NASA Plum Brook Station In-Space Propulsion Facility Test Stand Characterization Hot Fire Test

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A test facility modification to enable small scale altitude propulsion testing at the NASA Glenn Research Center's In-Space Propulsion (ISP) Facility was verified with a hot fire test campaign. As the facility's primary steam supply system undergoes refurbishment, the alternate facility configuration, known as the "vacuum accumulator" mode, would enable rocket engine testing up to 10,000 lbf thrust. The NASA Johnson Space Center developed the vehicle for the verification test campaign: the Integrated Cryogenic Propulsion Test Article (ICPTA). Constructed primarily from assets of the former Morpheus Project, the ICPTA provided an integrated liquid oxygen (LOX) / liquid methane (LCH$_4$) propulsion system including a 2,800 lbf thrust main engine. The ISP Facility's vacuum accumulator configuration leveraged the large test volume of the facility and a diffuser insert to maintain altitude conditions. During hot fire, the ICPTA main engine "started" the diffuser insert constructed for the test campaign. As a result, the test chamber upstream of the diffuser insert remained at altitude conditions throughout the hot fire. Upon engine shut down, a backflow deflector mitigated blow back into the test chamber by restricting the mass flow and redirecting it away from the test article. The test campaign successfully characterized the performance of the vacuum accumulator configuration. In addition, it provided an opportunity to collect data for an integrated LOX / LCH$_4$ propulsion system in an altitude and thermal vacuum environment.

Nomenclature

COPV = Composite Overwrap Pressure Vessel
ICPTA = Integrated Cryogenic Propulsion Test Article
ISP = In-Space Propulsion
gpm = Gallons per Minute
JSC = NASA Johnson Space Center
K = Kelvin
L/D = Ratio of Diffuser Length over Diffuser Diameter
lbf = Pound Force
lbf-vac = Pound Force Vacuum
LCH$_4$ = Liquid Methane
LH$_2$ = Liquid Hydrogen
LN$_2$ = Liquid Nitrogen
LOX = Liquid Oxygen
psig = Pounds per Square Inch Gauge
RCS = Reaction Control System
Sec = Seconds

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I. Introduction

NASA actively pursues efforts to modernize its facilities and reduce unneeded infrastructure and underutilized assets[1-2]. In an environment of “right sizing,” test facilities must maximize their flexibility in supporting the Agency’s mission. The In-Space Propulsion (ISP) Facility, formerly known as the Spacecraft Propulsion Research Facility (B-2), was designed to test large scale upper stage vehicles in a simulated space environment[3-5]. In addition to rocket engine testing, the facility has fostered many thermal vacuum space environment tests[6-15]. These tests include hardware such as the Mars Pathfinder inflatable airbag landing system, a variety of cosmic ray detection instruments, and electric propulsion experiments.

For propulsion testing, the ISP facility traditionally requires the use of its steam system and main steam ejectors to provide simulated altitude conditions. If those systems are being refurbished or are otherwise unavailable, then the facility cannot accommodate propulsion tests. An alternative facility configuration seeks to enable small scale altitude propulsion testing without having access to the facility’s full exhaust capability. This alternative operating configuration, referred to as the “vacuum accumulator” mode, utilizes a rental boiler to provide steam in lieu of a dedicated onsite steam system. Furthermore, the facility’s auxiliary steam ejectors are used to maintain altitude instead of the main steam ejectors. The auxiliary steam ejectors would typically not remove enough rocket exhaust to maintain altitude conditions on their own. Combined with a diffuser insert, the large volume of the facility is exploited to provide suitable test durations.

In 2017, a facility characterization hot fire test campaign was conducted at the ISP Facility to satisfy two objectives. The first objective was to characterize the performance of the facility’s vacuum accumulator configuration. In collaboration with the NASA Johnson Space Center (JSC), the Integrated Cryogenic Propulsion Test Article (ICPTA) provided a rocket exhaust load for this facility characterization. Based on hardware assets from the Morpheus Project[16-19], the ICPTA delivered an integrated propulsion system that included a main rocket engine, reaction control engines, and propellant tankage. The second objective was to collect altitude and thermal vacuum environment data for the ICPTA test bed to benefit similar, future lander programs. Engine propulsion data was collected at ambient temperature as well as cryogenic temperature conditions[20-22].

The facility characterization test campaign also served as the first altitude propulsion test at the ISP Facility since the Delta III test campaign[5]. To prepare for the test, the facility’s liquid oxygen system (LOX) was refurbished and brought back online. Furthermore, the liquid hydrogen system (LH_2) was converted to supply liquid methane (LCH_4) fuel for the test.

In the context of limited funding for NASA’s facilities, the vacuum accumulator configuration provides propulsion test capability to the ISP Facility when it would otherwise not be available. The configuration contributes to near term cost savings by renting equipment in place of capital improvements. Currently, the steam supply system that supports operation of the main steam ejectors is undergoing refurbishment. During this activity, the vacuum accumulator configuration represents a flexibile alternative means for the facility to support the Agency’s mission.

II. ISP Facility and ICPTA Hardware

A. ISP Facility Baseline

The In-Space Propulsion Facility’s primary purpose is to test upper stage vehicles and their component systems in a space environment. The facility provides this capability with two baseline modes of operation. The first mode is thermal vacuum simulation[3]. In this mode, oil diffusion pumps subject a test article inside of the facility’s test chamber to absolute pressures as low as 1×10^{-6} Torr. In addition, the cold thermal environment of space is simulated with a liquid nitrogen (LN_2) heat sink that surrounds the inner surfaces of the chamber. The range of simulated temperatures extends to as low as -320°F (77 K). With the heat sink active, the lowest possible absolute pressure in the test chamber becomes 5×10^{-8} Torr. Lastly, quartz lamps approximate the radiative heating of the sun in low earth orbit and can be operated with or without the LN_2 heat sink.

The second mode of operation for the facility is altitude propulsion testing. In this mode, altitude conditions up to 100,000 feet (8 Torr) are maintained in the facility’s test chamber during a rocket engine hot fire test. Rocket engines producing up to 100,000 lbf thrust may be run for durations up to 270 seconds with the LOX/LH_2 propellant combination. Rocket engines producing less thrust may be run for longer durations. Figure 1 and Figure 2 depict

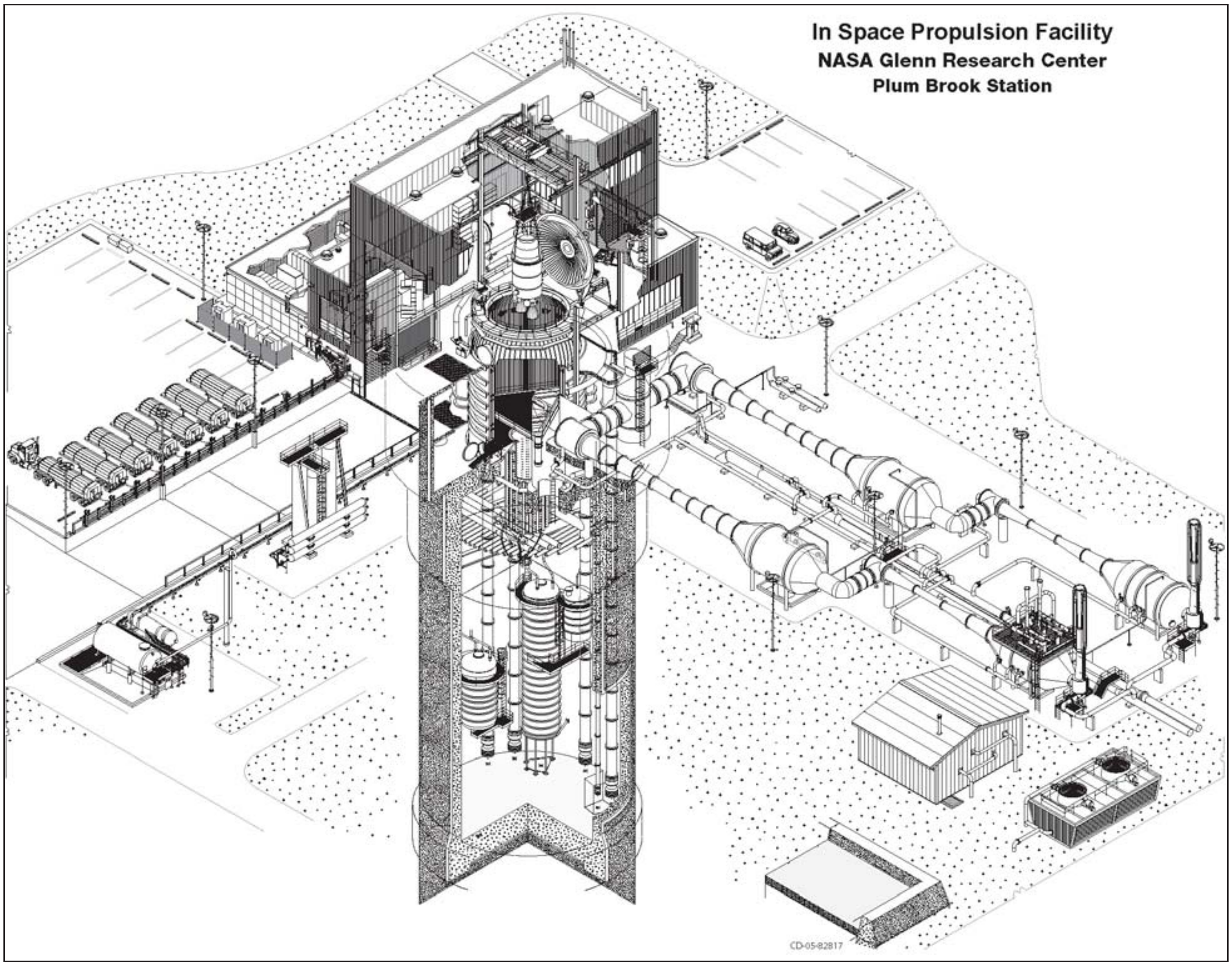

Figure 1. A cutaway view of the In-Space Propulsion Facility. In the center of the test chamber, the facility's diffuser provides the interface between the test chamber and the spray chamber. The steam ejectors are located outside of the test building in the yard on the right.

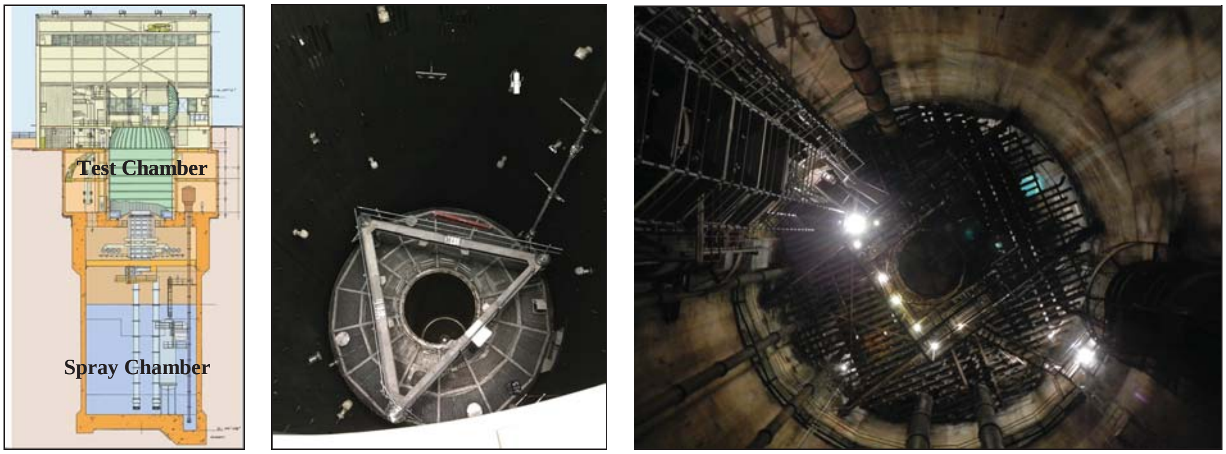

Figure 2. (Left) Illustration side view of the ISP Facility. (Middle) View from the top of the test chamber looking to the bottom. The diffuser and its isolation valve may be seen in the middle. (Right) View from the bottom of the empty spray chamber looking up. The diffuser's isolation valve may been seen in the middle.

general views of the facility. The depicted facility systems include the facility's diffuser, spray chamber, and steam ejectors. By conditioning and removing a rocket's exhaust during propulsion tests, the combination of these facility systems maintain altitude conditions. The path of a rocket's exhaust originates in the test chamber. Then, it proceeds through the diffuser into the spray chamber and finally exits the facility via the steam ejectors.

In terms of a baseline altitude propulsion test, the first step of a rocket exhaust's excursion through the facility is the test chamber. The test chamber's dimensions afford enough space to accommodate a full scale upper stage vehicle. Its nominal test envelope encloses 22 feet diameter by 52 feet maximum vertical clearance. Before or after a propulsion test, the test article may be exposed to thermal vacuum conditions in the test chamber. These conditions represent the environment of loitering in low earth orbit. Eventually, thermal equilibrium between the facility and test article will be established. Subsequent propulsion testing would then emulate restarting an engine after loitering in space. At the end of the hot fire propulsion test, another simulated space loiter sequence may be repeated.

The next step in the rocket exhaust's excursion is the facility's diffuser. Measuring 11 feet diameter and 37 feet long, the ISP Facility's baseline diffuser maintains altitude conditions during a hot fire propulsion test. A rocket engine's exhaust forms a system of shocks that isolates the test chamber from the downstream spray chamber pressure. Upon the conclusion of a test, both of the chamber pressures equalize.

At the end of the diffuser is a vacuum isolation valve. This valve serves as the vacuum boundary between the test chamber and the spray chamber, shown in Figure 2. When the valve is closed, thermal vacuum conditions as low as $5x10^{-8}$ Torr are possible in the test chamber. When the valve is open, only altitude conditions as low as 8 Torr are possible in the facility.

Beyond the diffuser, the rocket exhaust enters the spray chamber. The spray chamber's 67 feet diameter and 120 feet depth hold up to 1.75 million gallons of water, whichs fills the chamber roughly halfway. Four 2,000 horsepower vertical turbine pumps move the water up to an array of spray nozzles at a rate of 56,000 gpm each. The spray nozzles then evenly distribute the water to cool the rocket exhaust. Water vapor in the exhaust is cooled to the extent that it condenses. The condensed portion of the exhaust then reduces the overall demand on the steam ejectors. Since the majority of the exhaust from LOX/LH$_2$ rocket engines is steam, a large portion of the exhaust is condensed. Therefore, the LOX/LH$_2$ propellant combination is ideal for the facility. Rocket engines with other propellant combinations are still acceptable to test. Their greater fraction of noncondensable exhaust species, however, places a bigger burden on the steam ejectors. So, compared to the facility's LOX/LH$_2$ rocket capability, rockets with other propellant combinations would need to have lower thrust levels.

In the ceiling of the spray chamber, the exhaust travels through a 12 feet diameter duct to its final destination: the steam ejectors. The main steam ejectors consist of two identical trains of three-stage ejectors, Figure 3. Initially, exhaust goes through the first steam ejector stage. It then encounters the first intercondenser. Intercondensers are chambers that house an array of water spray nozzles. These nozzles cool and condense the steam from the ejectors as well as any remaining steam in the exhaust. To supply water to the cooling nozzle arrays, three 1,000 horsepower vertical turbine pumps deliver water from the spray chamber to the intercondensers at a rate of 14,000 gpm per pump. Excess cooling water in the intercondensers is collected and returned to the spray chamber to cool the backside of the diffuser, forming a closed loop. After the first intercondenser, the exhaust proceeds to the second stage steam ejector and then the second intercondenser. At this point, the exhaust is mostly noncondensable gas.

Figure 3. ISP Facility steam ejectors. (Left) Main steam ejectors used in baseline altitude propulsion testing. Typical steam ejector stage and intercondenser highlighted. (Right) Auxiliary steam ejectors shown exhausting steam on top of the east second stage intercondenser.

The final third stage steam ejector then exhausts vertically into the atmosphere. The main steam ejectors remove enough of the noncondensed exhaust to maintain pressure conditions to keep the baseline diffuser "started."

A set of auxiliary steam ejectors exists above the east second stage intercondenser, Figure 3. Similar to the main steam ejectors, these ejectors consist of two trains and three stages. The difference is that they do not have intermediate intercondensers and are much smaller than the main steam ejectors. Traditionally, the auxiliary steam ejectors do not directly evacuate rocket exhaust in the baseline configuration. They are used to evacuate the spray chamber ullage volume, approximately 200,000 cubic feet, before a hot fire test to conserve steam usage for the main steam ejectors.

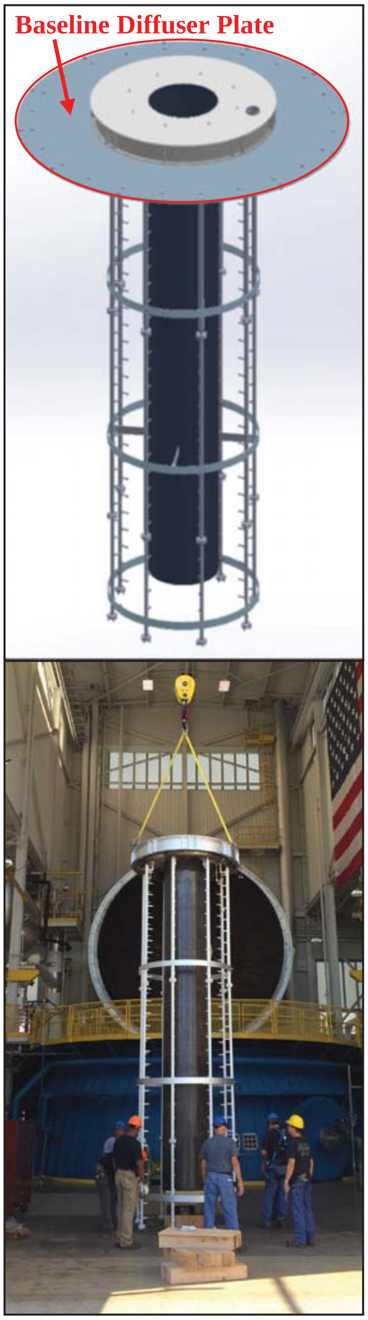

Figure 4. (Top and Bottom) ISP Facility Diffuser Insert

B. ISP Facility Vacuum Accumulator Configuration

The "vacuum accumulator" alternative facility configuration restores a limited subset of the ISP Facility's altitude propulsion capability. This capability serves a purpose when the facility baseline configuration is unavailable or not cost effective. Even when the baseline capability is available, reducing the need for facility systems intended for larger scale test could reduce costs, depending on the test article. The nominal predicted propulsion run duration for the vacuum accumulator mode is two minutes for rocket engines with 3,000 lbf thrust. Rocket engines with thrust levels less than 3,000 lbf could be run for longer durations. The maximum rocket thrust level using this configuration may be up to 10,000 lbf thrust depending on engine characteristics. Run durations for rockets this large would be limited to a few seconds.

Similar to the baseline altitude propulsion configuration, the vacuum accumulator configuration requires the use of the facility's test chamber, diffuser, spray chamber, and steam ejectors. The test chamber in this configuration is relatively unchanged compared to baseline. Modifications to the baseline diffuser include an optimized diffuser insert and a backflow deflector.

Specifically sized for the ICPTA, the diffuser insert measures 30 inch diameter by 20 feet long. Similar to the baseline facility diffuser, the diffuser insert enables pressure isolation of the test chamber by facilitating the formation of a system of shocks, "starting" the diffuser. The area ratio between the nozzle exit diameter and the 11 feet baseline diffuser diameter would have prohibited this function without the insert. The diffuser insert is backside cooled with a 7,000 gallon gravity-fed water supply. Cooling water flowrates operate at up to 1,200 gpm. Its L/D dimension is 8, exhibiting ideal starting pressure ratios and minimizing hysteresis[23]. The insert interfaces with the existing diffuser through the baseline diffuser plate shown in Figure 4. The plate seals the majority of the 11 feet diameter opening. If no diffuser insert were in place, then the test article would need to "start" the baseline diffuser. Small scale rocket engines could not do this.

The momentum of a rocket engine needs to "start" a diffuser to pump the test chamber and maintain altitude. At engine ignition, the test chamber and spray chamber begin at the same pressure. Over time, the test chamber pressure will decrease as the engine pumps through the diffuser. The spray chamber will typically rise to match the exhaust removal capability of the steam ejectors. As long as the diffuser remains "started," this pressure differential between the two chambers can exist.

Altitude conditions in the test chamber are maintained as long as a rocket engine is running. The test may end prematurely, however, if the pressure difference between the spray chamber and test chamber is large enough to "unstart" the diffuser. During a hot fire test, facility pressure instruments in the spray chamber are monitored to avoid this scenario. When the engine is shut down, the pressure difference between the test chamber and spray chamber will equalize. Exhaust gases in the spray chamber will then backflow into the test chamber, entraining water used to cool the diffuser and exhaust. The

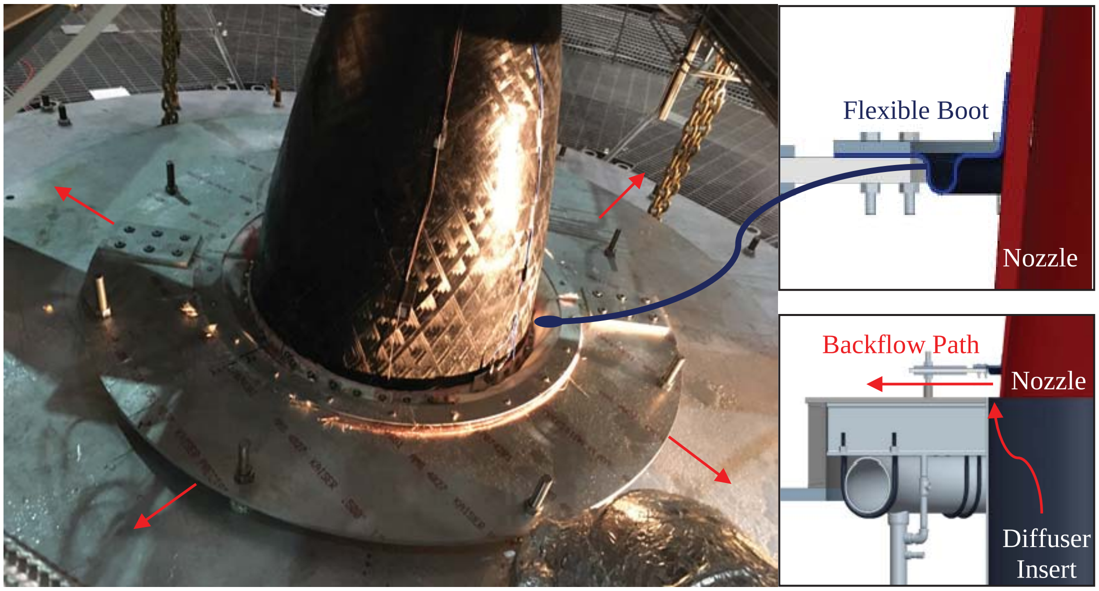

Figure 5. Engine nozzle with backflow deflector and flexible boot. Backflow path shown in red.

entrained cooling water will expose the test article to a significant amount of moisture. On the test article, moisture could potentially form frost on cold components, add heat to cryogenic materials, or cause electrical problems.

Attached just above the diffuser insert, the backflow deflector is shown in Figure 5. It mitigates the severity of backflow in two ways. First, the open area between the nozzle and the diffuser is restricted. The restricted opening reduces the severity of pressure equalization by reducing the flow area and choking the mass flow upon engine shutdown. Second, the deflector redirects the path of the backflow away from the test article. A flexible boot, constructed of high tensile strength ceramic cloth, provides the seal between the deflector and the engine nozzle, Figure 5.

In the spray chamber, the vacuum accumulator configuration does not use most of the baseline hardware for propulsion testing. Since the vacuum accumulator mode seeks to maximize facility volume, the water level in the spray chamber is maintained at a level of 40 feet. The vertical turbine pumps and the spray nozzles are not utilized. These pumps require a spray chamber water level of 60 feet to 70 feet. Overall, reduced cooling is required in this configuration due to the less energetic engines. Exhaust cooling comes from excess cooling water from the backside of the diffuser insert.

To maintain altitude, the vacuum accumulator facility configuration relies exclusively on the auxiliary steam ejectors. The baseline main steam ejectors are not utilized. Before a propulsion test, the auxiliary steam ejectors pull down the combined volume of the test chamber, spray chamber, and exhaust train: approximately 400,000 cubic feet. Then, the ejectors continue evacuating throughout the propulsion test. The exhaust load of even small scale rocket engines typically exceeds the capacity that the auxiliary steam ejectors can continuously remove. As a result, the spray chamber pressure will increase throughout the test.

Since the spray chamber pressure increases over time, the test duration is limited by the diffuser insert's sensitivity to unstart. Excessive backpressure causes diffuser unstart. Therefore, minimizing the spray chamber backpressure will augment test run durations. The facility's large chamber volume aids in keeping the backpressures low. Because the facility volume "stores vacuum" and dissipates it over time, this facility configuration is known as the "vacuum acccumulator."

C. ICPTA Hardware

Based primarily on the Morpheus prototype planetary lander, the ICPTA is a LOX/LCH$_4$ propulsion system test bed[20]. All of ICPTA's rocket engines are pressure-fed and utilize the LOX/LCH$_4$ propellant combination. They include a 2,800 lbf-vac main engine, two 28 lbf-vac reaction control engines, and two 7 lbf-vac reaction control engines. Four spherical aluminum propellant tanks store up to 4,700 lbm LOX and 1,700 lbm LCH$_4$. A spherical composite overwrap pressure vessel (COPV) contains 8 lbm of helium gas at 3,600 psig and -250°F (116 K) to pressure feed the engines. During each main engine hot fire test, the cryogenically stored helium provided active propellant tank pressurization after first being warmed via a main engine nozzle-mounted heat exchanger and then regulated down to tank pressure. Figure 6 shows the test bed integrated with the facility and its relative scale.

The ICPTA provided a hot exhaust load for the ISP Facility Characterization Test. At 2800 lbf-vac, its main engine thrust level fit within the capability of the facility's vacuum accumulator configuration. The diffuser insert was sized specifically for the ICPTA main engine nozzle. As a result, hot firing the rocket engine successfully started the diffuser insert. Maintaining altitude conditions in the test chamber would verify an effective operation of the vacuum accumulator mode.

Utilizing the ICPTA for the characterization test also provided other benefits. Since the ICPTA was selected, some test-specific hardware did not need to be procured. The integrated propellant tanks eliminated the needed for test-specific run tanks. Test article controls and instrumentation were mostly provided by the test bed. Also, since the test bed was proven with past test programs, the risk of testing unproven hardware at the facility was reduced.

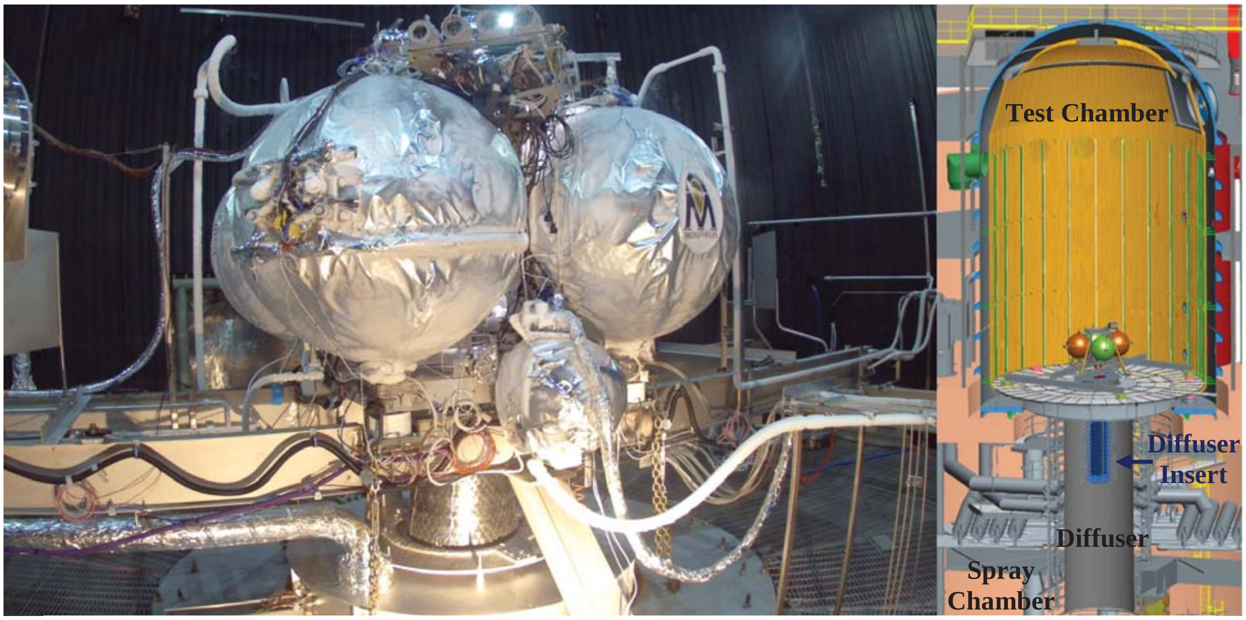

Figure 6. (Left) The ICPTA integrated in the ISP Facility test chamber with the backflow deflector. (Right) The relative scale of the ICPTA and the diffuser insert in the test chamber.

A final facility benefit of testing the ICPTA was the opportunity to test the LOX/LCH4 propellant combination. Previously, only LOX/LH_2 had been tested at the facility. In order to prepare for the test, the facility's LOX system was cleaned and used for the first time since the Delta III test campaign[5] in 1998. To save money on cleaning the facility's on-site storage tank, a roadable dewar stored the LOX for the test. Oxygen was still transferred through the facility systems into the ICPTA propellant tanks.

The facility's LH_2 system was utilized to transfer LCH_4 to the ICPTA's propellant tanks. Many of the fire safety systems for LH_2 were compatible with LCH_4. A roadable dewar was used to store the LCH_4 rather than the facility's on-site LH_2 storage tank. Similar to the LOX system configuration, using the dewar avoided the challenges of certifying the LH_2 tank for use with LCH_4. Since LCH_4 is heavier than LH_2, a temporary propellant volume restriction on the on-site LH_2 storage tank would have been necessary. Using a roadable dewar was also more expendient than going through the tank certification process.

III. ISP Facility Characterization Test Results

A six-week propulsion test campaign sought to evaluate the performance of the ISP Facility and the ICPTA. Tests were conducted in two different facility configurations. In the thermal vacuum facility configuration, the ICPTA was thermally conditioned up to 40 hours. Propellants were loaded onto the test article and the Vehicle

Reaction Control System (RCS) was exercised in this environment. In the vacuum accumulator facility configuration, the main engine and RCS were hot fired at altitude conditions and ambient temperature.

Throughout the propulsion test campaign, JSC personnel collected model validation data for the ICPTA's many subsystems. These experiments included main engine propulsion testing, evaluation of a coil-on-plug ignition system, RCS assessment, vehicle heat transfer characterization during cryogenic thermal vacuum exposure, novel propellant mass gauging, a multi-rocket ignition system, cold helium pressurization, and propellant tank spray-chilling[20-22]. Thermal vacuum RCS ignition testing, in particular, revealed challenges associated with no-lights of a LOX/LCH$_4$ system in deep space operation.

Only the main engine propulsion tests of the ICPTA were significant from the perspective of ISP Facility characterization. RCS hot fires did not have an appreciable impact on facility performance. As shown in Figure 7, main engine hot fires were conducted in two different positions. The first position elevated the nozzle exit plane three inches above the diffuser insert entrance plane. The backflow deflector was not installed to allow observation of the main engine exhaust plume. The second position lowered the nozzle exit plane three inches below the diffuser entrance plane. The backflow deflector was installed, though it obscured the exhaust plume.

To accommodate the two positions of the ICPTA, the thrust stand was adjustable. The ISP Facility crane could support the weight of the I-beams holding the test bed while the height of their supports was modified. Propellant supply lines were flexible so that they did not require disconnection. This was especially advantageous for avoiding contamination of the oxygen supply and vents lines.

A. Diffuser Insert Performance

With the help of the diffuser insert, the ICPTA main engine successfully pumped down the test chamber and maintained altitude during propulsion tests. Figure 8 shows a typical pressure plot for the test chamber and spray chamber during a main engine propulsion test in the elevated position with no backflow deflector: Hot Fire 4.17. Before main engine ignition, the two chambers began at the same pressure, 34.4 Torr. This initial pressure was limited by three factors: water temperature in the spray chamber, facility vacuum leaks, and test article leaks. Throughout the test campaign, the temperature of the water was approximately 50°F. Therefore, the absolute minimum initial pressure in the chambers would be limited by the vapor pressure of water at that temperature, approximately 10 Torr. The lowest observed initial pressure in the campaign was 28 Torr. So, facility and test article leaks were the limiting factor for the initial propulsion test pressure. After the main engine began its hot fire, the test chamber pressure (CM1000 shown in orange) decreased approximately 11 Torr in 20 seconds. After that time, the engine shut down, and the test chamber pressure equalized with the spray chamber pressure. A momentary spike in pressure occurred immediately after shut down, which was likely due to the rocket plume backflowing into the test chamber.

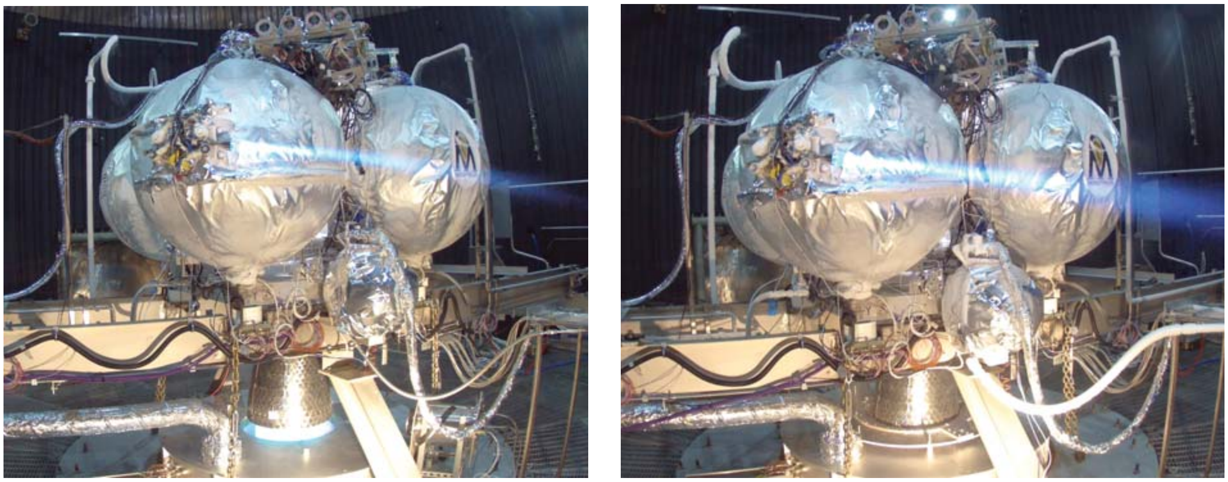

Figure 7. (Left) The ICPTA main engine and 28 lbf-vac reaction control engine hot firing in the elevated position with no backflow deflector. (Right) The ICPTA main engine and 28 lbf-vac reaction control engine hot firing in the lowered position with the backflow deflector and flexible boot installed.

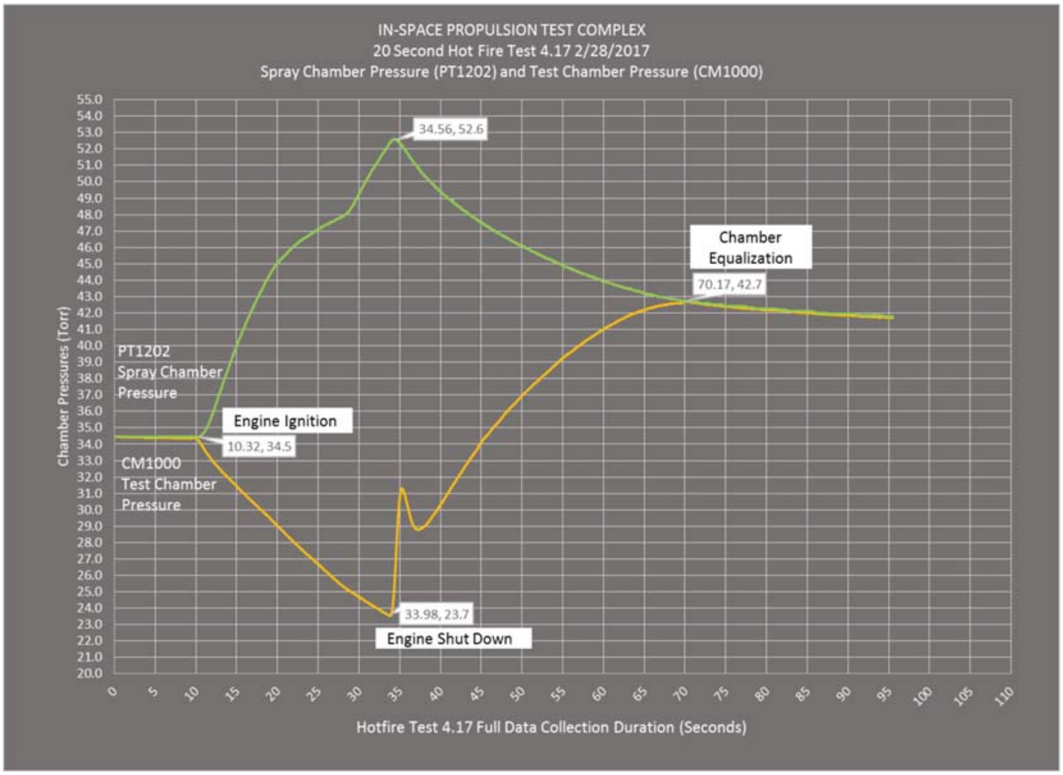

Figure 8. Hot Fire 4.17 test chamber and spray chamber pressures during a 20 second main engine hot fire test in the elevated position with no backflow deflector, with throttle step 15 seconds after main engine ignition.

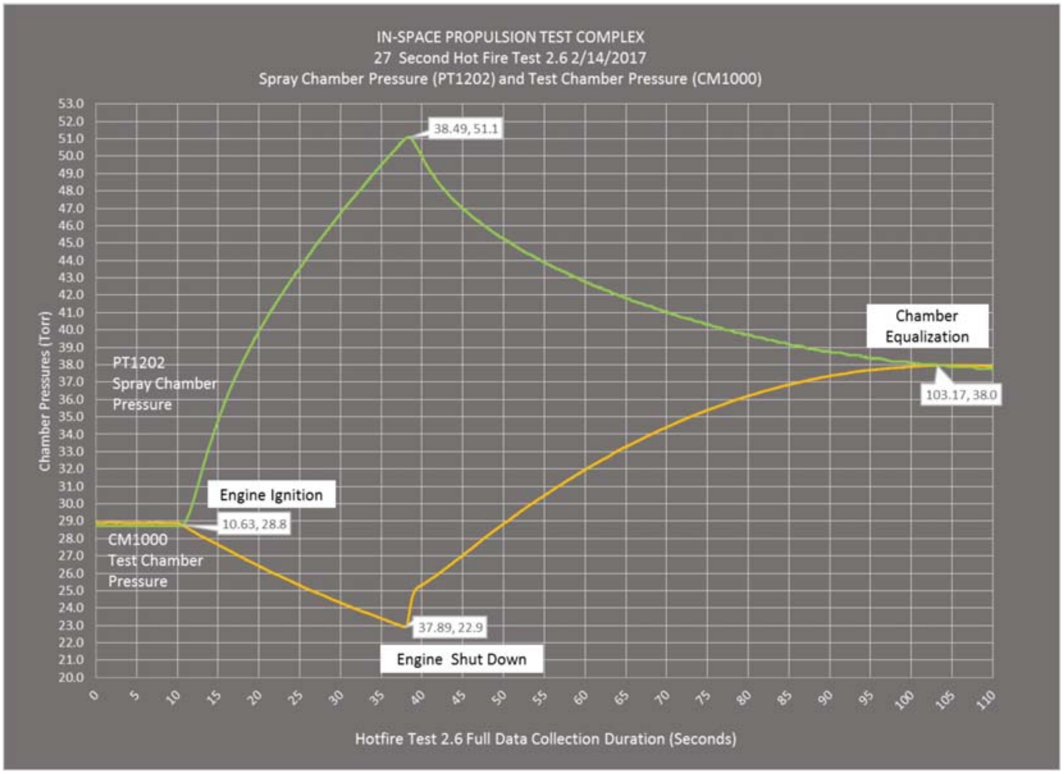

Figure 9. Hot Fire 2.6 test chamber and spray chamber pressures during a 27 second main engine hot fire test in the lowered position with the backflow deflector.

Similarly, the spray chamber pressure (PT1202 shown in green) increased approximately 18 Torr in 20 seconds until the engine shut down. At approximately 15 seconds into the hot fire, an intentional throttle step caused the rate of pressure rise to increase. Post shut down, the test chamber and spray chamber pressures took approximately 26 seconds to equalize. The final equalized value pressure was 8 Torr greater than the initial pressure before engine testing began. This was due to the main engine putting exhaust into the facility faster than the auxiliary steam ejectors could remove it.

Figure 9 shows a typical pressure plot for the test chamber and spray chamber during a main engine hot fire in the lowered position with the backflow deflector. The pressure profile with the backflow deflector followed a similar trend to the profile without the deflector. The major difference was that the pumpdown and equalization rates were more gradual due to the restricted flow through the backflow deflector. During the 27 second hot fire, the test chamber pressure decreased approximately 6 Torr. The spray chamber pressure increased 21 Torr in the same amount of time. Post test, the test chamber and spray chamber pressures took approximately 65 seconds to equalize.

Additional main engine hot fire results are included in Table 1. Changes in the test chamber and spray chamber pressures from engine start to engine shut down are presented. The longest hot fire run duration was Hot Fire 5.11 at 57 seconds. That maximum duration was based on test schedule constraints rather than the facility capability. Based on estimates assuming a normal shock in the diffuser insert, the maximum predicted run duration was 120 seconds. After this time, the backpressure in the spray chamber would cause the diffuser to unstart.

Table 1 . ICPTA Main Engine Hot Fires Facility Chamber Pressure Change and Equalization Time. The test cases for Figure 8 (Hot Fire 4.17) and Figure 9 (Hot Fire 2.6) are highlighted in yellow.

ENGINE HOT FIRE TEST NUMBER / DATE PERFORMED	MAIN ENGINE HOT FIRE DURATION (SEC)	BACKFLOW DEFLECTOR (YES/NO)	TEST CHAMBER PRESSURE CHANGE (TORR)	SPRAY CHAMBER PRESSURE CHANGE (TORR)	POST TEST CHAMBER EQUALIZATION TIME (SEC)
2.4 2/14/17	10	YES	-2	+14.5	58.3
2.6 2/14/17	27	YES	-6	+22	65.3
4.15 2/28/17	2	NO	-1	+2.6	12.9
4.16 2/28/17	13	NO	-6	+14.0	26.7
4.17 2/28/17	23	NO	-10.5	+18.1	36.2
5.11 3/2/17	57	YES	-12	+71	100.2

B. Backflow Deflector Performance

The backflow deflector successfully mitigated the impact of backflow in two ways. The first method was to reduce the flow area between the engine nozzle and diffuser insert. This increased the amount of time it would take for the test chamber and spray chamber pressures to equalize. Based on Figures 8 and 9, the equalization time was increased 60%. This trend continues as displayed in Table 1. Hot Fire 2.4 and Hot Fire 4.16 were very similar except

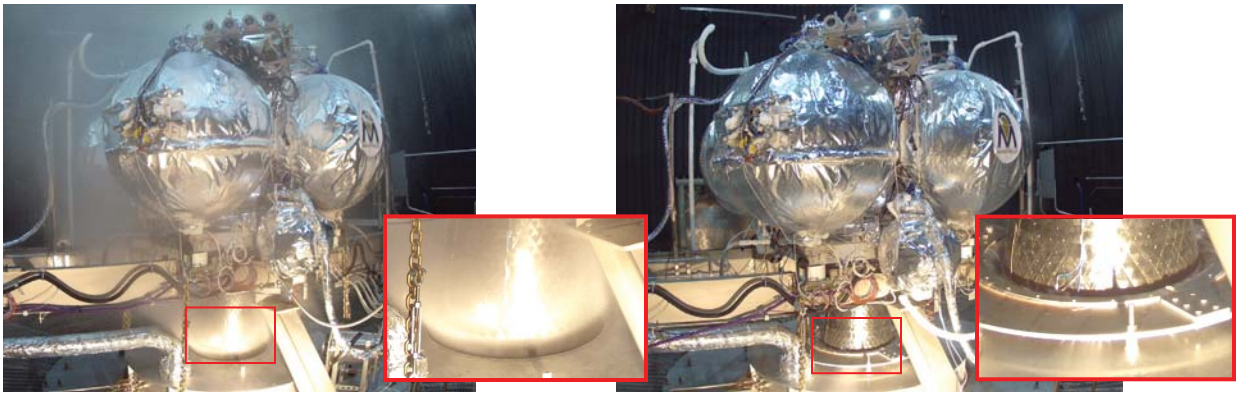

Figure 10. (Left) Unmitigated backflow during engine shutdown, Hot Fire 4.17. (Right) Backflow during engine shutdown with the backflow deflector in place, Hot Fire 2.6. Streaks of water are barely visible in the direction of flow.

for the position of the ICPTA and the presence of a backflow deflector. The equalization time was more than doubled with the backflow deflector restriction in place.

The other method was to deflect the flow away from the test article. A flexible ceramic boot sealed the area between the engine nozzle and the backflow deflector. Figure 10 shows the effects of having a deflector in place upon engine shutdown. On the left of the figure, the unmitigated backflow entrains moisture into the test chamber and on the test article. On the right of the figure, the entrained moisture is barely visible and clearly directed away from the test article.

IV. Conclusion

A propulsion test campaign demonstrated the viability of the vacuum accumulator configuration of the ISP Facility. Based on the results of the test, the diffuser insert successfully isolated and maintained altitude conditions at the engine nozzle during main engine propulsion testing of the ICPTA. Nearly one minute of main engine hot fire was supported. If the resources of the test campaign would have allowed it, longer main engine propulsion test durations could have been explored. Future testing at the ISP Facility may include other small planetary landers or rocket engines of a scale similar to the ICPTA.

The configuration represented a flexible use of the facility, addressing issues previously encountered with large scale baseline propulsion testing. Backflow upon engine shutdown was mitigated and redirected with a backflow deflector. To provide steam, a rental boiler successfully drove the auxiliary steam ejectors.

Forward work includes investigating the limit of diffuser unstart backpressures. The backpressure in the spray chamber would need to be increased until the diffuser was unstarted. This data could then be input into a model to better predict the unstart pressure.

Acknowledgments

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