NTP Demonstration Vehicles and Mission Concepts for Generation 1

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Nuclear thermal propulsion (NTP) maintains continued interest in support of NASA's goal to produce a human rated spacecraft for Mars exploration. The NASA/DARPA DRACO effort aims to demonstrate the first nuclear thermal rocket through a flight in 2027. This paper considers the option of a follow-on in-space demonstration supported by a more extensive pre-flight ground test campaign. A concept of operations to accomplish the objectives is outlined and figures of merit for selection of a spacecraft concept are defined. Conceptual designs of various nuclear thermal propulsion demonstration vehicles are presented, spanning a wide trade space. Each concept differently balances performance capability and extensibility to operational missions with schedule, risk, cost of the ground and flight demonstration. Key attributes of notable concepts are provided, with these demonstrating the degree to which each concept can accomplish the objectives considered.

I. Introduction

Nuclear thermal propulsion (NTP) is under development by NASA's Space Nuclear Propulsion (SNP) project as an option for a crewed Mars transit vehicle [1]. Recent investigations have shown that NTP also has the potential to enable new types of robotic science missions that take advantage of its high specific impulse (I_{sp}) and thrust [2], [3]. NASA and DARPA are currently partnered to develop the Demonstration Rocket for Agile Cislunar Operations (DRACO), which will demonstrate an NTP engine in space for the first time. Development beyond the DRACO demonstration will lead to operational propulsion systems capable of performing sustained missions from cislunar space to the outer planets, including human-rated propulsion systems and spacecraft that align with NASA's goals of Mars exploration. The next engine to be developed beyond DRACO is termed the "Generation 1" or "Gen 1" NTP engine. It is envisioned to be significantly matured through a ground test campaign prior to flight demonstration. Testing and associated modeling and simulation must be sufficient that demonstration of the Generation 1 system leads to a Generation 2 operational NTP engine system. This system is envisioned to be the first mission-operational (non-demonstration) NTP system, with first applications in cislunar space. Key performance parameters for Gen 2 missions have been investigated in Refs. [4], [5], [6]. Continued development and maturation will produce successive engine generations capable of performing deep-space science and human-rated Mars missions.

The Generation 1 NTP engine ground test campaign is envisioned to include full-thrust engine operation. This requires ground test capabilities not presently available [7]. The Gen 1 engine may achieve technology readiness level (TRL) 7, operating in the space environment on the nominal propellant option of liquid hydrogen (LH_2), and demonstrating sufficient operational Gen 2 mission lifetime on the full-scale engine through the ground test campaign.

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However, Gen 1 development may be performed using a sub-scale engine that could employ an alternate propellant. NTP engine designs using alternate propellants, primarily ammonia (NH_3), have been considered due to the easier storability of the propellant compared to LH_2 [8]. Use of a sub-scale engine or an alternate propellant can provide cost or test-duration advantages but results in a trade-off where all extensibility goals for the technology are not demonstrated.

Mission and test objectives are developed to define the requirements for a Generation 1 system, and the trade space for engine and spacecraft designs is outlined. Concepts of operations (ConOps) for both ground testing and flight demonstration are considered and the figures of merit that can be assessed to determine the value of a particular concept to accomplish the objectives are discussed. A variety of spacecraft concepts are presented that span a range of cost/schedule and capabilities/strategic value. A subsystem-level sizing constrained by a launch vehicle selection defines each concept with sufficient depth to illustrate the capabilities.

II. Gen 1 NTP Mission Test Objectives

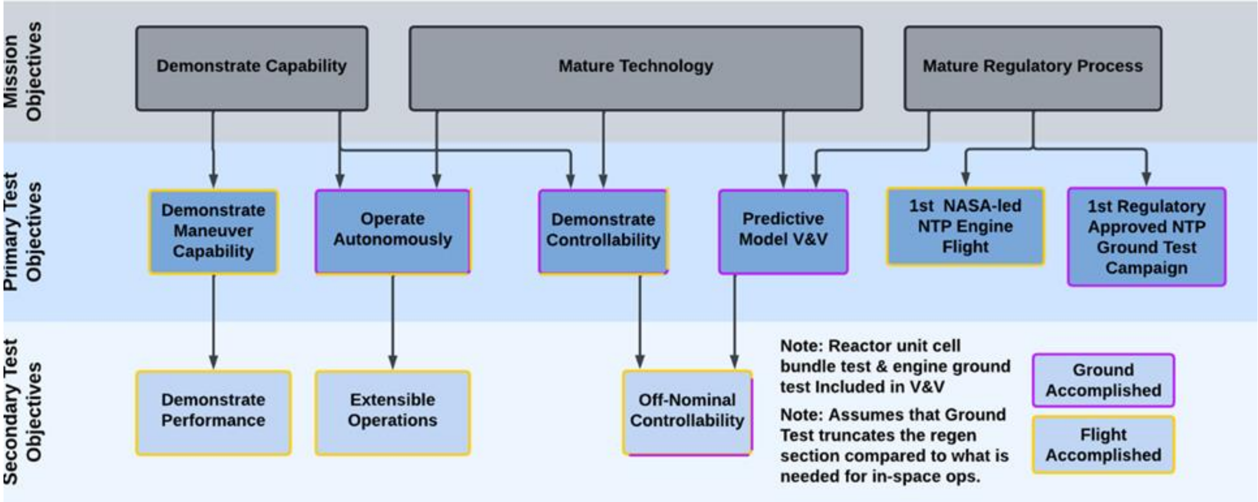
The Generation 1 NTP engine is envisioned to be the first to be tested thoroughly during development through a ground test campaign. This requires ground test capabilities not presently available, resulting in an engine that advances NTP development, achieving a set of Gen 1 mission objectives. Overall, the mission goal is to develop, test, and fly an NTP engine that leads to development of the first operational (Gen 2) NTP engine.

There are three mission objectives to accomplish this goal: Demonstrate NTP Capability, Mature the NTP Technology, and Mature the Regulatory Process.

1. **Demonstration of NTP Capability** – The Generation 1 mission provides demonstrable evidence of NTP engine performance capabilities which are applicable in supporting a range of new NASA and DoD missions and/or commercial applications.
    - The demonstration provides a proof point of the performance and feasibility of an NTP engine for performing mission-relevant maneuvers in a future operational environment.
    - The flight is a demonstration test and may not represent the full performance or capabilities of an operational Gen 2 engine.
    - The demonstration is extensible to the performance of an operational Gen 2 system in terms of both I_{sp}, thrust and burn durations and restarts.
2. **Maturation of NTP Technology** – Maturation of the Generation 1 system through extensive ground testing advances NTP technology development prior to a flight demonstration.
    - Ground development testing verifies performance and operational lifetime and validates predictive modeling capabilities.
    - Ground testing supports technology maturation up to TRL6, demonstrating the system in a relevant environment.
    - The value of the combined approach of ground testing culminating in a flight demonstration of the Gen 1 system, evaluated in terms of technology maturation benefit vs. cost and schedule, will be greater than an approach that only uses ground development and testing.
3. **Maturation of Regulatory Processes** – An NTP flight demonstration preceded by nuclear ground test and evaluation exercises nuclear regulatory processes for space fission systems, including development of procedures to comply with requirements for ground testing, launch, and end-of-life disposal at the end of a flight mission.
    - This will be the first NASA-led NTP engine flight.

From the mission objectives, primary and secondary test objectives are derived. The flow-down from mission to test objectives is illustrated in Fig. 1. Some of the test objectives can be satisfied either completely or partially through ground testing alone, while others require in-space testing to complete. These are denoted by the colored box outlines in the figure. Some boxes are outlined in both colors, indicating that both ground and flight testing will lead to the full demonstration and achievement of those objectives. Table 1 provides additional definition for each test objective.

The envisioned ground test capability is not yet fully defined. There are a few attributes that affect the ability to accomplish the test objectives with ground testing. The engine ambient exit pressure experienced during a ground test is one such attribute, with a high-pressure (at or near atmospheric levels) being likely [7]. With atmospheric exhaust, the regenerative-cooling portion of the nozzle may need to be shortened for ground test compared to what would be needed to achieve full expansion and maximum I_{sp} during flight, resulting in slight power cycle differences. Consequently, the in-space power cycle and maximum achievable I_{sp} can only be fully demonstrated in space, where the low-pressure exit condition enables testing of the full regenerative nozzle. In addition, when using propellants other than LH_2, there may be chemical processes occurring in the nozzle flow that would be difficult to fully quantify through ground testing at elevated exit pressures with a shortened nozzle.



Note: Reactor unit cell bundle test & engine ground test Included in V&V

Note: Assumes that Ground Test truncates the regen section compared to what is needed for in-space ops.

Fig. 1 Mission objective tracing to test objectives, showing how each is accomplished through ground testing, flight testing, or a combination of the two.

Demonstration of maneuver capability involves executing a full NTP burn, including startup and shutdown transients and a cooldown flow period, to impart a controllable, precise velocity change (ΔV) to a spacecraft. While the engine performance needed to execute this could likely be demonstrated on the ground, the integration of pointing and vehicle control necessary to achieve this may only be demonstrable during flight. Controllability of the hydrogen supply can be mostly demonstrated in ground testing, but the integration with a flight control system and operation in the microgravity and full thermal-vac environments can only be realized in space.

A well-designed ground test campaign, with post-test disassembly and inspection capabilities, can provide verification and validation (V&V) of the predictive models of fuel and reactor performance and engine operation and control, much of which can be accurately quantified prior to a flight test. This allows for the development of an accurate digital twin of the Generation 1 flight engine well in advance of a flight demonstration. There may be some extremes in the modeling capabilities, such as off-nominal condition behavior, that a Generation 1 development project may choose to V&V at end of the flight test campaign rather than as part of the ground test campaign. Obtaining detailed data through ground testing, in combination with additional high-fidelity data from operation in the space environment, will provide mission designers with tools spanning a range of operating conditions that will be needed to design engine systems and spacecraft capable of successfully executing operational missions.

Table 1 Test objective descriptions.

Objective	**Description**
Demonstrate Maneuver Capability	Demonstrate that the system is capable of progressing through startup, operation, shutdown, and cooldown as anticipated and imparting the expected ΔV.
Operate Autonomously	Operate the system with autonomy to show that operation can be executed and mission objectives can be achieved with limited input from ground control.
Predictive Model Verification & Validation	Verify and validate the model predicting the behavior of the engine system. Measured data from the test compared with the predictive model to show accuracy of: •Reactor conditions (power, temperature, pressure) •Engine performance (thrust, I_{sp}, propellant flow) •Radiation flux and leakage, including through the shield
Demonstrate Controllability	Demonstrate that the system responds as expected to input from the controller. Demonstrate that the controller can respond to changes and uncertainty in: •Material properties & neutronic coefficients •Propellant flow and resulting reactivity insertion •Temperature reactivity feedback •Turbomachinery transient behavior (especially during start-up)

Objective	Description
	•Control drum position & behavior
NASA-led NTP engine flight	Obtain authorization for system testing and operations on the ground and in space. Establish/solidify regulatory path for the launch, operation, and end-of-life disposal of space fission systems, setting the precedent for future missions using nuclear fission-based systems.
Demonstrate Performance	Achievement of the engine performance KPPs: • I_{sp} threshold / target values • Thrust • Controllable ΔV imparted
Extensible Operations	Demonstrate and measure performance for key aspects of operational extensibility: • Restart after operation • Multiple restart capability and limitations owing to fission product build-up and decay. • Engine operation duration
Off-nominal Controllability	Demonstrate safe operation in key off-nominal scenarios, including (for examples): • Individual and multiple control drum actuation failure • Control value actuation failure

III. Demonstration Concept of Operations (ConOps)

To satisfy the test objectives outlined above, two phases of demonstration must be considered: the ground demonstration campaign and the in-space flight demonstration.

A. Ground test campaign ConOps

A ground test campaign could be conducted in multiple ways. The engine size and number of engines available to be tested will significantly influence the design of the campaign. This is especially important given that changes within the fuel occur with accumulated operation time and with each thermal cycle. The first test with an assembled engine will likely be a zero-power critical test that confirms reactor-level modeling and simulation. Next, an incremental approach is pursued where the power is methodically increased over either a series of tests or in steps within a single test, allowing for data collection that incrementally increasing the understanding of the controllability while verifying and validating predictive models across the low-power range. This sort of incremental testing could be repeated multiple times, quantifying operational variability. After low-power testing, the test engine (Engine 1) could be disassembled for post-test inspection is the data from inspection at this point in the test sequence is deemed valuable. If the engine is not disassembled at this time, it could be operated for a full-power test with operational-like start-up. Again, after this test, the plan could entail disassembly and post-test inspection of Engine 1 to obtain V&V data.

If no disassembly is performed after the first full-power test, Engine 1 can be operated through additional full-power tests. If Engine 1 is disassembled and a second engine (Engine 2) is available, the latter unit could be operated through multiple full-power tests. These tests may be structured in such a way as to approximate the individual operational durations and number of restarts required for a full mission. After completion of testing, the engine is disassembled and inspected to acquire the maximum amount of V&V data at various length scales and locations in the reactor. Post-test inspection is also performed to quantify lifetime and margin against various known failure modes and to determine if additional unknown failure modes manifest during the testing.

Over the test campaign, the amount of autonomy of the operations is increased until an autonomous test is performed, implementing to the greatest extent possible a test-like-you-fly approach. It should be noted that even if a full autonomous mission sequence is performed during the ground test campaign, some residual risk will remain for the flight test due to differences in the ground and flight test environments (e.g., back pressure, thermal vacuum) and due to the still-limited number of nuclear test units likely to be available compared to the number available for a commensurate chemical engine ground test campaign. In addition, each liquid-fed chemical engine can be tested prior to flight, yielding additional data on the ‘as flown’ units, while the flown nuclear engines have never been operated, launching ‘cold’ and reaching a ‘nuclear-safe’ orbit prior to initiation of the fission process.

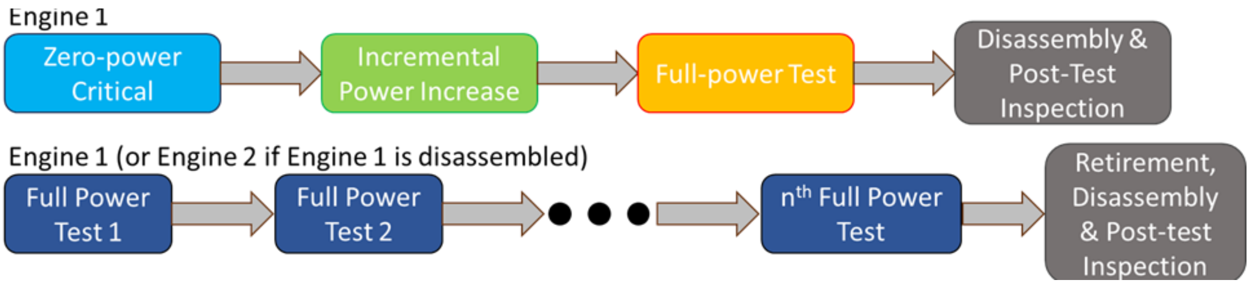


Fig. 2 Notional ground test ConOps progression.

B. Flight demonstration ConOps

Even after the conclusion of a successful ground test campaign, there remain test objectives that can only be achieved through flight testing. The flight mission ConOps primarily addresses demonstration of maneuvering capability, overall in-space propulsive and system performance, and the extensibility of operations to longer and more complex missions. In-space testing gathers data in the full relevant environment, demonstrating engine operation and propellant management under microgravity conditions and illustrating interactions between an engine and a spacecraft. Control of the spacecraft must be maintained through operation, including the start-up/shut-down transients and the additional time required for decay heat removal. The unique thrust profile of an NTP system will be measured throughout all phases of engine operation to aid in the further development of spacecraft guidance, navigation, and control algorithms and modeling.

The total mass of available propellant is the first key flight test limitation. The choices of launch vehicle, propellant type, and overall vehicle design are key factors in determining this limit. The next key engine design choice is the overall engine thrust, which directly correlates with the flow rate of propellant, setting an upper limit on the available time for engine operation.

To accomplish all Gen 1 flight test objectives, there must be sufficient propellant to:

- Ensure engine health and confidence in start-up to full power. There may be a series of tests performed that effectively link the in-space data to ground test results, validating digital twin modeling. This might include operating at multiple zero/low/moderate power levels before executing a full-power maneuver.
- Perform a complete operational cycle to demonstrate and assess engine controllability and spacecraft maneuvering performance. Multiple engine cooldown and decay heat removal approaches may be tested during one mission (e.g., pulsed flow, continuous trickle flow).

If there remains sufficient propellant for additional testing, the flight test can also:

- Perform additional full- or partial-power cycles to in space demonstrate re-start capability, which will be needed for interesting and non-trivial missions.
- Test certain off-nominal scenarios that might be considered ‘too risky’ for the ground test campaign.

Total mission duration is an important consideration, especially for hydrogen propellant that is subject to significant boil-off without an active cryogenic fluid management (CFM) system. Procedure-driven constraints like time required for checkout and inter-test data analysis will be factors in determining the time between launch and the first test and then the time before the execution of subsequent tests. Mission duration will ultimately be set by the propellant expended during each test, propellant boil-off losses, and the amount of propellant expended during each engine cooldown cycle. The cooldown duration is a function of reactor power, overall reactor operating time, and to a limited extent the reactor design.

C. Figures of merit for a flight mission concept

The Generation 1 flight demonstration addresses the test objectives defined above, via a ConOps as described. The flight ConOps and thus the ability to achieve the test objectives is constrained by the capabilities of the demonstration vehicle. To assess a trade space of potential spacecraft and missions, figures of merit (FOM) have been developed and are given in Table 2. Sub-criteria are identified where multiple attributes contribute to a FOM. Each FOM can be quantified for a given spacecraft and mission concept using the metrics in the quantification column.

The intent of these FOMs is to quantify the extent to which various concepts can accomplish the test objectives. The test objectives can be traced to the FOM as follows. The objective “demonstrate maneuver capability” requires sufficient propellant to perform one complete engine operation from startup through cooldown. Demonstration of “extensible operations” is accomplished through increasing the overall full-power operating duration, which demonstrates greater propulsive utility and more-extensible overall operation. Long overall operating time also permits the possibility of demonstrating the multiple restarts required for extensibility to more complex missions. While longer total operating time is always better, it should be noted that none of the Gen 1 concepts in the trade space exceed the aggregate operating time required for Generation 2 mission concepts or for a crewed Mars mission. The extent to which off-nominal controllability can be demonstrated in space beyond what is possible through ground demonstration is also limited by total operating time available for a given concept. The extent to which each of these test objectives can be accomplished is therefore primarily limited by the available overall operating time.

The "demonstrate performance" objective can be evaluated on both reactor-level and engine-level performance. To achieve at least 900 sec I_{sp}, operation on hydrogen propellant requires a very high reactor temperature to heat the gas to at least 2700 K prior to exhausting it through the nozzle. Operation on an alternate propellant (e.g., ammonia or methane) may have a high reactor performance FOM as it could permit the reactor to reach those same high reactor temperatures as in the hydrogen case, but such a system will demonstrate less than 500 sec I_{sp} during the flight test, resulting in a low engine performance FOM. The higher end of the FOM ranges correspond to an engine performance demonstration that meets the requirements for a Gen 2 system.

To quantify the extensibility of the Gen 1 system to Gen 2 needs, six attributes are identified to judge commonality with the Gen 2 design and ConOps.

Design of the flight demonstration engine and mission involves an evaluation against the first three FOMs in Table 2, which must then be balanced against mission cost & schedule, risk, and the difficulty in developing the ground test capabilities required to reduce risk and produce quantified reactor and engine data prior to a flight demonstration.

Table 2 Figures of merit for a Generation 1 NTP flight demonstration

Figures of Merit	Sub-criteria	Quantification	Range
Operations Demonstration	Total full power operation time	S/C model result	3 to 83 min
	Propellant lifetime for demo mission	S/C model input	3 days to indefinite
Performance Demonstration	Reactor Performance Demonstration	1. Propellant/reactor chemistry environment 2. Temperature 3. Power level	Minimal traceability to equivalent reactor design operated at equivalent temperature, pressure
	Engine Performance Demonstration	1. I_{sp} 2. Thrust	700 – 900+ sec 10 – 25 klb$_f$
Extensibility	Reactor Extensibility to Gen 2 (difficulty to increase performance to Gen 2 needs)	1. Fuel form 2. Moderator form 3. Manufacturing process 4. Power density 5. Flow schedule 6. Design decisions including fuel loading, enrichment control drum, shield, etc.	
Cost/Schedule	Spacecraft (except engine) dry mass	S/C model result	6 – 16 mt
	Engine mass	S/C model input, reactor/engine model result	3000 – 5000 kg
	Technology development cost	Engine components complexity, Reactor components & design complexity, Spacecraft design complexity	Ammonia to hydrogen, Simple, common fuel elements to non-repeating design; fuel TRL/MRL
	Launch vehicle and pad infrastructure accommodations	Fairing modifications required, propellant storage and loading capabilities at launch site	Storable ammonia to hydrogen loaded through new fairing umbilical with new storage
Risk	Development unknowns (as of today)	Propellant chemical behavior/compatibility Reactor design test heritage	

Figures of Merit	Sub-criteria	Quantification	Range
	CFM TRL		Passive, short duration storage Active, larger size, long duration storage
Test Capabilities Development	Existing and new ground test capabilities to mature concepts	Engine ground test & exhaust capture complexity & size, Reactor assembly and sub-assembly irradiation test capability	Testing on Hydrogen Testing on other propellants

IV. Demonstration Spacecraft Concepts

A. Spacecraft Trade Space

Custom spacecraft concepts were considered, constrained by launch vehicle (LV) capabilities. This trade space includes the range of potential commercial launch vehicles projected to be available within the next five to ten years. The trade space of propellant options are hydrogen (H-NTP), methane (M-NTP), or ammonia (A-NTP). Engine thrust is considered from 10 to 25 klb$_f$. Spacecraft sized to fully utilize the LV capability were considered, as were smaller and less costly spacecraft that would be limited imparting down to 1 km/s of ΔV. Both active and passive CFM were considered.

Table 3 Trade space considered for Generation 1 NTP flight demonstration systems.

Thrust - Engine Mass	Propellant - I_{sp} (s)	Launch Vehicles	# thrusting operations (equally distributed ΔV)
10 klb$_f$ - 3000 kg 12.5 klb$_f$ - 3400 kg 15 klb$_f$ - 3400 kg 25 klb$_f$ - 3400 kg 25 klb$_f$ - 5000 kg	Hydrogen - 750, 825, & 900 Ammonia - 375 & 450 Methane - 350 & 494	Starship-Super Heavy New Glenn Falcon 9 (Reusable) Falcon Heavy (Reusable) Vulcan-Centaur	1 (limit to 1 km/s) 2 (max-sized spacecraft) 4 (max-sized spacecraft) 1 (limit to 2.5 km/s)

Spacecraft concepts covering the trade space outlined in Table 3 were generated using a subsystem-level spacecraft sizing tool described in Ref. [9]. That publication also discusses the trade space in more depth. An example H-NTP spacecraft concept sized using this tool is provided in Fig. 3. This particular concept uses less than the full volume and mass capability of the launch vehicle, with the center of gravity (C.G.) of the spacecraft within the limits of the launch vehicle's standard payload interface. A larger vehicle that used the full volume and mass capability would require a custom launch vehicle interface to account for a higher center of gravity. In this example, the engine is launched pointing upwards, requiring the transfer of significant loads through the tank structure to the LV. Launching engine down would enable lightening of the tank structure, it would require a large payload attachment fairing and would constrain the tank diameter at the top of the vehicle. This option has not been rigorously explored in the present study but could also be included as an option for future demonstration mission vehicle designs.

In the Fig. 3 example, sized to launch on New Glenn, the tank is 6.3 meters in diameter and 6.8 meters long and has a liquid hydrogen propellant capacity of 13 metric tons (mt). An NTP engine with 12.5 klb$_f$ thrust and a nominal specific impulse of 900 s results in a total operating time budget of roughly 31 minutes, spread over equal length thrusting operations. Overall operating time is slightly increases if only a single thrusting operation is executed since that case avoids the need for a second cooldown cycle. A summary of this example concept's metrics is provided in Table 4.

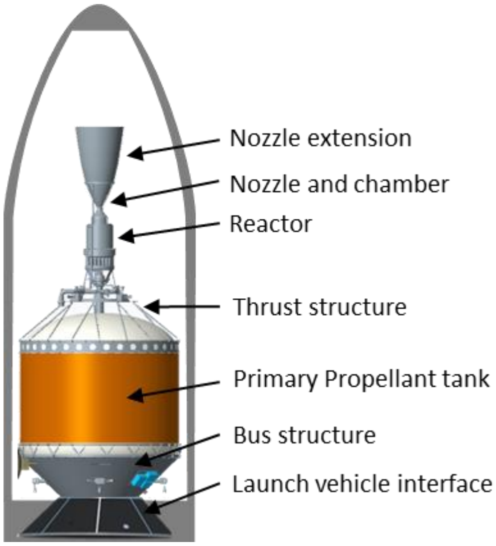


Fig. 3 Spacecraft concept example illustrated within a New Glenn launch vehicle fairing.

Table 4 Example spacecraft capability summary.

Capability	Values
Wet mass (kg)	24000
Liquid hydrogen capacity (kg)	13000
Mission profile	Two thrusting operations
Estimated total full power operation time (min)	31
CFM type	Active 20K-class (no boil off)

B. Notable Options for a Generation 1 Flight Demonstration

Table 5 lists the resulting metrics and figures of merit for seven concept candidates in the trade space considered. These options are likely on or near the pareto front of overall value among the options available. Included are the lowest cost options overall and using liquid hydrogen propellant, the most-capable concepts (defined as the cases with the greatest overall engine operating time and imparted ΔV) for each propellant option, and a high-thrust H-NTP option that represents the closest analogue to the expected performance and ConOps of a Generation 2 engine. Finally, one mid-size H-NTP concept is included in the table to represent a case that balances capability and cost while remaining within the constraints of the standard New Glenn payload interface.

As observed in the table, each option differently balances the figures of merit, maximizing specific FOMs or sub-criteria. Most of the options considered use the lowest thrust considered (10 klb_f). These low-thrust engines have the lowest propellant consumption rates, enabling the longest total engine operating times These engines can provide great demonstration value by permitting the longest duration tests. However, there will still be additional work needed to develop engines with higher thrust. This highlights the need to balance the Gen 1 testing requirements with the risk and residual development work that may be required to realize an operational Gen 2 engine.

The results of this study are likely on or near the overall pareto front of value in terms of the test objectives achieved relative to cost. However, there may be additional options occupying the spaces between those already examined that provide marginal added benefit. A more in-depth study should examine those options in greater detail. The results of this effort and follow-on studies aim to aid in the development of requirements both for the Gen 1 demonstration system and the Gen 2 operational system.

Table 5 Metrics and figures of merit for selected notable concepts from the Generation 1 demonstration spacecraft/engine trade space.

Option	Engine Type	Thrust (klb_f)	ΔV (km/s)	Total Engine Operating Time (mins)	Number of Thrusting Operations	Prop Mass (mt)	Dry Mass (mt)	Launch Vehicle	Notes
Smallest, lowest cost overall	A-NTP	10	1	3	1	1.75	6.25	New Glenn	Minimum capability demo mission. Minimum cost.
Smallest, lowest cost H-NTP	H-NTP	10	1	3.5	1	1.25	7.8	New Glenn	Minimum-cost H-NTP demonstration. May leverage LH_2 infrastructure developed for Blue Moon lander.
Mid-size H-NTP	H-NTP	12.5	6.5	31	2	13	10.3	New Glenn	Maximum size within New Glenn standard C.G. limits. Balance of capability (operating time and ΔV) and cost.
Most capable M-NTP	M-NTP	10	11	110	4	90	13	Starship-Super Heavy	Highest combined M-NTP capability. Leverages methane's I_{sp}/density ratio.
Most capable H-NTP	H-NTP	10	9.8	90	4	37	13.75	Starship-Super Heavy	Highest combined hydrogen capability. Most comprehensive H-NTP demonstration.
Most extensible to Gen 2	H-NTP	25	7.75	30	4	36	15.7	Starship-Super Heavy	Closest analogue to the engine size and operating capabilities projected for a high-thrust Gen 2 operational engine.
Most capable A-NTP	A-NTP	10	8.4	120	4	90	12.25	Starship-Super Heavy	Highest combined ammonia capability. Maximum engine operating time across all options studied.

V. Conclusions

There are technically viable engine and vehicle concepts that could support NTP engine technology maturation to TRL 7 through a ground test campaign followed by a flight test, reducing the development required to field an operational Gen 2 system. The testing ConOps described herein depends on the existence of sufficient testing capabilities to support extended ground testing of the Gen 1 demonstration engine prior to flight. There are Gen 1 engine design options that satisfy mission objectives and mature NTP technology using smaller and/or less capable flight engines/vehicles or employing alternate propellants to reduce the cost of the mission. These missions, while being lower in cost, will leave larger gaps between the resulting Gen 1 test engine and the envisioned Gen 2 operational mission engine.

The Gen 1 flight is used to provide verification and validation data to support modeling and simulation efforts and close gaps that remain after the ground test campaign is complete. For examples, an in-space demonstration can retire additional risk associated with operation in microgravity, exposure to the thermal-vac environment of space, and exhausting to a vacuum, all of which can only be fully experienced in space. The in-space mission can demonstrate autonomous operation and provide a quantitative time history of the performance during an NTP operating cycle of engine start-up, full-power operation, shutdown, and finally cooldown.

A trade study using figures of merit was employed to examine the NTP engine and mission design trade space. These various figures of merit are traceable to specific mission and test objectives, quantifying the value offered against those objectives by various Gen 1 NTP engine types, launch vehicles options, and spacecraft/mission designs, The figures of merit can be used to aid in the development of a Gen 1 engine that will, within NASA’s available budget and programmatic constraints, significantly reduce the risk of developing and operating a Gen 2 engine.

Acknowledgments

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