

## Ground Test Technology Demonstration for Nuclear Thermal Propulsion Engines

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*Nuclear Thermal Propulsion (NTP) engines have been deemed a key technology to enable human missions to Mars due to their high efficiency, also known as specific impulse (Isp). Ground testing the NTP engine is critical in maturing the technology and increasing the design's Technology Readiness Level (TRL), thus mitigating risk from NTP engine performance/operations. NTP engine development began with open-air ground testing through the Rover/NERVA program back in the 1960s when regulatory requirements were not as stringent as they are today. Due to the formation of regulatory bodies, increase in oversight and environmental requirements, the exhaust gas released from NTP engines must be captured or processed to gain approval in the case that the exhaust gas contains fission products from the nuclear fuel elements within the reactor. Ground test campaigns following Rover/NERVA focused on the certification of a full scale NTP engine, which led to exhaust processing systems such as the Rocket Exhaust Capture System (RECS) and Real Time (RT) exhaust processing. These systems were deemed favorable for regulatory compliance but have a high initial investment cost. Reassurance on the feasibility of ground testing and the NTP engine technology likely need to be achieved before NASA invests in these systems. Recently the objectives for NTP engine ground testing have shifted from certification testing of a full scale engine to demonstration testing of a subscale engine. The shift to demonstration testing allows for a shorter testing duration and a lower operational thrust (for demo testing purposes only) to demonstrate the NTP engine (5k-12.5k lbf). Due to these factors, the infrastructure, consumables, total footprint, and exhaust system complexity are able to be drastically reduced, thus reducing cost significantly. The High-pressure Exhaust Capture System (HECS) concept was designed for a NTP engine ground test demonstration. The HECS concept greatly reduces cost compared to previous concepts and suggests favorable regulatory acceptance due to its ability to capture all of the exhaust gas from the NTP engine.*

### I. BACKGROUND

The development of NTP technology began with the Rover/NERVA program. NASA tested numerous reactors and engines with varying levels of capability from 1959-1972. Reactor and engine concepts were tested at partial and full power with multiple restarts and varying performance levels. Systems were tested with thrusts levels up to 250,000 lbf, burn durations from seconds up to 62 minutes, specific impulse over 800 seconds, and temperatures up to 2,750K<sup>1</sup>. These tests were all performed on highly enriched uranium (HEU) reactors in open-air without any processing of the hydrogen exhaust. Near the end of this program nuclear regulatory bodies were formed and safety factors became more of a focus, driving NASA to begin development of the first exhaust processing system through the Nuclear Furnace<sup>2</sup>. Following the lunar program NASA budgets were cut back and as a result of that and other factors, the NERVA program was halted. Since NERVA there have been several other NTP development programs through both NASA and the Department of Defense (DoD), but no other reactors or engines have been fully developed or tested in part due to the facility requirements and cost driven by safety and regulatory factors. From 1987-1993 Timberwind planned and gained approval for real time exhaust scrubbing at the Nevada National Security Site (then Nevada Test Site), but construction was not started before the program was cancelled<sup>3</sup>. Various alternate concepts have been proposed and developed to process or capture the engine exhaust from 1993-2018 including Subsurface Active Filtration of Exhaust (SAFE)/borehole, Rocket Exhaust Capture System (RECS), and Real Time (RT) exhaust processing. Current NTP designs utilize low enriched uranium (LEU) which eases some of the safety, regulatory and security factors. This change is in line with new policies such as Space Policy Directive 6 and aims to reduce cost and drive a test campaign more palatable to the general public.

Studies from 2018-2020 evaluated a full scale NTP engine that produced 25,000 lbf thrust for an engine certification campaign that would include multiple prototype, development, and certification engines with multiple restarts and for various durations, including up to a 50-minute certification test. The long test durations at peak temperature with multiple restarts drove a robust exhaust system design, which would fully capture or filter the exhaust that is likely to contain some amount of fission products. A RECS or RT processing system was recommended to ensure for a safe, conservative testing method that would allow for testing to continue even with fuel fracture or other issues due to the robustness of the systems that would process and contain any fission products released from the core. Additionally, a survey of NASA, DoD, Department of Energy (DOE), and commercial sites was conducted with Stennis Space Center (SSC), Idaho National Labs (INL), and Nevada National Security Site (NNSS) trading as the best options.

In fiscal year 2021, the Space Nuclear Propulsion (SNP) project changed focus from a flight certification program to a technology demonstration of a subscale engine (12,500 lbf thrust) with the goal of continuing to mature NTP technologies without fully investing in the infrastructure to human-rate a flight system. Given that the objective is a technology demonstration and not engine certification, the maximum test duration was reduced. The demonstration would be performed on a single engine with this reduced thrust and testing duration significantly decreasing the risk of harmful levels of fission products being released with the exhaust. Additionally, cost reduction is key in achieving buy-in for a technology demonstration. While the RECS and RT systems previously recommended are robust systems, likely to achieve regulatory approval, they are also expensive with a long lead-time, in part due to subscale exhaust processing demonstrations planned prior to completion of the full-scale design. These factors drove a review of the exhaust system options resulting in the Post Run Capture System (PRCS) concept to simplify the infrastructure requirements and reduce the cost. The concept would release the start-up and main stage engine exhaust flows into the open air. This relied on the assumption that the exhaust gas would not contain high levels of fission product. The system would include numerous sensors and in the case of fission product detection at unacceptable levels, the system would switch to a shutdown/cool-down mode where the vents to the open air would close, and the exhaust gas would be captured in accumulation tanks. The PRCS concept was seen with high risk around regulatory approval due to a portion of its operations relying on open air exhaust release. Additionally, overall cost was still higher than desired with the PRCS concept.

In 2022, the High-pressure Exhaust Capture System (HECS) design was developed from the PRCS concept. HECS slows, cools, and fully captures all exhaust gas produced by the NTP engine. The design accommodates a higher back pressure which allows for significantly decreased system volume, making full exhaust capture feasible for a short duration technology demonstration. The lower volume occupied by the exhaust gas reduces the size of the overall system and test stand, while also allowing for more commercial off the shelf (COTS) components/materials. These changes remove additional cost from the construction of the overall exhaust capture system. Additionally, since HECS contains and captures all the exhaust gas it is a more appealing design than PRCS from a regulatory approval standpoint. HECS is under evaluation for 12.5k and 5k lbf thrust levels of the NTP engine. A reduction to 5k lbf would further reduce the exhaust system size and is therefore being explored to further reduce the cost while still meeting project objectives for an NTP engine demonstration. The Isp requirements are assumed constant regardless of the thrust.

## II. GROUND RULES AND ASSUMPTIONS

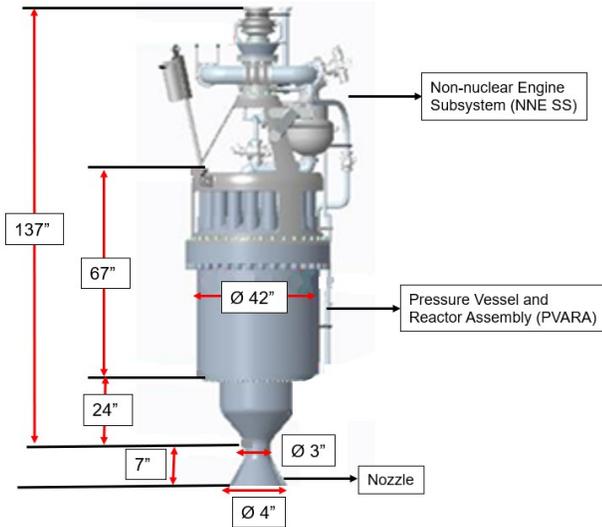
A full, comprehensive list of ground rules and assumptions can be found in AMA's "FY21-FY22 NTP Ground Test Report"<sup>6</sup> The following are high level ground rules and assumptions that are critical for the HECS concept design:

- The engine ground test facilities shall be capable of performing at least 1 full-power test for a minimum of 5 minutes.
- Gimbaling and altitude simulation of the engine will not be required for ground testing.
- The engine will be tested in the vertical, nozzle-down orientation.
- The nozzle skirt, external shield, and orbital maneuvering system are not included in ground test engine configurations. A flight-like configuration is not required.
- Initial test capability is for demonstration testing only; further investment will be required for development testing.
- The engine ground test facilities shall provide all water, power, hydrogen, nitrogen, helium and other consumables for purge, start-up, steady-state run, shut-down, cool-down, emergency shutdown, and other emergency operations.
- Engine ground test facilities shall provide the means to safely abort or halt a test, including powering down and safing of the test article and facility.
- Engine ground test facilities shall meet applicable licensing requirements.

## II.A. NTP Engine Characteristics

A smaller nozzle area ratio (AR) of 2:1 was agreed upon by NTP engine designers to support a higher exhaust system maximum back pressure of 300 psia. A smaller AR reduces the diameter at the nozzle exit and length of the overall nozzle, which improves the structural integrity, thus allowing for higher pressure loading upon the nozzle. The smaller AR also causes the exhaust gas to exit the nozzle plane at a lower velocity, thus making the handling of the exhaust gas easier improving the performance of HECS.

Figure 1 and Table I show preliminary engine envelope and performance criteria used to develop the HECS concept. Engine characteristics will likely change as the design matures leading to possible minor changes in the HECS concept or sizing.



**Fig. 1.** Approximate Dimensional Envelope of Subscale NTP Engine with 2:1 area ratio (AR)<sup>4</sup>

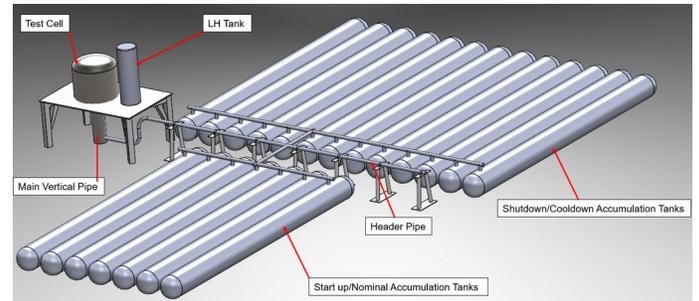
**TABLE I.** Subscale NTP Engine Properties 2:1 AR<sup>5</sup>

Property	Value
Thrust	12.5k or 5k lbf
Reactor Power	270 MW
Propellant	Hydrogen
Operational Mass Flow Rate	14 or 5 lbm/s
Cool Down Mass Flow Rate	0.01-1.4 lbm/s
Nozzle Exit Temperature	5000 R
Chamber Pressure	900 psia
Nozzle Area Ratio	2:1
Nozzle Back Pressure	300 psia

Pressure	
Burn Duration	5 minutes
# of Burns/Tests	≥ 1

## III. HECS DESCRIPTION

As seen in Figure 2, the HECS concept consists of a test cell, test stand, a liquid hydrogen supply tank, a main vertical pipe, a header pipe system, capture tanks, and other commodity supply systems (i.e. water, power, nitrogen, and helium). During all major phases of engine operations, the exhaust gas flows through the main vertical duct, through the header pipe, and into the accumulation tanks. Water sprays in the main vertical pipe slow/cool the exhaust gas, while water within the accumulation tanks at the beginning of a test are drained during testing to create volume for exhaust gas capture. The bottom of the main vertical pipe will contain borated water and catch any potential fission particulates or other objects ejected from the core in a failure scenario.



**Fig. 2.** HECS Model with Labeled Major Features

The internal pressure of the system is controlled by the water levels in the accumulation tanks downstream. With the higher back pressure, overall volume is compressed allowing for smaller COTS tanks, smaller COTS piping, and a shorter test stand, thus reducing the overall cost of the capture system. The reduction in volume is also what enables full capture of the exhaust gas. Since no exhaust gas is being released into the open air, regulatory approval is much more favorable for this concept compared to the previous PRCS concept.

The HECS concept was evaluated for a 12.5k lbf and a 5k lbf thrust NTP engine test with a 5-minute run duration to develop system sizing and estimated cost. Table II shows the impact of reducing the test article to 5k lbf thrust. The lower thrust reduces overall capture system dimensions downstream of the engine. The smaller dimensions drive easier manufacturing and assembly of the system, thus driving reduction in construction costs. A 5k lbf engine test also drives reduction in test stand height

and overall foundation footprint, thus further reducing construction costs. The following sections further describe these design features.

**TABLE II.** 12.5k lbf vs. 5k lbf Feature Changes

HECS Feature	12.5k Engine	5k Engine
Test Cell	20 ft x 15 ft	20 ft x 15 ft
Accumulation Tanks	20	16
Vertical Duct Diameter	6 ft	3 ft
Vertical Duct Length	22 ft	13 ft
Header Diameter	1.5 ft	1 ft
Header Length	175 ft	175 ft

### III.A. Test Cell

The current test stand design assumes that the reactor and non-nuclear engine subsystems are assembled prior to entry into the test cell. In order to minimize cost, the test cell shall only accommodate installation and integration of the reactor to the Non-Nuclear Engine Sub-System (NNE SS). The test cell shall still accommodate shielding, the subscale NTP engine envelope, instrumentation, lifting crane, and other equipment. The test cell will be isolated from the main vertical duct for ease of purging and to eliminate  $\text{GH}_2$  and  $\text{H}_2\text{O}$  back flow into the test cell. Engine entry and exit of the test cell is still under consideration. A top opening in the test cell is one option being considered with an external crane to lift subsystems and equipment in and out of the test cell.

### III.B. Main Vertical Pipe

The current conceptual design includes COTS carbon steel pipe for the main vertical pipe. The bottom of the main vertical pipe will have 3 feet of borated water acting as a catch tank. A CFD analysis was conducted for the previous PRCS concept to determine dimensions and assess the water spray system design within the main piping. The analysis evaluated a 12.5k lbf thrust test, operating for 5 minutes with a 20 psia system back pressure. This analysis was used to derive the specifications for the HECS concept until an updated CFD analysis is conducted. Pipe dimensions were designed to be 6 feet in diameter and 22 feet long for the 12.5k lbf thrust concept with the 5k lbf thrust concept having a diameter of 3 feet and a length of 13 feet.

The system contains 1 set of evaporative sprays and 1 set of condensing sprays. The evaporative spray system consists of 4 nozzles oriented downward at 60 degrees to vertical. Each nozzle releases water at 750 gpm at 75 ft/s. The condensing spray system consists of 18 nozzles oriented downward at 90 degrees to vertical. Each nozzle releases water at 72 gpm at 75 ft/s. The water spray

system reduces the inlet exhaust gas from 2700 K and Mach 2 to 367 K and  $\leq$  Mach 0.2. Due to the smaller AR ratio of the nozzle, the water spray systems effectiveness is greater compared to the prior PRCS concept. The water spray system will pull water directly from a pond or reservoir. Overall cost is greatly reduced from previous concepts due to the utilization of COTS piping, reduction of test stand footprint/height, and reduction in the catch tank size.

### III.C. Tanks

In the HECS concept, the hydrogen header pipe has two sets of accumulation tank configurations branching out from it. The accumulation tanks provide total capture of the exhaust gas during all stages of NTP engine testing. One set of accumulation tanks will collect the exhaust gas during start-up/nominal operations, while the second set of accumulation tanks will collect the exhaust gas for shutdown/cool-down. The accumulation tanks are rated for 300 psig and 250°F with a proposed size of 90k gallons (11ft in diameter, 130ft in length). For the 12.5k lbf HECS concept, 7 accumulation tanks are required for start-up/nominal operations and 13 tanks are required for shutdown/cool-down. For the 5k lbf HECS concept 3 accumulation tanks are required for start-up/nominal operations. The mass flow rates during cool down for a 5k lbf thrust engine test were not available, so the tank numbers for shutdown/cool-down were held constant at 13 as a conservative estimate. The tank quantities are established for a 5-minute run duration. Forward work includes determining 5k lbf thrust shutdown/cool-down flow rates and updating the tank quantities to reflect accordingly. Accumulation tanks are assumed to be COTS items to minimize cost.

Pumps will be required to supply water to fill the accumulation tanks to their appropriate levels from a reservoir before testing is to start. Pumps and drain valves will ensure appropriate water levels within the accumulation tanks during all stages of operations which controls internal back pressure and will also be used to evacuate the water from the accumulation tanks to a lined pond/reservoir.

### III.D. Tank Piping and Valves

A header pipe will feed the two sets of accumulation tank configurations. The carbon steel header pipe would likely be a COTS item. The header pipe diameter is 1.5ft for the 12.5k lbf HECS concept and 1ft for the 5k lbf HECS concept. The length is 175ft for both concepts. As cool-down flow rates are better understood for the 5k concept, the overall header pipe length will be reduced. A cool-down specific 12 inch carbon steel pipe will connect the main vertical pipe to the shutdown/cool-down tank manifold piping for direct exhaust capture at lower

pressures which is controlled by an isolation valve. A check valve is placed upstream of the start-up/nominal ops accumulation tanks to prevent back flow. A shut off valve is placed upstream of the shutdown/cool-down accumulation tanks and within the main vent header between the two tank systems to isolate the shutdown/cool-down tanks from nominal operations.

### III.E. Consumables

The consumables and supply tanks were sized for a 5-minute ground test of a 12.5k lbf NTP engine. A 12,000 gallon liquid hydrogen (LH) run tank will be required to supply propellant to the engine during start up, nominal operations, and shutdown/cool-down. The run tank itself and the piping entering/exiting the tank will be vacuum jacketed. The conceptual design sets the LH run tank level with the NTP engine outside of the test cell on the test stand. A gaseous hydrogen (GH) pressurization system requiring approximately 1,000 cubic feet of GH will be required in order to maintain the required pressures of the LH system. The pressurization system provides pressure to maintain adequate flow from the LH run tank to the NTP engine. Approximately 20 cubic feet of high pressure gaseous helium will be required for engine start up and purging of the engine/upstream piping. About 3,000 cubic feet of GN<sub>2</sub> will be used for purging of the volume within the exhaust capture system before and after ground testing. Purge gases will be stored in a bottle farm at the base of the test stand. Finally, approximately 1.5M gallons of water will be required for a 5-minute ground test. The water will be supplied and drained to a lined reservoir or retention pond that would also be located close to the test stand. The consumables required are reduced for a 5k lbf thrust NTP engine test due to a lower mass flow rate during nominal operations. Exact determination of consumables for a 5k lbf thrust level test is forward work.

### III.F. Test Stand/Structure

The foundation will need to support the main vertical pipe and the accumulated water within the pipe post-test. The main test stand will support the test cell and items within the test cell (engine, shielding, instrumentation, etc.). The main test stand will require a minimum height of 21 ft for the 12.5k lbf HECS concept and a minimum height of 12 ft for the 5k lbf HECS concept. The equally spaced support beams required to hold up the header pipe will be a minimum height of 16 ft for the 12.5k lbf HECS concept and a minimum height of 12 ft for the 5k lbf HECS concept.

### IV. HECS CONOPS

The following CONOPS was developed for the HECS conceptual design for a feasibility assessment and cost estimation. The CONOPS is somewhat complex

during engine transients and will be further refined as the design continues to mature.

As seen in Figure 3, prior to testing, all accumulation tanks are filled with water and the main vertical pipe is filled to 3 ft from the base. One set of accumulation tanks will collect the exhaust gas during start-up/nominal operations, while the second set of accumulation tanks will collect the exhaust gas for shutdown/cool-down. Both sets of tanks are controlled and isolated by valves.

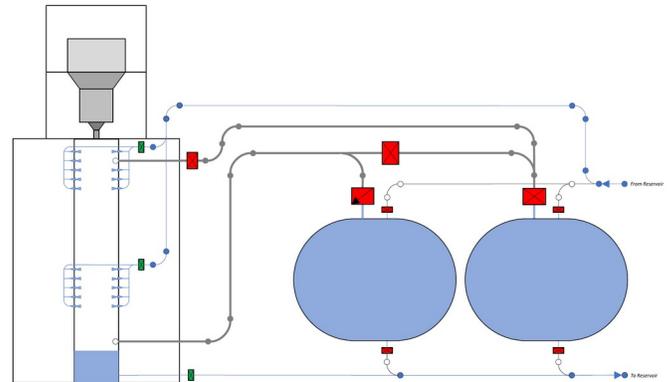


Fig. 3. HECS Prestart Phase

As seen in Figure 4, during start-up/nominal operations, the start-up/nominal accumulation tanks drain valves open, slowly evacuating the water and controlling the back pressure as the exhaust gas flows through the main vertical pipe while getting cooled and slowed by the water spray systems. A drain valve in the main vertical pipe is in the opened position at this time to control the water level. As the gas flows out of the main vertical pipe exit manifold, it flows through the start-up/nominal ops check valve and into the accumulation tanks. At this time the shutdown/cool-down accumulation tanks are isolated from the mainstage exhaust flow through two shut off valves and remain full of water.

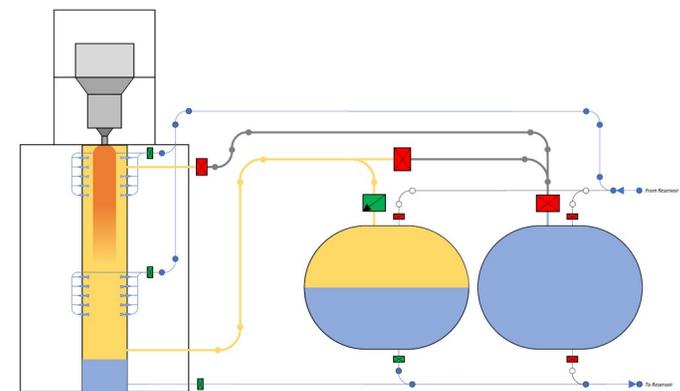
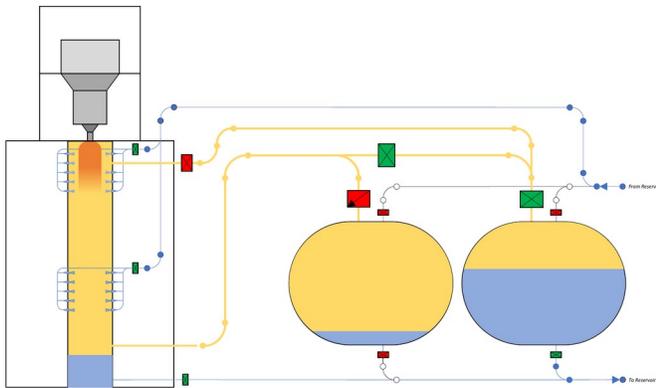
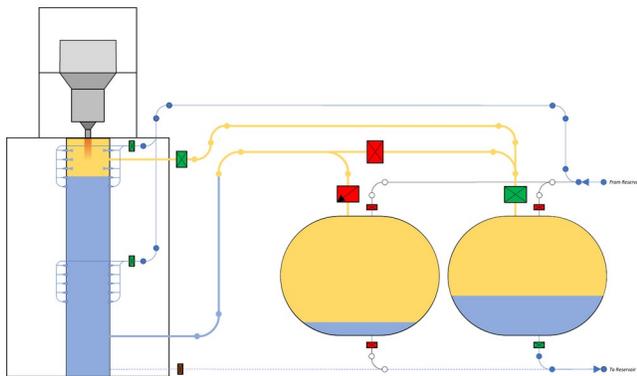


Fig. 4. HECS Start-up/Nominal Phase

Once nominal operations are complete, and shutdown begins, as seen in Figure 5; the start-up/nominal accumulation tanks drain valves close and the two isolation valves leading to the shutdown/cooldown accumulation tanks opens. The shutdown/cooldown tanks drain valves open as well, evacuating the water to create volume to capture the shutdown flow, and controlling overall capture system pressure. When the shutdown profile ends and the cooldown profile begins, a isolation valve within the main vent header closes and another isolation valve in the separate cooldown pipe opens, thus redirecting the cooldown flow only to the shutdown/cooldown tanks at a lower pressure as seen in Figure 6.



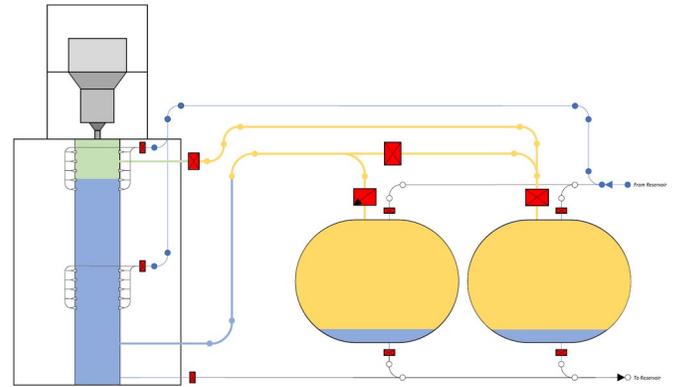
**Fig. 5.** HECS Shutdown Phase



**Fig. 6.** HECS Cooldown Phase

Once shutdown/cool-down ends and the associated accumulation tanks are filled, the shutdown/cool-down isolation valves and accumulation tanks drain valves close, as seen in Figure 7. The vertical pipe drain valve is closed as well. The water spray system continues to run, accumulating water into the main vertical pipe and the exit manifold since the vertical pipe drain valve is now

closed. The accumulation of water creates a water seal within the system to prevent exhaust gas backflow and also reduces the volume needed to be purged. Once the water accumulation is complete, the 1 inch nitrogen ( $GN_2$ ) purge inlet valve and the 12 inch vent valve connected to the main vertical duct are opened. A nitrogen purge floods the remaining volume in the main vertical pipe, pushing any remaining exhaust gas into the vent header, cooldown piping, and accumulation tanks, thus increasing overall safety around the test cell/duct interface.



**Fig. 7.** HECS Post-Cooldown/Purging Phase

## V. COST

The ROM cost estimate for the 12.5k lbf and 5k lbf HECS concept based on the above descriptions are approximately \$250M and \$200M respectively. This shows that a technology demonstration may provide a somewhat cost effective method to demonstrate both engine and ground testing technologies prior to making the estimated approximate \$1B investment for a RT or RECS system. As the HECS concept matures, updates will be made to refine the cost estimate.

## VI. EXHAUST GAS PROCESSING

A real-time processing system with COTS components for cooldown flow is currently being explored as well. The processing system shown in Figure 8 would take potentially contaminated, cooldown exhaust flow gas from the engine and remove the fission products (if any) with smaller, readily available equipment/components. The process is similar to International Atomic Energy Agency (IAEA) and DOE documented processes for isotope removal. As cooldown flow rates taper down, the exhaust flow can be redirected directly to the system instead of entering storage tanks. Processing the cooldown flow is appealing because it reduces the need to store large exhaust gas volumes, thus reducing the need for many tanks. It also reduces the amount of water required. Additionally, run durations greater than 5 minutes could be considered if cooldown flow is processed, which aids in data collection and development of NTP engines.

The liquid nitrogen spray cooler is the most complex component of the system. Running the exhaust gas through a liquid nitrogen bath, running the liquid nitrogen through copper piping that would coil around the exhaust gas, and directly injecting the exhaust gas with liquid nitrogen have been explored. Future work includes refining the liquid nitrogen spray cooler and exploring the processing system for a higher internal pressure equal to the pressure within the HECS concept.

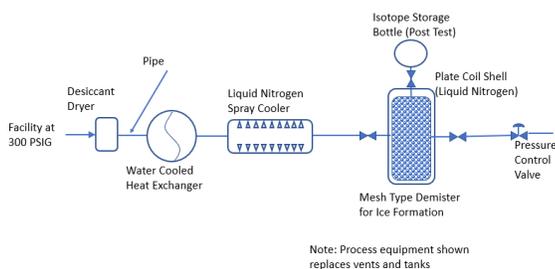


Fig. 8. Smaller Scale Real Time Processing System<sup>5</sup>

## VII. CONCLUSION AND FORWARD WORK

The HECS concept provides a simplified exhaust system that could be utilized for a technology demonstration. It reduces overall technical risk and cost with an approximate 75% cost reduction compared to the RT and RECS concepts. HECS also provides a higher likelihood for regulatory approval than prior technology demonstration concepts due to its total capture capabilities.

Forward work around the HECS concept includes determination of cooldown flow for a 5k lbf thrust level engine test, associated tank volumes, subscale RT processing of the HECS cooldown flow, and CONOPS refinement. An updated CFD analysis is underway to confirm the water spray configuration and effectiveness. Finally, exploration of reducing the Isp requirement and effects on the HECS concept is to be evaluated.

## ACKNOWLEDGMENTS

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