



Low Enriched Uranium (LEU) Nuclear Thermal Propulsion: System Overview and Ground Test Strategy

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**JANNAF Programmatic and Industrial Base Testing and
Evaluation Technical Interchange Meeting**

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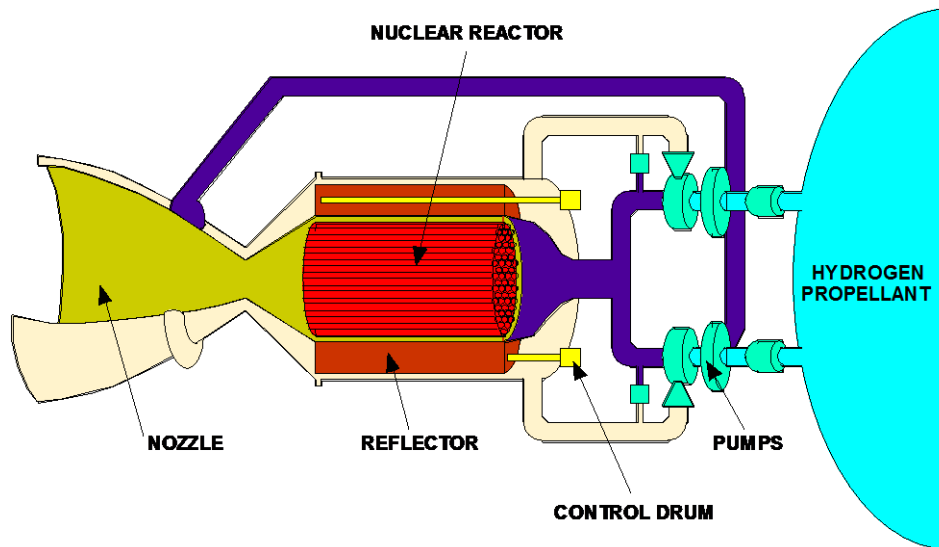


How Does Nuclear Thermal Propulsion (NTP) Work?

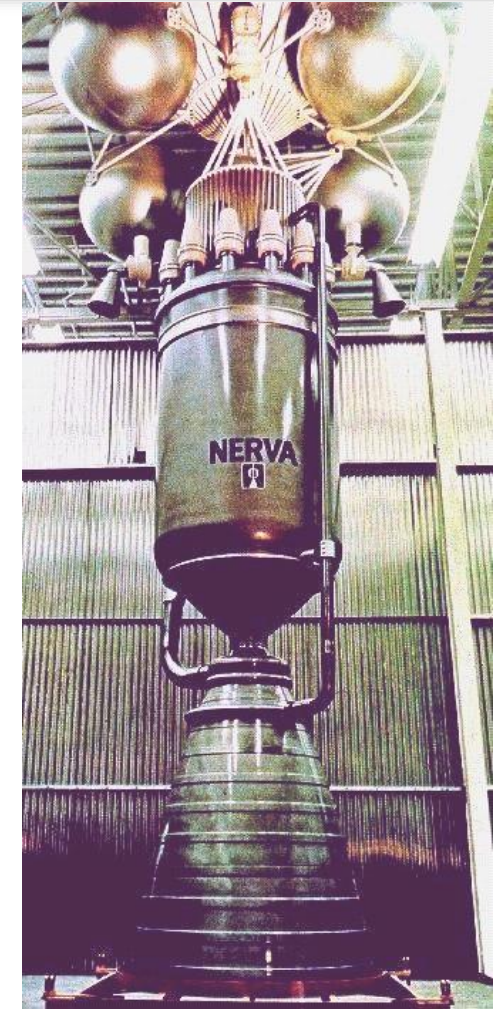
SPACE TECH'S GAME CHANGING DEVELOPMENT PROGRAM

Propellant heated directly by a nuclear reactor and thermally expanded/accelerated through a nozzle

- ❖ Low molecular weight propellant – typically Hydrogen
- ❖ Specific Impulse directly related to exhaust temperature, e.g.: 2850K exhaust temperature translates to ~900 sec Isp



Major Elements of a Nuclear Thermal Rocket



XE-Prime Nuclear Thermal Rocket Prototype



Nuclear Thermal Propulsion (NTP) Game Changing Development Project Overview

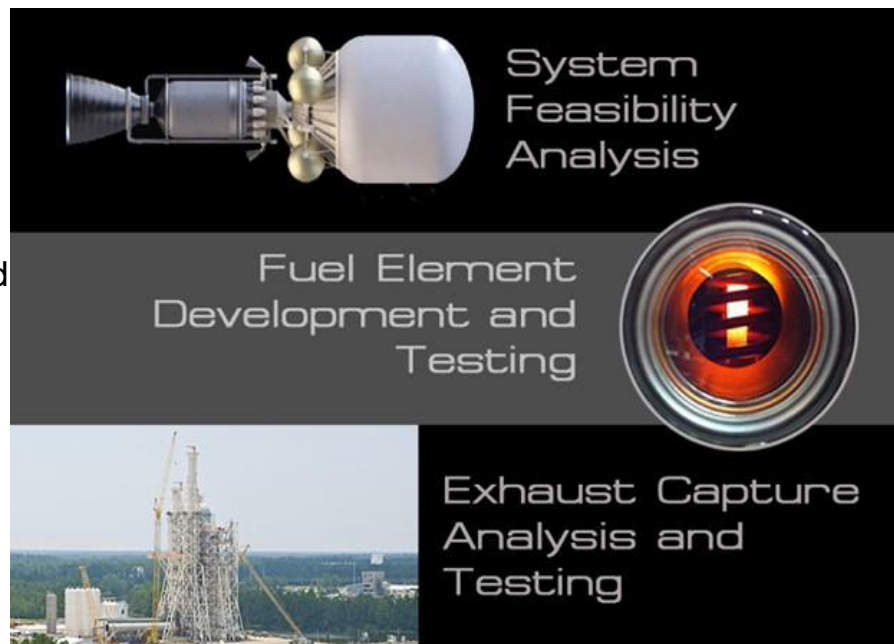


Project Description:

- Determine Low Enriched Uranium (LEU) NTP feasibility and affordability, with good cost and schedule confidence, prior to a decision to proceed with full scale development.
- Demonstrate the technology that enables the development of high temperature, minimum erosion/fission product release fuel elements (FE) using LEU.
- Leverages government, industry and academic expertise and existing facilities.

Roles and Responsibilities

- **MSFC:** PM, SE & Analysis Lead, Cryo ConOps Lead, FE Testing
- **GRC:** Cryocooler Testing, Cryo ConOps Support, Sys. Analysis Support
- **SSC:** Rocket Exhaust Capture System DDT&E
- **KSC:** Ground Processing ConOps / Propellant Densification
- **Aerojet Rocketdyne:** LEU Engine Analysis
- **AMA:** Engine Cost Lead
- **Aerospace:** Engine Cost Independent Review
- **BWXT:** Fuel Element / Reactor Design/Fabrication
- **DOE:** FE / Reactor Design and Fabrication Support



Full Funding Profile (all years):

• Budget vs. Requirements

	<u>FY16</u>	<u>FY17</u>	<u>FY18</u>	<u>FY19</u>	<u>Total</u>
Approved	5.754	19.200	20.000	7.032*	51.986
Required	5.754	19.200	20.000	7.032*	51.986
Delta	0.000	0.000	0.000	0.000	0.000

*FY 19 est.



NTP Current Baseline



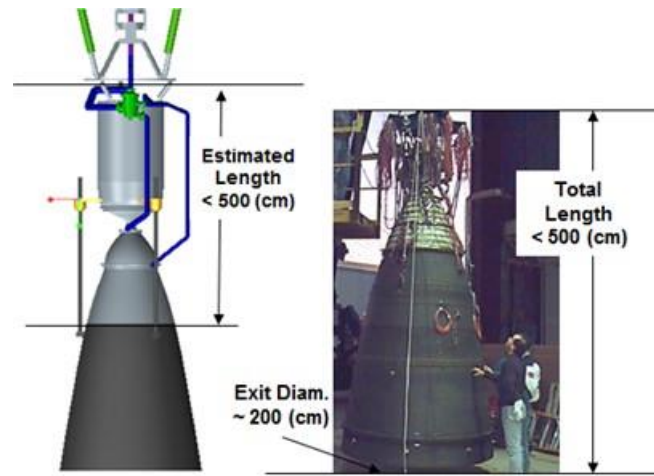
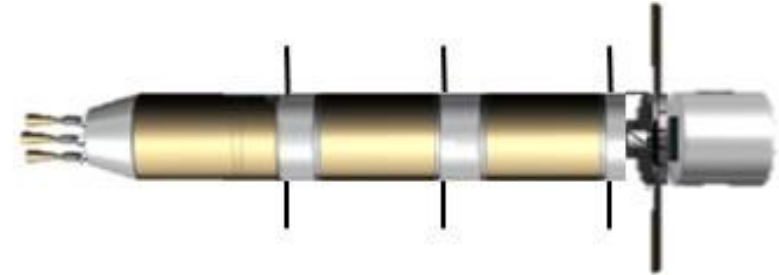
- Reviewed past design efforts and testing to construct most affordable path to an NTP for Mars missions

- Baseline Design

- 25,000 lbf thrust
- ~500MW
- Exhaust capture ground testing

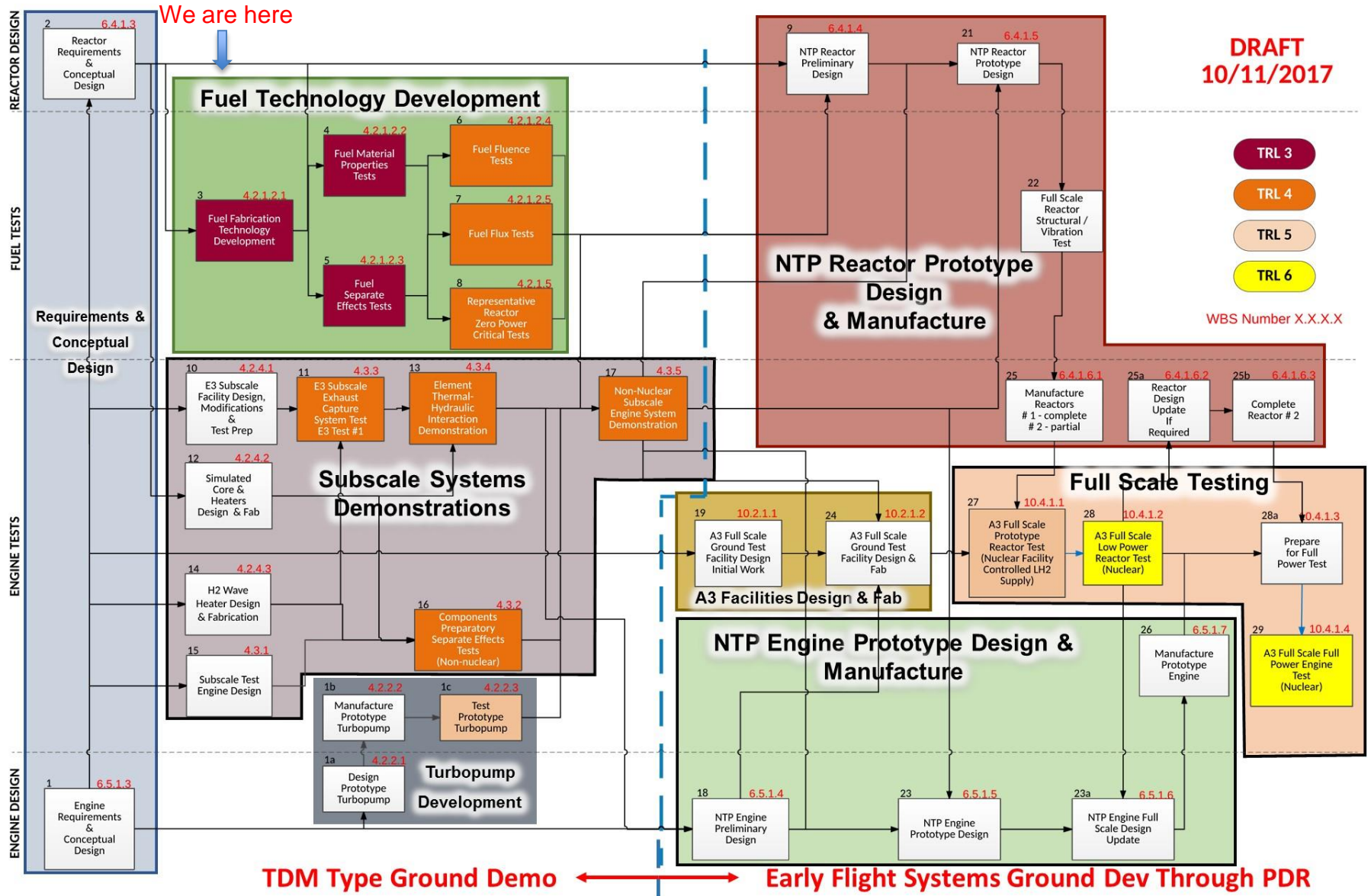
- Uses Low Enriched Uranium (LEU)

- Enables the use of commercial manufacturing methods to arrive at best NTP system design to reduce cost with no impact on performance
- Use of LEU is consistent with US/international efforts to eliminate HEU in all civilian applications
- Enables tremendous programmatic flexibility, increasing choice of facilities, and project participants



Size comparison: Baseline 25klbf NTP (Left) vs. RL10 (right) Source: Aerojet Rocketdyne

NTP Technology Maturation Plan



NTP Technology Ground Test Strategy



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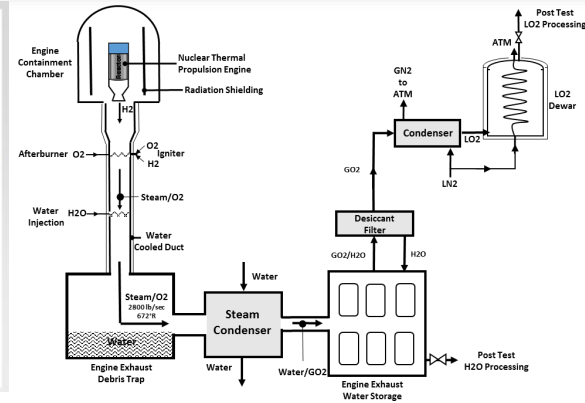
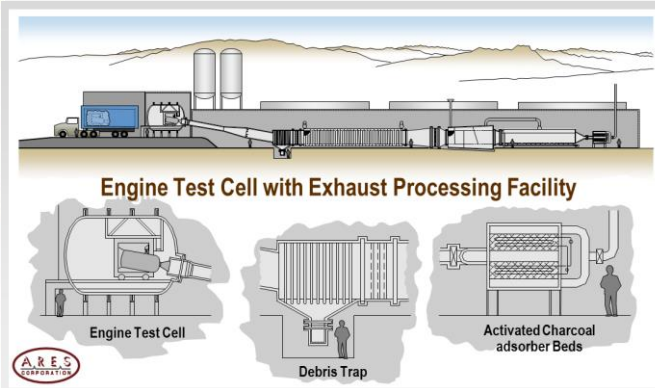
- **SSC has been supporting MSFC since FY14 on the AES/Nuclear Thermal Propulsion (NTP) Project.**
 - Project goal is to demonstrate the affordability and viability of nuclear thermal rocket propulsion
 - Current focus is to define an affordable development and qualification strategy

Background

NTP Ground Test Options



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◆ Bore Hole Bore Hole

- Relies on permeability of desert alluvium soil to filter engine exhaust
 - Unresolved issues on water saturation effects on soil permeability, hole pressure during engine operation, and soil effectiveness in exhaust filtering

Above Ground Scrubber

◆ Above Ground Scrubber and NNSS (Nevada National Security Site) P-Tunnel Scrubber Option

- Engine exhaust is filtered of radioactive aerosols and noble gases and directly flared to atmosphere
 - Nuclear Furnace (NF-1) ground test scrubber successfully tested at the end of Rover/NERVA project
 - DOE and ASME standards available for nuclear air cleaning and gaseous waste treatment

Engine Exhaust Capture

Current NTP Project Baseline

◆ Engine Exhaust Capture

- Engine hydrogen exhaust is burned at high temperatures with oxygen, producing O₂ rich steam that is cooled, condensed, and collected for controlled processing and disposal
 - All analyses to date indicate system will reliability and economically accomplish task
 - Subscale test project in design with testing planned for 2Q19

NTP Ground Test Engine Exhaust Capture System



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NTP Project decision to baseline the Exhaust Capture System as the NTP engine ground test approach was based on:

1. Its ability to reliably assure containment of potentially liberated reactor radionuclides and fuel element debris
2. Availability of existing NASA rocket propulsion test infrastructure uniquely suited to accommodate system requirements
3. Decision to baseline LEU reactor engine
 - Substantially minimizes the cost of site security and site licensing

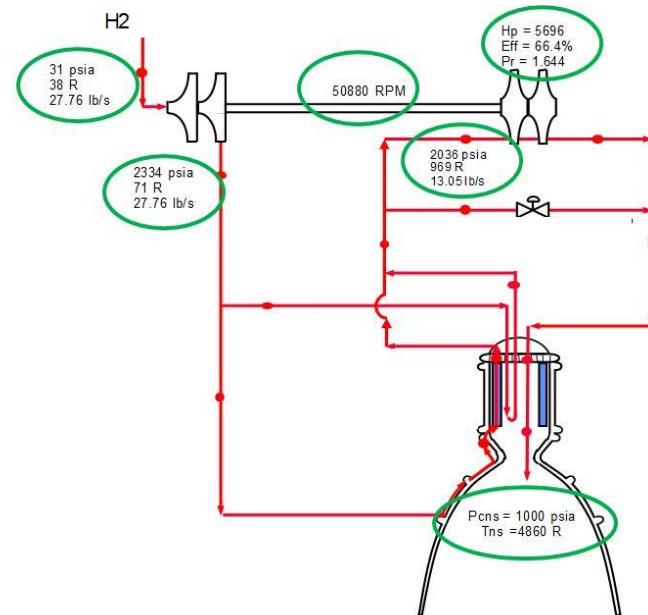
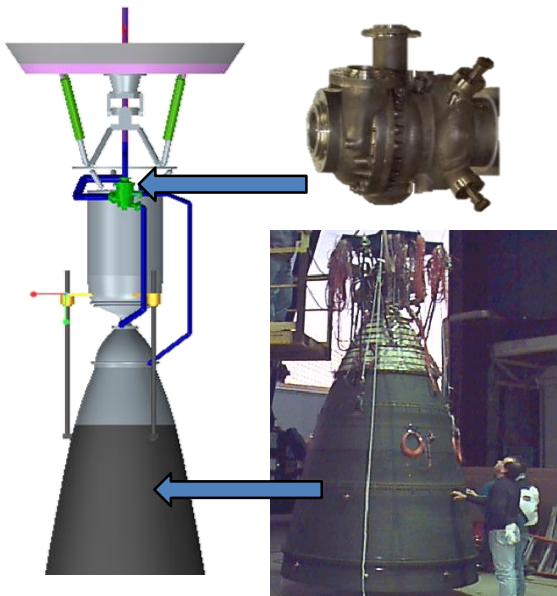
Recently initiated NTP Project study is re-reviewing Ground Test Options

LEU NTP Based on Liquid Rocket Engine Technology



- **LEU NTP has synergy with current cryogenic fluids system technology development (e.g., Mars lander chemical propellant storage)**
 - Engine operates similar to current liquid rocket engines (LRE) (e.g., expander RL10)
 - LEU NTP hydrogen flow-rates for 25,000-lbf engine similar to current expander cycle engines
 - Not a high pressure, complex SSME type propulsion cycle
 - Major systems just like O₂/H₂ and O₂/CH₄ engine designs
 - Similar turbine design, pump and chamber pressures, nozzle-chamber heat loads, nozzle size

Turbomachinery Sized Per RL60 (e.g., RL10 Derivative)

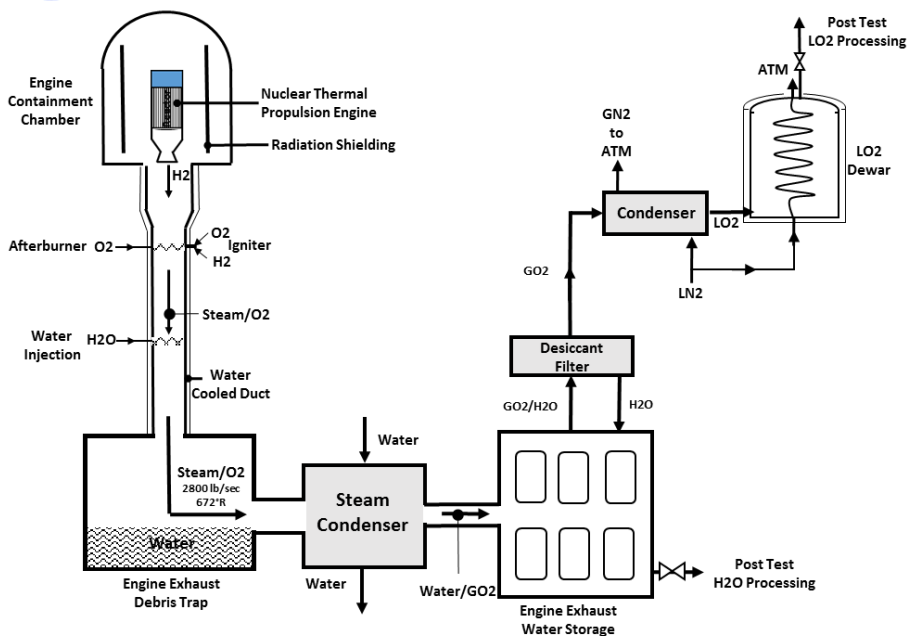


LEU NTP Technology Risks Reduced Using LRE Knowledge Base



NTP Ground Test Strategy

Engine Exhaust Capture System



Strategy:

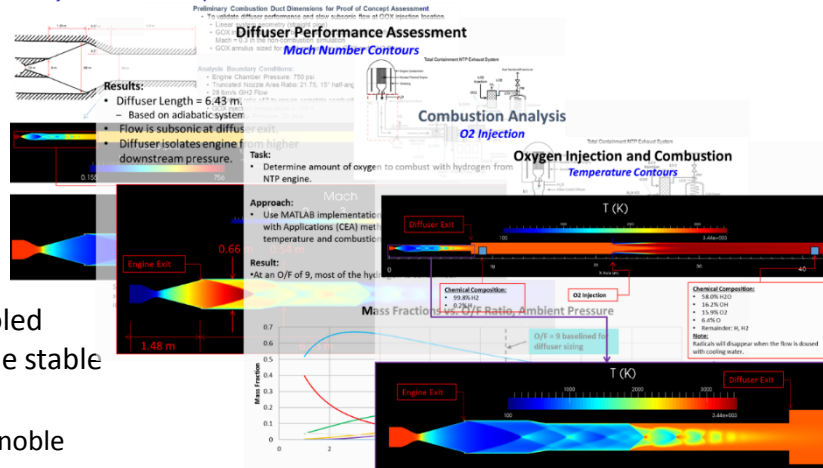
- Fully Contain engine exhaust
- Methodically drain containment vessels after test to ensure proper filtration

Preliminary system sizing and performance analysis of this concept have been completed and no operations performance issues have been identified

How it works:

- Hot hydrogen exhaust from the NTP engine flows through a water cooled diffuser that transitions the flow from supersonic to subsonic to enable stable burning with injected LO2
 - Products include steam, excess O₂ and potentially, a small fraction of noble gases (e.g., xenon and krypton)
- Water spray and heat exchanger dissipates heat from steam/O₂/noble gas mixture to lower the temperature and condense steam
- Water tank farm collects H₂O condensate and any radioactive particulates potentially present in flow.
 - Drainage is filtered post test.
- GO₂ condenser cools residual gas to LN₂ temperatures, condenses O₂ and noble gasses.
 - LOX Dewar stores LO₂ and noble gases, to be filtered post test.

System Pressure and Temperature Contours for Full Scale NTP



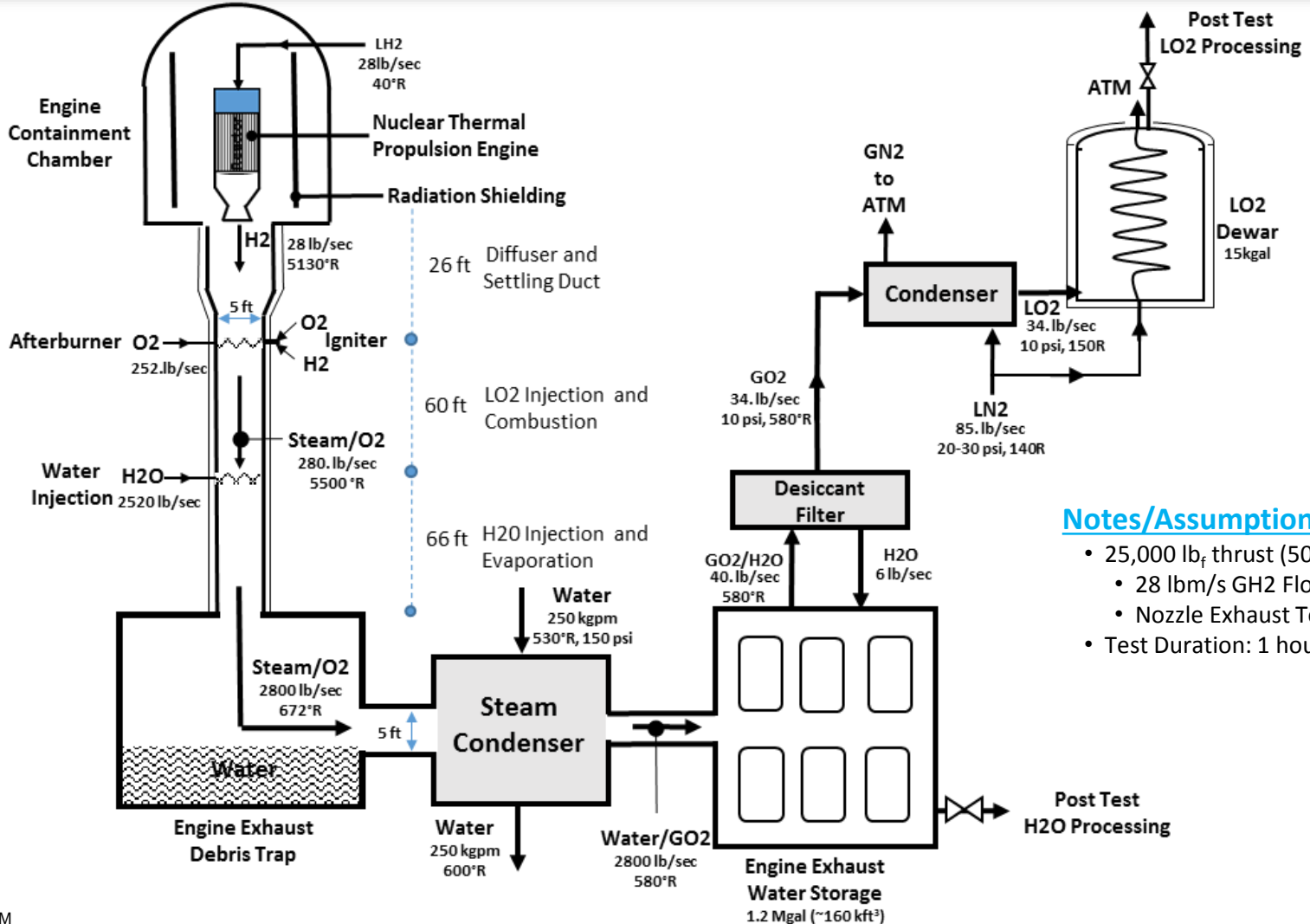
All system operating pressures and temperatures and fluid supply and flow requirements are well within existing chemical rocket propulsion test capability and experience.



Engine Exhaust Capture System

Preliminary System Sizing - 25 klb Engine

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Notes/Assumptions:

- 25,000 lb_f thrust (500MW)
- 28 lbm/s GH2 Flow.
- Nozzle Exhaust Temp: 2850 K
- Test Duration: 1 hour

Engine Exhaust Capture System

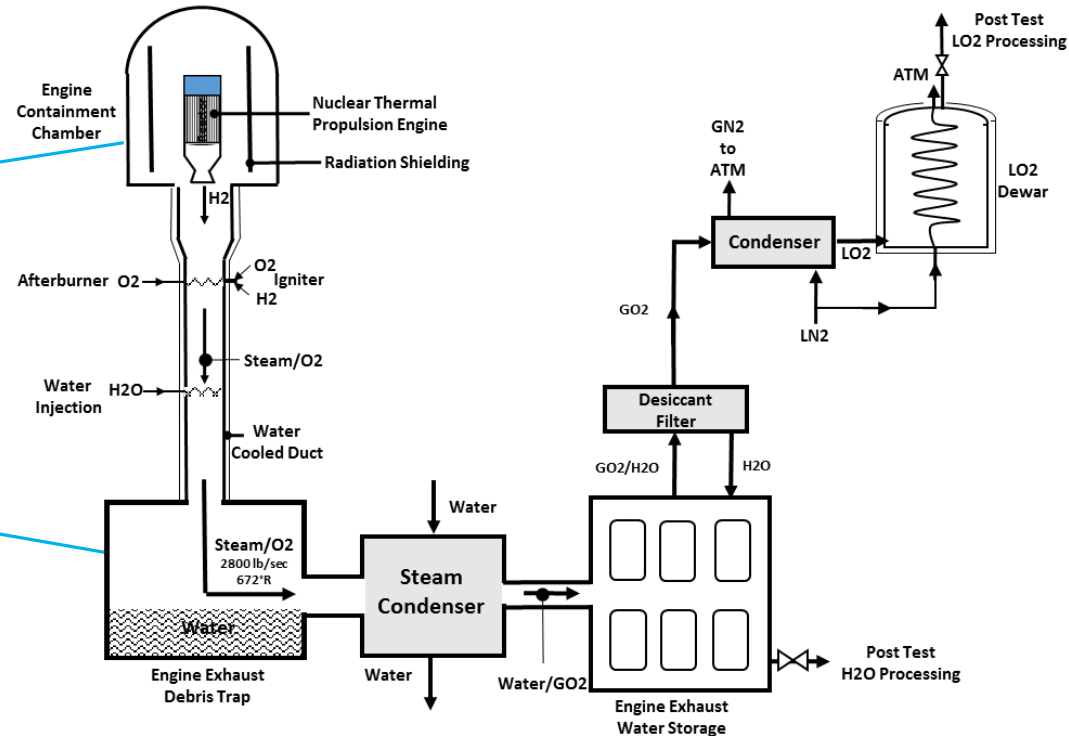
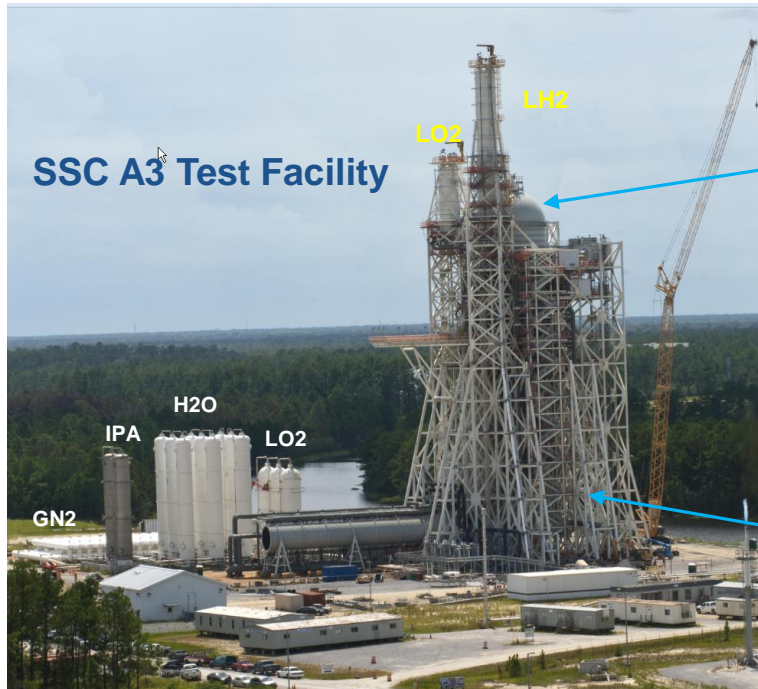
Conceptual System Design Layout (Full-Scale)



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Facility located at SSC's A3 Test Stand (Current NTP Project Baseline)

- Most of the infrastructure required by the NTP engine exhaust capture ground test facility is already in place:
 - Tower, test cell, propellant, HPIW, data acquisition and controls infrastructure, the Test Control Center, electric power, etc.
 - Major modifications, procurements, and construction work will be required and are captured in a ROM estimate.



ROM estimate to prepare stand for NTP engine test is under development



Nuclear Thermal Propulsion Technology Development

- **Evolving Baseline Scope for NTP Ground Test Activities at SSC**
 - **Current, Non-Nuclear Test Project at SSC's E3 (FY18/19)**
 - **Sub-scale Engine Exhaust Capture System**
 - Project and funding approved for Phases 1 & 2
 - Phase 1 underway with testing in FY19
 - **Phase 3: Tunable Hydrogen Wave Heater follow-on (FY20)**
 - **Non-Nuclear NTP Engine Development Tests**
 - **Sub-Scale Turbopump Testing**, potentially starts in 2-3 years
 - **Sub-Scale Reactor Simulator**, potentially starts in 4 to 6 years
 - **Nuclear Systems Test**
 - **NTP Engine Testing**, start testing in 12-14 years
 - **NTP engine PowerPack testing**
 - **Full Flow, non-nuclear test** (a depleted uranium reactor, hot hydrogen flow) to evaluate flow characteristics and structural integrity of the engine before testing an actual NTP engine.
 - **NTP reactor multi-element test** (<20 MW testing vs 500MW of the full scale NTP engine)



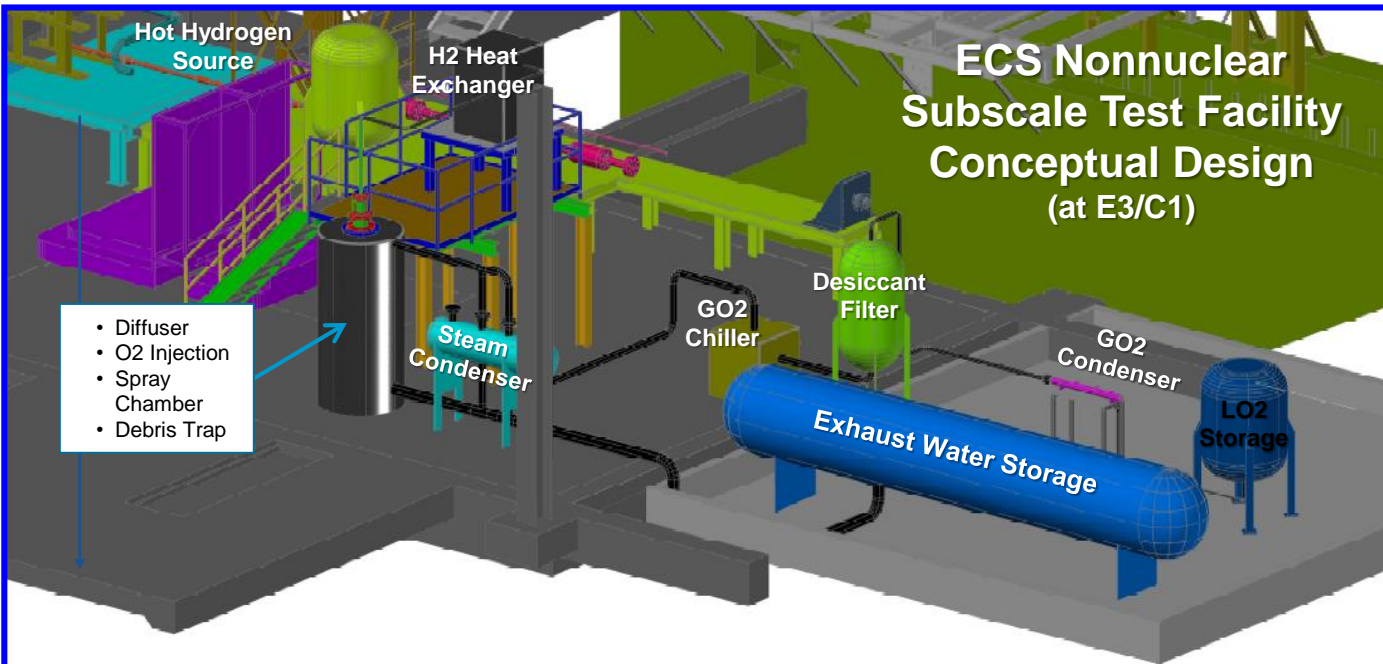
Nuclear Thermal Propulsion Technology Development

- **Evolving Baseline Scope for NTP Ground Test Activities (continued)**
 - **Potential New Facilities**
 - **Zero-power reactor facility/project**, a new facility for nuclear reactor element quality evaluation
 - **Engine Maintenance and Disassembly Facility (EMAD)**, a new facility for engine assemble and post test disassembly and evaluation.

NTP Engine Exhaust Capture System Testing

Nonnuclear Subscale Demonstration Testing

Facility being designed to demonstrate the feasibility, safety, efficacy, and affordability of the RECS concept.



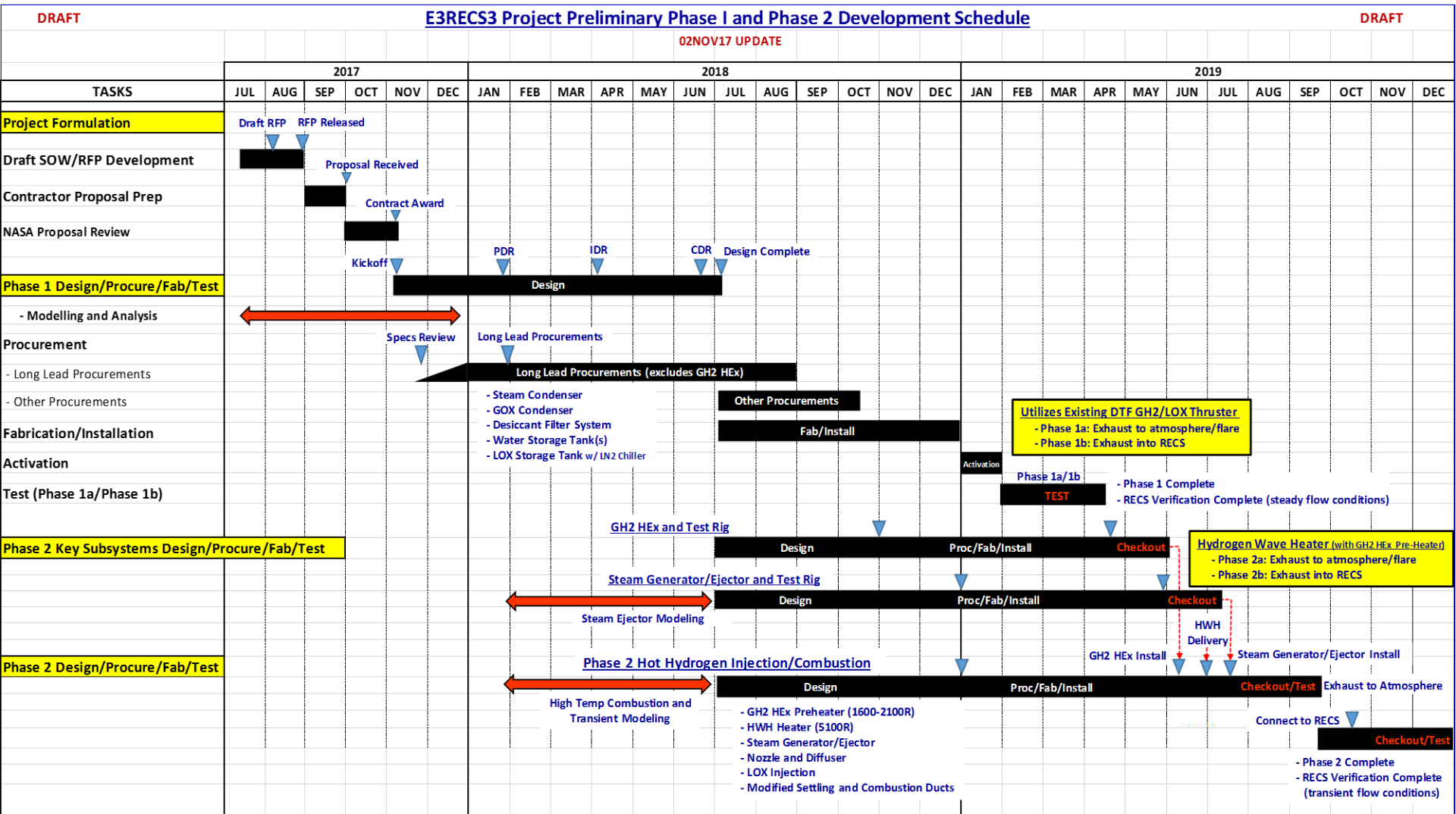
Key Subscale Test Program Goals

- Demonstrate efficacy of the RECS concept
- Verify H2 afterburning
- Understand system startup and shutdown transients
- Assess alternative design and technology infusion options
- Develop and validate test ops procedures
- Supports nuclear site licensing regulatory and NEPA/EIS processes
- Builds public confidence in test safety

• Nonnuclear RECS Subscale Demonstration Testing is currently the #1 priority for augmented STMD/GCD NTP Program funding (within the current congressional budget):

- Phase 1 (FY18-19), \$6.7M, Initial Design, Construction, and GH2 operating temperature = 1,600°R/1,140°F
- Phase 2 (FY19-20), \$2.0M, GH2 temperature increase to 5,000°R/4,540°F

E3RECS3 Project Preliminary Phase 1 and Phase 2 Development Schedule





Summary

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LEU NTP has synergy with current cryogenic fluids system technology development

- Engine operates similar to current liquid rocket engines
- Major systems just like O₂/H₂ and O₂/CH₄ engine designs
 - Similar turbine design, pump and chamber pressures, nozzle-chamber heat loads, nozzle size

NTP Engine Ground Test Exhaust Capture System Project baseline based on :

1. Its ability to reliably assure containment of potentially liberated reactor radionuclides and fuel debris
 2. Availability of existing NASA rocket propulsion test infrastructure uniquely suited to accommodate system requirements
 3. Decision to baseline LEU reactor engine
 - Substantially minimizes the cost of site security and site licensing
- Subscale ground test demonstration project underway

Recently initiated NTP
Project study is re-reviewing
Ground Test Options