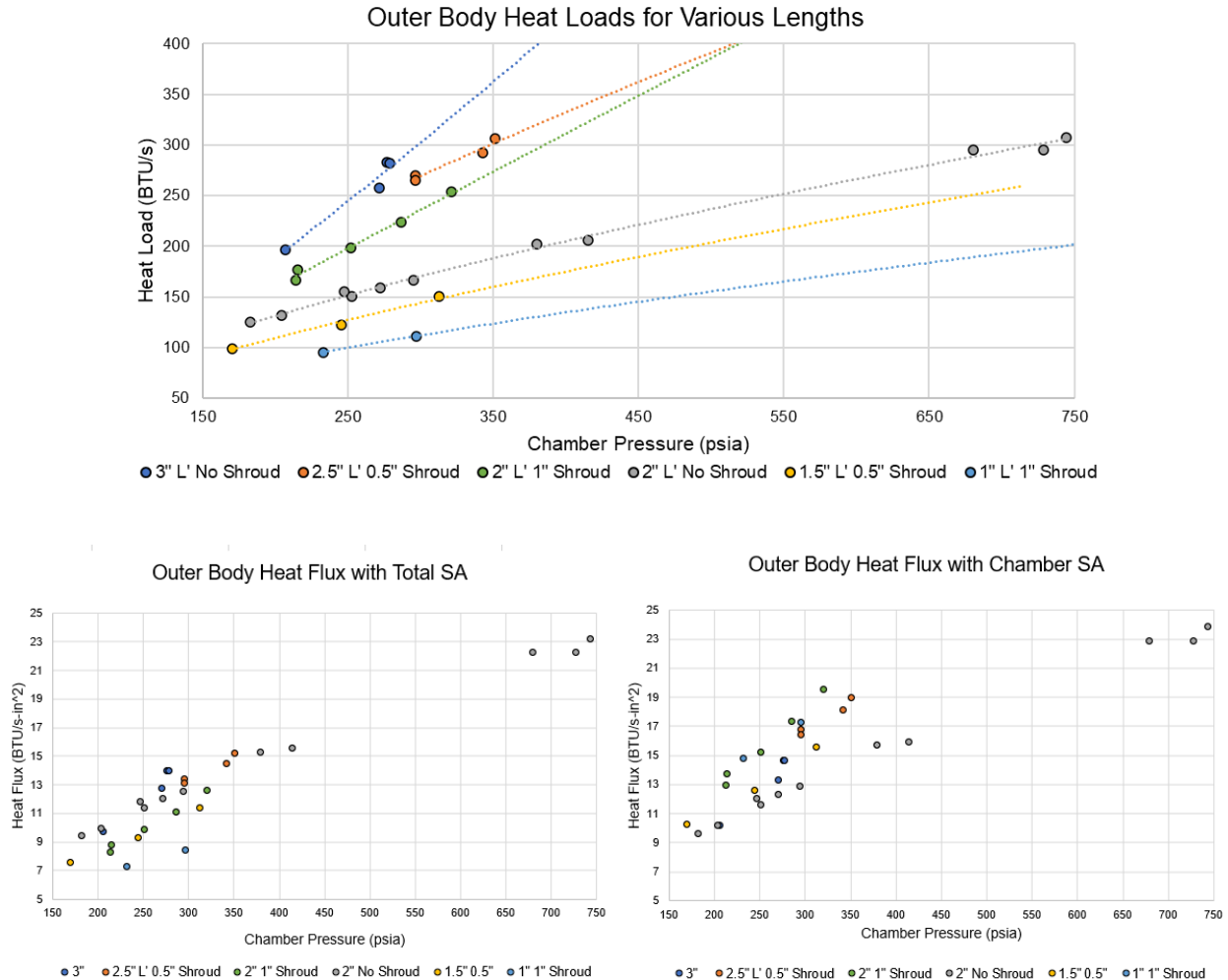


Figure 13. Outer body heat loads for various lengths (top) and heat flux calculated with total and chamber surface area (bottom).

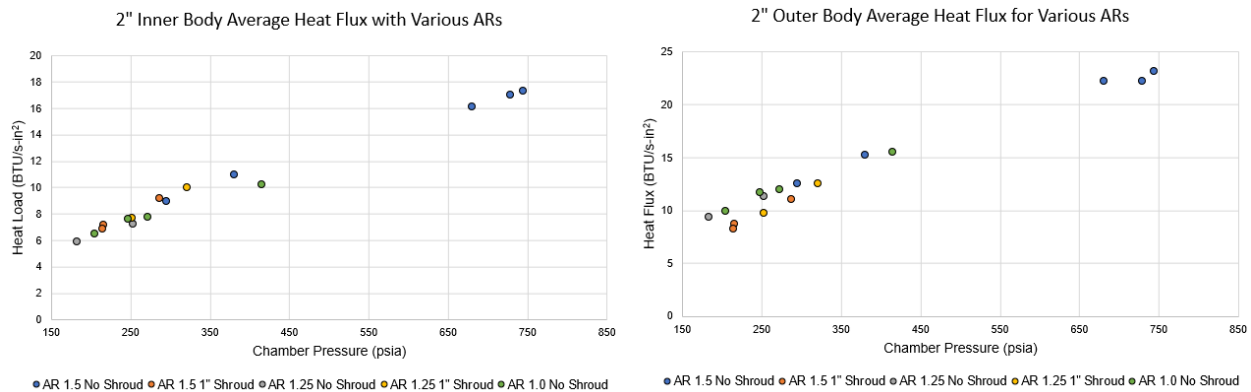
Just as with the inner bodies, the chamber surface area was also used to calculate the bulk heat flux to see if the data would collapse and see the influence of the nozzle heat flux. This spread out the data more, but roughly collapsed the data based on shroud length. With this method, the 1" shrouds appeared to have the highest bulk heat flux, and then the 0.5", and lastly the no shrouds. This indicates that the heat load to the shroud of the outer body plays a larger role than to the inner body. When comparing the "2" L' no shroud" to "2" L' 1" shroud", there is about an additional 30% increase in heat load to the outer body. With the same comparison for the inner body, there is only a 10% increase in heat load. This different in heat addition is not entirely unsurprising, however, as in all inner body cases a plug nozzle is present regardless of an external shroud, so even in the "no shroud" cases the hot gases are expanding between the plug nozzle and ambient pressure and imparting some heat load to the nozzle. If an inner body with no plug nozzle was tested, it would be expected to be more similar to the 30% difference the outer body saw. Lastly, the power trendlines for the heat load are shown in Table 3.

Compared to the inner body, the outer body saw higher heat loads because of more surface area, but to compare heat fluxes it is most accurate to compare tests with a 1" shroud. In these configurations, the plug nozzle is almost fully shrouded and thus both the inner and outer body have a similar ratio of chamber to nozzle surface area. When doing this, both components have roughly the same bulk heat flux when calculated with total surface area. In some cases, the outer body appears to have slightly higher bulk heat flux, but only around 1-2 BTU/s-in².

Table 3. Outer body heat load power trendline equations.

Inner Body L'	Heat Load Power Trendline	R ² Value
3" L' No Shroud	$y = 0.3851x^{1.1688}$	0.9553
2.5" L' 0.5" Shroud	$y = 4.163x^{0.7310}$	0.9543
2" L' 1" Shroud	$y = 0.9658x^{0.9639}$	0.9898
2" L' No Shroud	$y = 4.3261x^{0.6440}$	0.9966
1.5" L' 0.5" Shroud	$y = 3.0434x^{0.6763}$	0.9860
1" L' 1" Shroud	$y = 2.9008x^{0.6406}$	1.0000

By testing inner bodies with the same length and various contraction area ratios, the influence of AR on heat flux was examined. The results are shown in Figure 14, and it becomes immediately apparent that the primary driver for heat flux is chamber pressure. This is true for both the inner and outer body. Since this is only presenting bulk heat flux, there could still be locally slight increases in heat fluxes in the contraction region, but this shows that it is essentially negligible compared to the magnitude of the heat fluxes being measured. Additionally, this data only looked at slight contraction ARs from 1.0-1.5, and thus the results of a much higher contraction outside this region may be different.

**Figure 14. Heat flux for various ARs for inner body (left) and outer body (right).**

All the above heat load data was for the same injector, which was an early iteration of the subscale hardware and ended up having poor performance compared to other designs evaluated since then. Additionally, it was found that for a different injector the heat load and bulk heat flux trends can be significantly different, so in practice general relations will need to be specific to an injector design. More testing is needed to determine what injector design parameters contribute to these differences in heat load trends. It is not advised that these data are used explicitly for design of future RDREs.

C. Wave Activity

This series of testing saw a wide range of wave modes with very little trends on what was causing the number of waves. Figure 15 shows some of the wave modes the hardware saw such as a 2 wave co-rotating mode, 2 wave counter rotating (1x1), and a 5 wave co rotating mode. Majority of the tests saw 5 waves co-rotating in the clockwise direction, although random tests would show counterclockwise or counter-rotating activity. Other wave modes not shown were a 1 wave, 4 wave counter rotating (2x2) and 6 wave mode. For each test, microphones were used to correlate wave number, as done in full scale testing [1]. As shown below, it was observed during testing that the more waves there were, the dimmer they were, and the 1 and 2 wave mode showed much brighter luminosity.

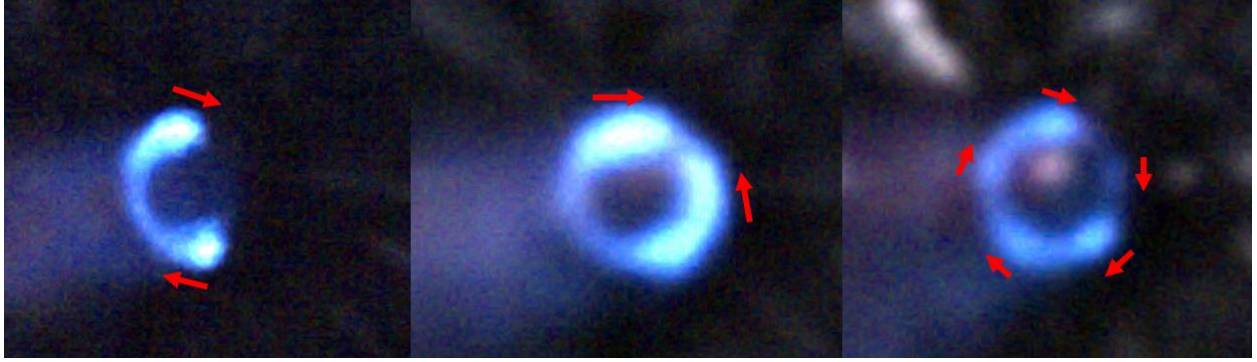


Figure 15. Example wave modes from subscale testing: 2 wave co-rotating, 2 wave counter rotating, and 5 wave co-rotating.

There were no observable trends to wave number with chamber pressure, AR, chamber length, mass flux, or mixture ratio. The chamber pressure is compared to wave number below in Figure 16, with the different inner body lengths shown. As shown by the pictures of the radiatively cooled nozzles, the chamber was likely seeing maldistribution at higher flowrates which also could have affect the wave activity. While there is no trend for estimating wave number, an important take-away of this was that wave number did not impact heat loads or heat flux that the hardware saw. For the same given P_c , the hardware will see the same heat load whether it's experiencing a 1 wave or 5 wave mode. This is good from a design standpoint to not need to target a particular wave number. Although, the one wave mode tests did show higher dynamic loading in the thrust trace as shown prior in other subscale and full-scale testing and thus should be avoided.

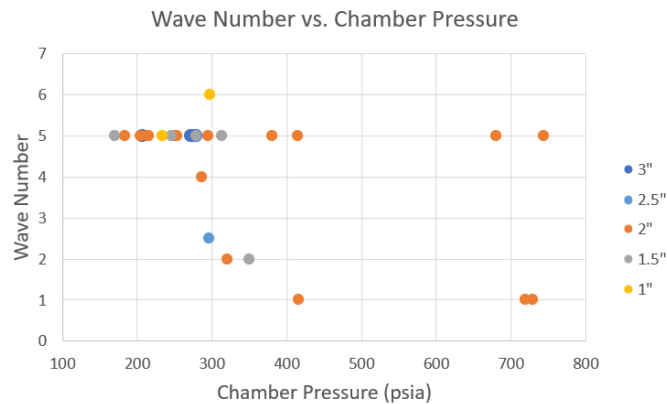


Figure 16. Wave number vs P_c for all tests.

V. Summary and Conclusions

This test campaign was a continuation of NASA's subscale RDRE development to study various parameters of RDREs quickly and cost-effectively. With the buildup of a new test position, higher flowrates of both propellant and water coolant were able to be achieved. This campaign's main goals were to directly compare how various chamber lengths (L') and subsonic area ratios impacted the performance of RDREs. Nine different inner bodies, two different inner bodies, and three radiatively cooled nozzle extensions were tested at a wide range of P_c s and MR. This hardware saw chamber pressures as high as 744 psia with CTAP measurements. The heat loads and bulk heat fluxes for each configuration were measured and compared. The data showed that for the same injector, factors such as mixture ratio and subsonic AR (in the range of 1.0-1.5) effectively have no impact on heat loads and fluxes so long that chamber pressure is constant. Additionally, increasing length increased the total heat load but bulk heat flux was roughly the same, indicating that the heat flux doesn't change but is extended at the same magnitude. This is supported by the heat staining and wall streaking of the inner bodies for various lengths. Lastly, for the same injector, chamber pressure seems to be the largest influence on heat loads, but as shown previously it doesn't scale well with Bartz heat transfer correlations so new scaling relations will be investigated.

Future Work

Findings from this study as well as the calorimeter study are being incorporated into future full-scale hardware designs to evaluate the scaling relations between the two. Several unknowns are still present, and future subscale tests will look at evaluating the effects of gap width, wall contours, various injector designs, and propellant temperature on combustion performance. These data will feed into iterations on the full-scale design, with the goal of being tested as a full RDRE engine system.

Acknowledgments

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