DRACO On-orbit Nuclear Thermal Rocket Experiment Preliminary Plans

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I. INTRODUCTION

I.A. Demonstration Rocket for Agile Cislunar Operations (DRACO) Program

On 1 April 2022, The Defense Advanced Research Projects Agency (DARPA), on behalf of the Department of Defense (DoD), was granted authorization to manufacture, produce, and acquire a utilization facility in order to demonstrate a nuclear thermal rocket (NTR) on orbit for the Demonstration Rocket for Agile Cislunar Operations (DRACO) program. The nomenclature "utilization facility" refers to the nuclear reactor within DRACO's NTR engine. This authorization was granted by Secretary of the Department of Energy (DOE) in accordance with section 91.b of the Atomic Energy Act of 1954 (AEA), Public Law 83-703, as amended, codified at 42 U.S.C. § 2121(b), and in accordance with National Defense Decision Directive 282 (1987).

One of the most well-known examples of how these authorizations were utilized by the DoD in the past, comes from the delegation of authority from DOE to Naval Reactors for the Navy to manufacture, produce, and acquire reactors for the Navy's sea-going vessels. Naval Reactors has exhibited an excellent track record for reactor safety, performance, and programmatic execution and leverages a reactor manufacturing plant at an industry performer site which is licensed by the Nuclear Regulatory Commission (NRC). Naval Reactors has implemented its own standards at shipyards and ports which then receive the reactor for integration into their ships. The Navy also has devised means for conducting experiments on its own reactors on board its own Naval vessels.

DARPA plans to mirror many of the existing processes, such as those demonstrated to work by the Navy for its own reactors, and DARPA has been very proactive in ensuring that the DRACO reactor will be held to stringent safety and handling procedures that are on par. One future possibility that could unfold, is to envision a parallel entity to Naval Reactors (such as, "Space Reactors" run by the Space Force) which brings reactors to its "ports" at the rocket launch site, and that nuclear reactors could similarly be conducted onboard spacefaring "ships". These future spacefaring vehicles could derive lessons learned from how the DRACO program conducts its own in-space reactor experiments.

One of the hallmark unique technical approaches for the DRACO program is that DARPA plans to conduct the NTR rocket engine test in space sometime in fiscal year 2027 (FY27). Most of the non-nuclear aspects of the NTR engine can be tested on the ground, and there will be years leading up to the in-space demonstration for on-the-ground testing during Phase 2 and Phase 3 of the DRACO program. Many components of the non-nuclear engine (NNE), to include pumps, valves, the nozzle, and lines and ducts that are routed around the reactor, can be tested on the ground at pre-existing rocket component test facilities. DARPA has partnered with the National Aeronautics and Space Administration (NASA) to ensure a well-informed NNE and NTR engine testing leading up to the in-space demonstration for these components.

The reactor is nested within the NTR engine, and because of the immense cost and time estimated to build a modern, specialized nuclear-rocket test facility, or be restricted to an existing facility's requirements that are not capable of supporting an NTR engine test campaign in which to bring the NTR reactor to a state of heated-criticality, the DRACO program had always baselined conducting powered reactor tests in-space.

I.B. NERVA/Rover: A Foundation for NTR Engine Test Objectives

NERVA/Rover (1953 – 1972) built at least 22 nuclear reactors and NTR engines. Each reactor or engine had hundreds of test objectives, per reactor or engine, that demonstrated many techniques and components, such as sensors, control methods, valve sequencing, startup techniques, reactivity and thermal calibration techniques, mechanical and structural tolerances to high pressure propellant flow, and so forth. After each reactor/engine test was complete, the NERVA/Rover engineers would apply the lessons learned in an evolutionary manner to the next build. Many NERVA/Rover experiments varied in their <u>primary objectives</u>, because each reactor/engine test sought to capture the evolution of the next reactor/engine as compared to its predecessor reactor/engine.

For instance, KIWI B4D had objectives to evaluate if the reactor would structurally survive based on design changes that were made from the prior KIWI B4C reactor, which had been destroyed due to flow vibrations[1]. Specifically, one particular KIWI B4D primary objective was: "*To investigate the structural integrity and dynamic stability of the B4D design under reactor operating conditions of full design flow rate and three-fourths of full design temperature and neutronic power*" [1]. After a cold-flow test with the reactor at zero power, but with flowing propellant at full thrust, engineers verified that radial restraint techniques were adequate to prevent destruction of the reactor from flow-induced vibrations. This type of testing is envisioned to be done on the ground for DRACO prior to the in-space demonstration.

As another example of a primary objective: the NRX-EST was the first engine to use the "bootstrap" technique, as compared to its predecessor NRX-A4. Specifically, this NRX-EST Objective was the "*Demonstration of the bootstrap startup capability of the engine system*" [1]. This type of primary objective may be done in-space for DRACO, as it involves full-power reactor start-up. Before bringing the reactor to full power, the DRACO engine will measure the reactivity of the hydrogen at low power levels.

One of the primary differences as compared to the series of NERVA/Rover predecessor reactor/engine tests, is that DRACO will be the first NTR reactor to incorporate high-assay low enriched uranium (HALEU) fuel. Furthermore, this will be the first time the following HALEU NTR engine modes will be demonstrated via remote engine control for: 1. Start-Up to full power; 2. Operation at steady state at full rated power; 3. Shut down after steady state; 4. Spacecraft maintenance at ambient conditions; 5. Potentially re-started after full power. Therefore, primary and secondary objectives should capture the information that won't be captured during terrestrial reactor tests on the HALEU NTR engine, as they pertain to some of the greatest comparative unknowns of the HALEU NTR demonstration engine, as compared to the predecessor NERVA/Rover engines that used highly enriched uranium.

Many of the NERVA/Rover tests set secondary/experimental objectives that involved the use of new measurement and control techniques, specific hardware (ie: new nozzles, new fuel coatings, new core materials, new control methods, etc.). Additionally, these secondary objectives commonly required instruments to acquire data to validate pre-predicted values that would impact things like nuclear stability of the reactor. An example KIWI B44 Secondary Objective was: "*To close the temperature control loop using core material temperature thermocouples rather than core exist gas thermocouples*" [1]. An example PHOEBUS 2A Secondary Objective was to: "*Determine the reactivity contributions of hydrogen in the tie-tube system with the reactor operating at low and intermediate power levels*" [1] Many similar low-level reactivity objectives and diagnostics objectives will be carried out in the early phase of the DRACO in-space demonstration.

II. CAUTIOUS APPROACH TO IN-SPACE NTR ENGINE STARTUP

II.A. First, the Reactor

The most prototypic NERVA/Rover NTR engine which included a turbopump, valves, and a full powered nuclear reactor was the XE′ (or experimental engine PRIME) engine. The XE-PRIME demonstrated 28 restarts, and many lessons came from this engine alone [2]. The NNE for XE-PRIME were arranged inline with the reactor, and the hot bleed top-off cycle was demonstrated. The (most likely to be) highest performing NTR engine is the closed cycle expander, in which there is no bleeding from the turbopump. This may be the engine cycle to be utilized for the DRACO engine on-orbit demonstration. Because of its novel use with an NTR engine, a closed cycle expander concept would need to undergo cold-flow testing on the ground for DRACO prior to in-space use.

Once in space, a delicate balance will unfold between the time it will take to keep the liquid hydrogen cryogenic on-orbit and the amount of time it will take to characterize the reactor before it is deemed reasonable to bring the reactor to full power in order to attempt a near-characteristic operation of the NTR engine. The DRACO engine will be limited in the amount of cryogenic liquid hydrogen propellant that it may utilize prior to the demonstration, which will be constantly boiling off. The experiments may take weeks to conduct, but the cryogenic liquid hydrogen may not last longer than an order of weeks.

The primary purpose of preliminary reactor testing is to obtain the information needed to achieve a successful full-power startup. If all goes well, this testing will provide the numerical parameters and instrumentation status to tune the control system, but it is also possible for unknowns or failures to require a rethinking of the entire test program and overall control approach while the experiment is being carried out in real-time. To succeed, this preliminary testing must be designed to eliminate the potential dilemma posed by the first flight of a complex reactor system; i.e. a system with 1) uncertain physical performance and 2) uncertain instrumentation and control (I&C). The performance of the reactor cannot be determined/controlled without reliable I&C, and the reliability of the I&C system cannot be determined without predictable reactor performance. This requires a preliminary test program that starts with very simple experiments to isolate particular phenomena and I&C instruments/actions as much as possible. The secondary benefit of these tests will be to understand the behavior of the reactor for future design, modeling, and benchmarking activities. Alternatively, if startup is unsuccessful this data will be needed to understand what went wrong.

The following are a table of possible, preliminary reactivity insertion tests as well as an example of a predicted reactivity insertion test for a generic NTR reactor (not DRACO's reactor). The prediction was modeled using the tool FRINK, which was also used to successfully predict the reactivity insertion tests for KRUSTY [3].

TABLE I. A possible table of preliminary tests. In-space ZPCs can be done very quickly, perhaps 3 to 4 per hour, with the entire campaign in ~8 hours. Warm critical tests can be 1 to 6 hours per test, depending on whether H_2 is used to cool between tests. The number of preliminary tests we run will depend on H2 leakage.

Dry Zero Power Crits
Command drums to 25 sec reactor period (20 cents)
Command drums to 9 sec reactor period (40 cents)
Command drums to 3 sec reactor period (60 cents)
Drums to 20 cents, move 1 drum to fixed position predicted to add another 20 cents
Drums to 20 cents, move 1 drum to fixed position predicted to add another 40 cents
Freeze 1 drum in, command drums to 25 sec reactor period (20 cents)
Freeze 1 drum in, command drums to 3 sec reactor period (60 cents)
Freeze 2 drums in, ...
…continue until can't reach criticality
Wet Zero Power Crits
Drums to 20 cents - open PCV, flow for 10 seconds
Drums to 20 cents - open PCV, motor pump to get 2x the pressure of test 2A, for 10 seconds
…increase and repeat if time/propellant/pump/power allows
Warm Crits Followed by Tank Driven Flow
20 cent free run, hold for ~30 min, open PCV, flow for 5 seconds
40 cent free run, hold for ~30 min, open PCV, flow for 5 seconds
60 cent free run, hold for ~30 min, open PCV, flow for 5 seconds
…after each test, wait until Rx cool back down, or quench with flow
Dry Steady-State Run
80 cent free run, hold for several hours

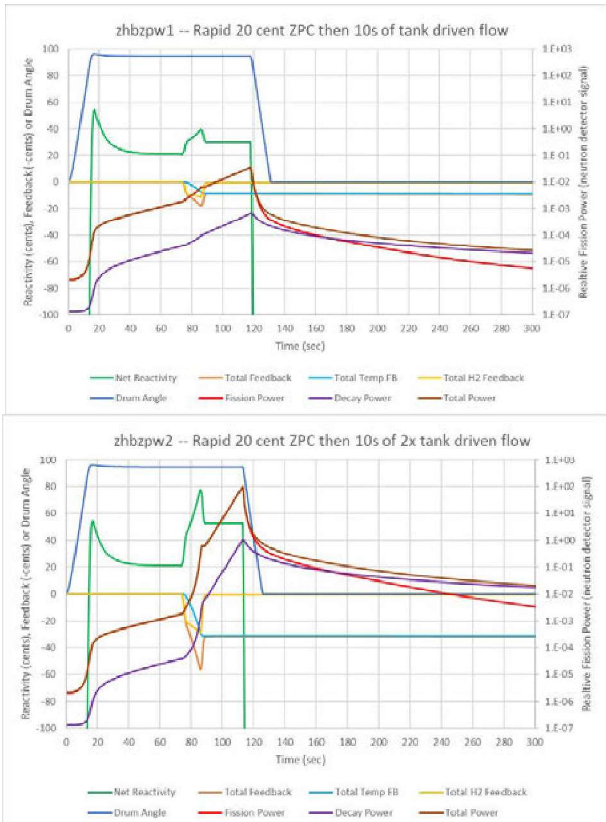

Fig. 1. An example of a prediction for a "pre-startup" reactivity insertion test, simulated by the code FRINK. This particular test is for the rapid 20 cent ZPC insertion, followed by 10s of tank-driven flow, after which the PCV is closed. Upper plot depicts flow at 0.3MPa and the bottom is flow with twice as much pressure. This simulation is for a generic NTR core, and it is not the DRACO reactor.

The ideal baseline insertion depends on many factors, and it is likely the optimal insertion will be determined in real-time, while the experiment is being conducted. It is likely that 20 cents will be preferred, because it will be possible to turn tests around quicker (reactor period is 50% faster, so it will take less time or the flux to get up to a range where good measurements can be made). When doing reactor experiments on the ground, as was done with KRUSTY, more conservative (lower insertion of 15 cents versus 20 cents) steps are required, because humans were inside of the same facility as the reactor. One benefit (of many) of testing in space, is DRACO will not have these insertion limitations.

The insertion that is chosen will depend on many factors, such as: how sensitive and how well coupled the neutrons detectors are to the core, how time critical the operations turn out to be, how good and reliable communications are with the spacecraft, how reliable thermocouples are and how much lag they might have, and so forth.

II.B. Preliminary DRACO Primary and Secondary DRACO NTR Flight Demonstration Objectives

The following are example DRACO NTR flight demonstration objectives which were created with agreement over the years between DARPA and NASA after studying the primary and secondary objectives of the NERVA/Rover experiments. These in-space objectives were provided for consideration by the proposer during the Phase 2 and Phase 3 DRACO Broad Agency Announcement solicitation, released 4 May 2022[4]. DRACO's industry performers in Phase 2 and Phase 3 will work collaboratively with the DRACO government team to tailor their objectives and test sequences in accordance to their proposed design. Additionally, demonstration objectives are expected to evolve as the design progresses in Phase 2 and Phase 3. The interspersed "TBDs" are meant to be placeholders for descriptions otherwise specified to the proposer's specific design, and performer's planned methods for analysis and experimentation.

TABLE II: Potential DRACO Primary Objectives

Primary Objectives	Description	Minimum Threshold	Maximum Goal
Pre-Startup (PSU)	Verify the ability to conduct pre-startup confirmation of system readiness.	Perform pre-startup checks and transmit results to Earth.	Same as minimum threshold.
Low-Power Critical Operation (ZPC)	Verify that the reactivity behavior of the reactor is consistent with models, and verify temperature coefficients are within modeled error bands over the range of temperatures safely achievable without coolant flow.	Ensure data supports reactor startup and low power operation predictions	Run on-orbit ZPC and additional low power tests in space, and verify the results support continued operation of the DS mission.
System Startup (SU)	Demonstrate a controlled startup, in which the engine responds to automated controls in a manner which is predicted by pre-launch Multiphysics modeling.	Collect sufficient data to verify controlled startup to full thrust	Demonstrate at least one successful controlled, automated startup to full rated thrust.
Steady-State (SS)	Demonstrate the ability to hold power at full rated thrust until steady-state conditions are reached.	Collect sufficient data to verify holding power at full thrust	Demonstrate a steady state mode of operation at full power and thrust following at least one successful startup. During a separate steady state run, demonstrate capability of engine to throttle while incorporating power variations.
System Shutdown (SD)	Demonstrate the ability to shut down, cool down, and adequately remove reactor decay heat.	Collect sufficient data to verify control of shutdown	Demonstrate adequate control of shutdown plant conditions for at least one shutdown.
Cryogenic Fluid Management (CFM)	Demonstrate ability to provide cryogenic cooling for	Have enough cryogenic fluid to remove	Support NTR engine operation for at least one full

	the duration of the DS mission.	decay heat following the last shutdown.	power burn.

The following are potential DRACO secondary objectives. Each table of secondary objectives corresponds to a row in the primary objectives table seen above. As explained in the previous section, there should be several pre-startup diagnostic experiments. This is in order to both “diagnose the diagnostics” and validate that sensors and I&C are working, and this is also in order to ensure that reactivity worth for the various elements of the reactor and control drums are in-line with what was predicted by modeling and simulation. If the measurements are different than what was predicted, terrestrial modeling and simulation will be updated to incorporate the new data, and updated flight software will be uploaded to the space platform before additional testing is carried out.

TABLE III: Potential DRACO Secondary Objectives based on Primary Objective PSU.

Pre-Startup Secondary Objectives	**Description**	**Minimum Threshold**	**Maximum Goal**
PSU: Remove inadvertent criticality inhibitors	Any TBD controls that were added to prevent inadvertent criticality (on the earth prior to and during launch) will be removed in-space.	To demonstrate the remote, full and complete removal of any TBD (ie: locks, poisons and neutron absorbers, explosive destruct, etc.) launch accident/safety features to enable free movement of actuating components to begin functional, confirmatory, and exploratory testing. Verify that no scram-producing interactions exist between the engine and the host platform.	Same as minimum threshold
PSU: I&C	Demonstrate ability of the NTR engine controller to execute TBD pre-startup tests and report results.	Run the predetermined pre-startup TBD diagnostic tests that are unique to TBD methods (remote, and/or autonomous with TBD sensors).	Same as minimum threshold
PSU: Mechanical testing of moving components	Actuate TBD mechanical components (such as valves and motors) prior to attempting startup to ensure they will function.	Demonstrate successful remote operation of TBD “moving parts”, (such as drums, pump, valves, etc.) and confirm their continued function (such as, rotation rate, torque strength, spin, etc.), prior to further testing.	Same as minimum threshold
PSU: Downlink	Demonstrate ability of the system to communicate data to the ground.	Conduct secure downlink of start-up telemetry throughout transient to mission control.	Same as minimum threshold

Once the pre-startup actions, and reactivity free-runs are conducted (such as those shown in Table 1 and Figure 1), then tests which heat the reactor and begin to take information on reactivity feedback due to the thermal feedback will be conducted. The reactor will need to be brought to a temperature which is high enough in order to get information on the thermal feedback coefficient, while at the same time keeping the reactor at an insignificant amount of thermal power (hence, "zero power critical" (ZPC) such that hydrogen is not required for cooling).

TABLE IV: Potential DRACO Secondary Objectives Based on Primary Objective ZPC.

Low-Power Critical Operation Secondary Objectives	Description	Minimum Threshold	Maximum Goal
ZPC: I&C	Demonstrate ability of the NTR Engine Controller to bring the reactor to a critical state and perform warmup with I&C	Bring the engine to a ZPC state	Bring the engine to a ZPC state, warm it, and provide data sufficient to demonstrate that TBD performance of I&C and reactor physics
ZPC: Reactor Health	Some means to inspect the health and status of the engine post-launch may be desired before bringing reactor to startup and full power attempts	Acquire necessary reactivity data during ZPC to assess potential changes between terrestrial ZPC and in-space ZPC.	Evaluate the TBD health of the reactor (structural, mechanical, etc.) through some TBD inspection method.
ZPC: Control Drums	Drum worth data may be limited.	Evaluate drum worths as the reactor heats up	Evaluate drum worths as the reactor heats up. Also evaluate drum worths for single drum movement.
ZPC: Temperature Coefficients	A careful measurement of reactivity coefficients associated with temperature changes over a limited range may be desired prior to initiation of coolant flow when the time to take such measurements may be limited by the scarcity of propellant.	Ensure reactivity coefficients associated with temperature changes are within predetermined error bands relative to models, or revise models as needed to reflect actual data.	Same as minimum threshold
ZPC: Downlink	Demonstrate ability of the system to collect and communicate data to the ground.	Conduct secure collection and downlink of start-up telemetry throughout transient to mission control	Same as minimum threshold

As depicted in Figure 1 and explained in Table 1, cryogenic liquid hydrogen will have been purposefully leaked into the core during the reactivity measurement tests at very low mass flow rates, which will better inform the confidence levels of conducting a startup attempt to full power. This full-power startup attempt will involve the turbopump attempting to flow propellant at some fraction of maximum mass flow rate.

TABLE V: Primary Secondary Objectives Based on Primary Objective SU.

System Startup Secondary Objectives	Description	Minimum Threshold	Maximum Goal
SU: I&C	Demonstrate ability of the NTR engine controller to bring the reactor through startup conditions.	Collect sufficient data with TBD sensors and methods to understand and enable startup attempt	Demonstrate use of a pre-programmed engine controller to conduct start-up of the NTR reactor with or without ground-based interventions.
SU: Temperature Coefficients	Ensure a safe progression to the temperature associated with full power at the end of the startup.	Achieve sufficient data (ie: at intermediate temperatures and reactivities) to verify reactivity coefficients so that an uncontrollable reactivity transient is precluded, and then have enough propellant remaining to enable at least one full power run. This will be the first time the reactor is heated above the isothermal condition attained in the low power critical test. As this heatup will encompass a temperature change likely in excess of 1000K, and a different temperature profile throughout the reactor, phenomena unknown prior to the first startup may lead to significant perturbations such as prompt critical excursions.	Acquire data in a manner efficient enough to safely conduct and gather data on one full power run.
SU: Intermediate Engine Conditions	Assess turbopump and drum's ability to bring the reactor through temperature and reactivity ranges (e.g., evaluate engine conditions at 10%, 40%, 60% flow) during startup.	Collect sufficient data to verify adequate control of the turbopump and drums.	Acquire data in a manner efficient enough to safely conduct one full power run after the startup attempt. Verify TBD pre-flight estimated performance based on TBD modeling and simulation (M&S)

SU: LH2 Pressurization and Transient Fluid Management	Verify the ability to establish and maintain tank pressure throughout the startup.	Collect enough data to ensure tank pressure is being adequately maintained.	Bring tank to TBD conditions (ie: temperature, pressure, flow rate, settling, etc.) in order to demonstrate TBD LH2 tank pressurization method(s) for nominal and/ or off-nominal startup attempt profile. Verify TBD pre-flight estimated performance based on TBD M&S
SU: NTR Full-Multi-Physics Modeling Validation During Startup	Given that the flight demonstration will be done without ground testing, the test will be used to verify the full-up multi-physics modeling and simulation that will go into predicting the TBD behavior of the engine during a startup (reactor/neutronics, engine/power balance, TH, etc.) had predicted prior to launch.	Verify the ability of multi-physics models to predict how to bring reactor to TBD critical state(s) in TBD controlled manner(s) for startup.	Further examine upon a re-start attempt(s) if the reactor is able to conduct more TBD complex start-up objectives (such as, prolonged start-up, modified mass flow rates during start-up, purposeful off-symmetry drum tests, etc.) as models predict.
SU: Downlink	Demonstrate ability of the system to communicate data to the ground.	Conduct secure downlink of start-up telemetry throughout transient to mission control	Same as minimum threshold

TABLE VI: Potential DRACO Secondary Objectives Based on Primary Objective SS.

Secondary Objectives	Description	Minimum Threshold	Maximum Goal
SS: I&C	Demonstrate ability of the NTR Engine Controller to hold the engine at a full power condition.	Collect data to allow adequate engine control.	Demonstrate use of a pre-programmed engine controller to hold steady-state full thrust conditions in NTR engine.
SS: LH2 Pressurization and Management During Transient Fluid Operation at Increased Mass Flow Rate	Verify the ability to maintain tank pressure throughout the maximum planned mass flow rate.	Collect enough data to ensure TBD tank conditions (ie: pressure, temperature, mass flow rate, etc.) can be maintained.	Demonstrate LH2 tank pressurization and management methods through nominal burn profile. Verify TBD pre-flight estimated

			performance based on TBD M&S
SS: Specific Impulse (Isp) greater than 700 s	Demonstrate the ability to hold an Isp of at least 700 seconds.	Demonstrate operation of engine of at least 700s upon one start and one re-start.	Demonstrate operation of the engine approaching its maximum operational limits (in terms of Isp). Validate TBD pre-flight estimated performance based on TBD M&S
SS: NTR Modeling verification	Given that the flight demonstration will be done without ground testing, the test will be used to validate the full-up multi-physics modeling and simulation that will go into predicting the TBD behavior of the engine during a startup (reactor/neutronics, engine/power balance, TH, etc.) had predicted prior to launch.	Validate the ability of multi-physics models to predict that the reactor is able to be brought to a critical state in a controlled manner and shut down in a controlled manner.	Further examine upon re-start if the reactor is able to conduct more TBD complex objectives (such as multiple restarts) as models predict.
SS: Downlink	Demonstrate ability of the system to communicate data to the ground.	Conduct secure downlink of telemetry throughout transient to mission control	Same as minimum threshold

TABLE VII: Primary Objective SD: Demonstrate the ability to shut down, cool down, and adequately remove reactor decay heat.

Shut-Down Secondary Objectives	Description	Minimum Threshold	Maximum Goal
SD: I&C	Demonstrate ability of the NTR Engine Controller to shut down the engine and reactor.	Collect data to allow adequate shutdown control	Demonstrate use of a pre-programmed engine controller to shut down the engine and reactor Verify TBD pre-flight estimated performance based on TBD M&S.
SD: Control of reactor shutdown	Verify ability to shut down the reactor and reduce propellant flow while controlling the temperature transient	Collect sufficient data to ensure control of shutdown will be acceptable	Verify that the reactor power and temperature transient match Multiphysics predictions on at least one shutdown Verify TBD pre-flight estimated performance based on TBD M&S
SD: Residual Heat Removal	Verify ability to remove decay heat, either via trickle flow or pulse flow, after completion of the initial shutdown transient	Collect sufficient data to ensure control of shutdown will be acceptable	Verify that the temperature transient matches Multiphysics predictions on at least one shutdown Verify TBD pre-flight estimated performance based on TBD M&S
SD: Downlink	Demonstrate ability of the system to communicate data to the ground.	Conduct secure downlink of telemetry throughout transient to mission control	Same as minimum threshold

TABLE VIII: Potential DRACO Secondary Objectives Based on Primary Objective CFM.

Cryogenic Fluid Management Secondary Objectives	Description	Minimum Threshold	Maximum Objective
CFM: Cryogenic hydrogen propellant heat management	At a minimum, the CFM must be maintained at sufficient quantities and durations to enable the host platform to be able to achieve its start, shut down, restart, and cooldown objectives	Demonstrate necessary TBD CFM techniques to maintain TBD quantity of liquid hydrogen needed to conduct the flight demonstration	Same as minimum threshold
CFM: Means of measuring boil-off rates	Demonstrate boil-off as compared to ground tests and pre-test analyses.	Collect sufficient data with TBD liquid hydrogen quantity measurements methods to	Same as minimum threshold

		allow comparison with models	

III. CONCLUSIONS

The DRACO program strives to incorporate as much caution and observance of safety and liability into the program as possible, starting with design, leading into manufacture and through launch and on-orbit experimentation of the DRACO reactor and engine. This paper discussed the cautious way in which DRACO will start and step through the on-orbit experiments for the reactor and engine before attempting a full-power startup. For the entire program's lifecycle, as discussed in the NETS 2022 paper, the DRACO program has implemented four General Design Criteria which sets a foundation for the safe handling, launch, and on-orbit operations of the NTR engine and the reactor contained therein [5]. DRACO's safety, environmental, and launch approval strategies are grounded in DRACO's General Design Criteria (GDC), as a requirement imposed on industry by DARPA. Setting GDCs are standard in the nuclear industry. The GDC's are based upon historical precedence and current risk guidance and will be evaluated as part of the system design review:

- GDC-1: The reactor shall not be operated prior to space deployment.
- GDC-2: Inadvertent criticality shall be prevented for both normal and accident conditions in accordance with the risk criteria in NSPM-20.
- GDC-3: The radiological risk to the public from the accidental hot re-entry of a reactor shall be prevented in accordance with the risk criteria in NSPM-20.
- GDC-4: In-space disposal shall be limited to sufficiently high orbits in accordance with US Space Policy Directive-6 guidelines

The combination of these terrestrial standards to keep the reactor off, radiologically inert, and safe to the public, combined with the safe and responsible approach to conducting the on-orbit experiment, give the DRACO program management team within DARPA and NASA confidence to proceed with Phase 2 and Phase 3 of the DRACO program, ultimately concluding with the historic on-orbit flight test of the nuclear thermal rocket.

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