A Nuclear Cryogenic Propulsion Stage for Near-Term Space Missions

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Development efforts in the United States have demonstrated the viability and performance potential of NTP systems. For example, Project Rover (1955 – 1973) completed 22 high power rocket reactor tests. Peak performances included operating at an average hydrogen exhaust temperature of 2550 K and a peak fuel power density of 5200 MW/m^3 (Pewee test), operating at a thrust of 930 kN (Phoebus-2A test), and operating for 62.7 minutes on a single burn (NRX-A6 test).[1] Results from Project Rover indicated that an NTP system with a high thrust-to-weight ratio and a specific impulse greater than 900 s would be feasible. Excellent results have also been obtained by Russia. Ternary carbide fuels developed in Russia may have the potential for providing even higher specific impulses.

Nomenclature

CFEET	=	Compact Fuel Element Environmental Test
DOE	=	Department of Energy
HAT	=	NASA Human Architecture Team
HIP	=	Hot Isostatic Press
NASA	=	National Aeronautics and Space Administration
NCPS	=	Nuclear Cryogenic Propulsion Stage

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NTP = Nuclear Thermal Propulsion
NTR = Nuclear Thermal Rocket
NTREES = Nuclear Thermal Rocket Element Environmental Simulator
PEC = Pulsed Electric Current
SLS = Space Launch System

I. INTRODUCTION

Many factors would affect the development of a 21st century nuclear thermal rocket (NTR). Test facilities built in the US during Project Rover are no longer available. However, advances in analytical techniques, the ability to utilize or adapt existing facilities and infrastructure, and the ability to develop a limited number of new test facilities may enable an affordable, viable development, qualification, and acceptance testing strategy for the NCPS. Although fuels developed under Project Rover had good performance, advances in materials and manufacturing techniques may enable even higher performance fuels. Potential examples include cermet fuels and advanced carbide fuels. Precision manufacturing will also enable NTP performance enhancements.

NTP will only be utilized if it is affordable. Testing programs must be optimized to obtain all required data while minimizing cost through a combination of non-nuclear and nuclear testing. Strategies must be developed for affordably completing required nuclear testing. A schematic of an NCPS engine is shown in Figure 1.

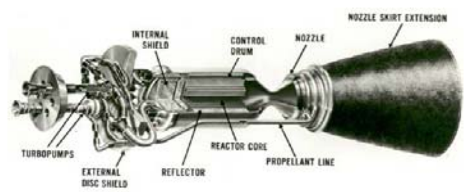


FIGURE 1: Schematic of an NCPS engine.

NASA's Nuclear Cryogenic Propulsion Stage (NCPS) project was initiated in October, 2011, with the goal of assessing the affordability and viability of an NCPS. Key elements of the project include: 1) Pre-conceptual design of the NCPS and architecture integration; 2) Development of a High Power (~1 MW input) Nuclear Thermal Rocket Element Environmental Simulator (NTREES); 3) NCPS Fuel Design and Testing; 4) NCPS Fuels Testing in NTREES; 5) Affordable NCPS Development and Qualification Strategy, and 6) Second Generation NCPS Concepts. In September, 2012 the decision was made to redirect the focus of the sixth element away from second generation concepts and towards devising NCPS designs suitable for near-term missions. Work in this area was then incorporated into the overall pre-conceptual design and architecture integration activity. The NCPS project involves a large (~50 person) NASA/DOE team supplemented with a small amount of procurement funding for hardware and experiments. In addition to evaluating fundamental technologies, the team is assessing many aspects of the integrated NCPS, and its ability to significantly enhance or enable NASA architectures of interest.

II. Pre-Conceptual Design of the NCPS and Architecture Integration

The NCPS is an in-space propulsion stage using fission as the energy source to heat propellant (hydrogen) and expand it though a nozzle to create thrust. The increase in engine performance available from even a first generation NCPS would enable more ambitious exploration missions, both robotic and human. It is the intent of the NCPS project to develop a pre-conceptual design of a first generation stage with one or more NTRs capable of interfacing with operational or soon to be available launch vehicles. Ideally, the NCPS would enhance or enable a wide variety of advanced missions of interest. One emphasis for the initial NCPS is affordability, and thus the design must utilize technologies that are readily available with minimal risk to development. The design must take into account the development viability/feasibility, affordability, and potential reusability. A strategic method of development must be considered; assessing both commonality and scalability for miniaturization or growth. Other strategic considerations are the testing approach (a combination of terrestrial and space testing to validate the engine) and the need for sustained funding. There are also significant programmatic reasons to keep system highly enriched uranium (HEU) requirements as low as reasonably achievable.

The NCPS must show relevance to the U.S. space exploration goals and must provide a development path toward a feasible, affordable, and sustainable Nuclear Cryogenic Propulsion Stage. United States' National Space Policy (June 28, 2010, pg. 11) specifies that NASA shall: By 2025, begin crewed missions beyond the Moon, including sending humans to an asteroid. By the mid-2030s, send humans to orbit Mars and return them safely to Earth. The NCPS design will focus on ensuring maximum benefit to human Mars mission, although the NCPS could have numerous other applications as well. Detailed studies are ongoing, building on work performed in previous programs[2].

NCPS mission analysis and definition will stay synchronized with the NASA Human Architecture Team (HAT) for application toward future human missions and the currently developing Space Launch System (SLS). One potential SLS configuration would help maximize the benefit from the NCPS by balancing mass and volume constraints.

The sensitivity of NCPS performance to specific impulse, engine thrust-to-weight ratio, and other parameters is being assessed as one initial step in stage design. The design of the NCPS will favor proven and tested technologies and the design will also identify critical technologies that will be required for development. A historical perspective for a common, scalable fuel element will help provide flexibility in design. During the Rover program, a common fuel element / tie tube design was developed and used in the 50 klb_f Kiwi-B4E (1964), 75 klb_f Phoebus-1B (1967), 250 klb_f Phoebus-2A (June 1968), and 25 klb_f Pewee engine (Nov-Dec 1968).

To help ensure affordability, the NCPS must take maximum advantage of technologies, components, and subsystems that are developed elsewhere in the architecture, as well as provide input and requirements to those technologies to obtain the capabilities needed for effective integration of the NCPS. The NCPS must also stay coordinated with the SLS and upper Cryogenic Propulsion Stage (CPS) projects to take advantage of common elements and to leverage technologies and configurations to reduce cost.

To support the NCPS design effort, available analytical tools will be enhanced and refined. The Department of Energy (DOE) has developed sophisticated computer modeling tools for nuclear system design. Since the initial fuel elements under consideration are very similar to those previously developed under the Rover/NERVA and other programs, the NCPS will be able to take advantage of these available models. In addition, NASA rocket system simulation tools will be applicable. The computational modeling tools from DOE and NASA will allow needed trade studies and mission analysis. Initial efforts will focus on benchmarking of the nuclear models with test data and/or between similar models. After confidence in the nuclear models has been established, an iterative design process will begin convergence of NASA and DOE models for best design solutions.

One engine system model under consideration is the closed expander cycle, which derives fluid-pumping power from excess heat generated within the engine and passes the entire propellant flow through the nozzle. The cycle is currently of interest due to its high I_{sp} performance. However, several other candidate cycles have been considered in the past and will be evaluated. Also, hydrogen is the most desirable propellant based on its thermodynamic properties; similarly for high I_{sp} performance. However, hydrogen is also very challenging to store for long duration missions without significant boil-off losses and will require cryogenic fluid management technology refinement. Liquid hydrogen also has a very low density and high volume tanks are advantageous for many missions. Coordination with the Space Launch System (SLS) program is helping ensure that high-volume shrouds will be available to accommodate the use of liquid hydrogen propellant. Potential near-term NCPS missions must take into account constraints on long-term hydrogen storage until cryo-coolers or other technologies to relax those constraints are developed.

The safety of all rocket engines (including nuclear engines) is paramount. Although a nuclear engine is essentially non-radioactive prior to operation at significant power, the engine must be designed to avoid inadvertent start. This is particularly true for times when individuals could be in close proximity to the reactor, such as launch processing.

Safety of the nuclear engine will be ensured via design and by drawing on seven decades of reactor operating experience.

Crew health and safety may benefit from the use of an NCPS. The NCPS may enable shorter mission times (reducing crew exposure to microgravity, cosmic rays, solar flares, and other hazards) or increased payload mass (allowing for increased shielding, supplies, or equipment).

III. Nuclear Thermal Rocket Element Environmental Simulator (NTREES)

A high temperature, high power density fissile fuel form is a key technology for an NCPS. In addition, affordable development and qualification of the fuel form is important to overall NCPS affordability. Fuel life and performance is largely limited by mass loss in a hot gas/cyclic environment. Hence a major milestone of the NCPS project is the completion of the 1-MW Nuclear Thermal Rocket Element Environmental Simulator (NTREES) test chamber. The purpose of the NTREES facility (including an arc heater and a compact hydrogen test chamber) is to perform realistic non-nuclear testing of nuclear thermal rocket (NTR) fuel elements and fuel materials. Although the NTREES facility cannot mimic the effects of the neutron and gamma environment of an operating NTR, it can simulate the thermal hydraulic environment within an NTR fuel element to provide critical information on material performance and compatibility.

Initial upgrades to NTREES have been completed. The hydrogen system has been upgraded to enable computer control through the use of pneumatically operated variable position valves (as opposed to manual hydrogen flow control). The upgrade also allows hydrogen flow rate to be increased to 200+ gm/sec. The operational complexity of NTREES has been reduced by consolidating controls and reworking the purge system so as to permit simplified purging operations.

Prior to initiating the second stage of modifications, NTREES was used to test a "fuel element like" test article. The purpose of the test was to evaluate the behavior of the fuel and to demonstrate the test capabilities of NTREES. The test element consisted of a 12 inch long, 5/8 inch diameter specimen having seven hydrogen flow holes. The materials comprising the test element consisted of pure tungsten with 40 volume % hafnium nitride particles encased in 0.030 inch niobium can.

The total duration of the tests was about 4.5 hours at maximum induction heater power (about 30 kW). The tests were performed in flowing hydrogen at a flow rate equivalent to what would be expected in a NERVA type engine operating at full power (about 0.7 gm/sec). Ten power cycles equivalent to about 2.5 Mars missions were performed on the fuel element. Because no suitable insulation was available for the test element so as to prevent high heat losses from radiation and convection processes, the nominal operating temperature of the test element was approximately 1300 K. Nevertheless, in one brief test sequence in which there was no hydrogen flowing, the temperature in the test element approached 2100 K. A picture of the specimen under test is presented in Figure 2.

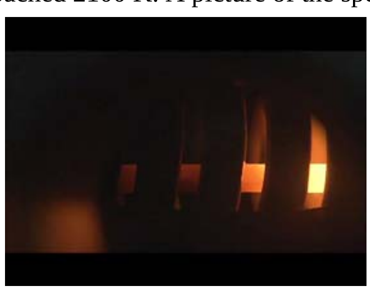


FIGURE 2. Material specimen under test in flowing hydrogen in NTREES.

In the second stage of modifications to NTREES, the capabilities of the facility will be increased significantly. In particular, the current 50 kW induction power supply will be replaced with a 1.2 MW unit which will allow more prototypical fuel element temperatures to be reached. To support this power upgrade, the NTREES water cooling system will also be upgraded to be capable of removing 100% of the heat generated during testing. Also required will be the upgrade of the nitrogen system and the complete redesign of the hydrogen nitrogen mixer assembly. In particular, the nitrogen system will be upgraded to increase the nitrogen flow rate from its current 1.2 lb/sec to at least 4.5 lb/sec. The mixer upgrade will incorporate a number of design features which will minimize thermal stresses in the unit and allow for the increased flow rate of nitrogen and water required by the increased operational power level. The new setup will require that the NTREES vessel be raised onto a platform along with most of its associated gas and vent lines. The induction heater and water systems will then be located underneath the platform. The new design will also allow for additional upgrades which could take the power level of NTREES to 5 MW. Once fully operational, the 1-MW NTREES test chamber will be capable of testing fuel elements and fuel materials in flowing hydrogen at pressures up to 1000 psi, at temperatures up to and beyond 3000 K, and at near-prototypic reactor channel power densities. NTREES will be capable of testing potential fuel elements with a variety of propellants, including hydrogen with additives to inhibit corrosion of certain potential NTR fuel forms; however the focus of FY 2012 activities will be on pure hydrogen propellants.

The NTREES facility is licensed to test fuels containing natural or depleted uranium. It includes a pyrometer suite to measure fuel temperature profiles and a mass spectrometer to help assess fuel performance and evaluate potential material loss from the fuel element during testing. Additional diagnostic upgrades planned for NTREES include the addition of a gamma ray spectrometer located near the vent filter to detect uranium fuel particles exiting the fuel element in the propellant exhaust stream and to provide additional information of any material loss occurring during testing. Using propellant fed from gas storage trailers located external to the facility, NTREES is configured to allow continuous, uninterrupted testing of fuel elements for any desired length of time. A picture of the most recent operational NTREES primary chamber configuration is shown in Figure 3.

FIGURE 3. Nuclear Thermal Rocket Environmental Simulator

FIGURE 4. Arc Heater.

Additional test facilities includes an operational arc heater (Figure 4) that is capable of flowing hot hydrogen over a material or fuel sample at a hydrogen gas temperature of up to 3160 K for approximately 30 minutes which could be used for the preliminary vetting of material samples.

Also available will be a compact test chamber capable of testing small fuel samples at high temperatures in a hydrogen environment. This small fuel sample test facility is called the Compact Fuel Element Environmental Test facility, or CFEET (Figure 5).

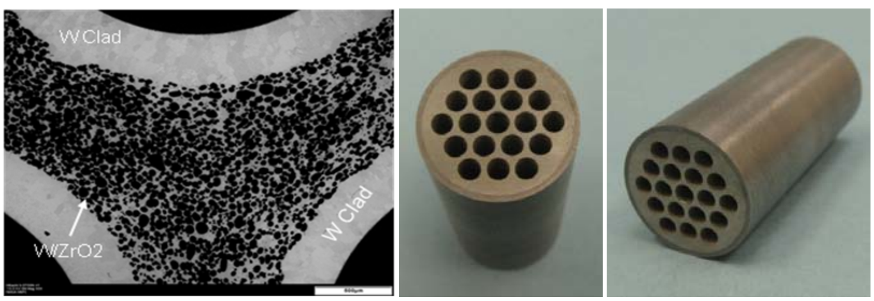
This project will also develop a detailed understanding of the energy deposition and heat transfer processes in NTREES, along with effects on material mechanics and fluid/material interaction, to better improve future test conditions and obtain as much information as possible to accurately extrapolate non-nuclear test data to real reactor conditions.

FIGURE 5. Compact Fuel Element Environmental Test facility (CFEET).

IV. NCPS Fuel Design / Fabrication

Early fuel materials development is necessary to validate requirements and minimize technical, cost, and schedule risks for future exploration programs. The development of a stable fuel material is a critical path, long lead activity that will require a considerable fraction of program resources. The objective of the NCPS Fuel Design and Fabrication task is to demonstrate materials and process technologies for manufacturing robust, full-scale CERMET and graphite fuel elements. The elements will be based on the starting materials, compositions, microstructures, and fuel forms that were demonstrated on previous programs. The development will be a phased approach to recapture key technologies and produce quality fuels. Samples will then be tested in flowing hot hydrogen to understand processing and performance relationships. As part of this demonstration task, a final full scale element test will be performed to validate robust designs. These demonstrations are necessary to enable a future fuel material down-select and potential follow-on non-nuclear and nuclear ground test projects. A major focus of the NCPS project is the use of a highly integrated NASA/DOE fuels development team. The goal is to enhance and utilize existing infrastructure and capabilities to minimize cost.

Current research at Marshall Space Fligth Center (MSFC) and Idaho National Laboratory (INL) is focused on developing fabrication processes for prototypical W/UO_2 CERMET fuel elements. CERMETS are typically formed by densification of powders using Powder Metallurgy (PM) processes. Tungsten based CERMETS with surrogate ceramic particles have been fabricated to near theoretical density using Hot Isostatic Press (HIP) and Pulsed Electric Current (PEC) techniques. During HIP, the CERMET powders are consolidated in sacrificial containers at 2000°C and pressures up to 30 ksi. The PEC process consists of high speed consolidation of powders using DC current and graphite dies. For both HIP and PEC processing, the powder size and shape, powder loading, and processing parameters significantly affect the quality and repeatability of the final part. Figure 6 shows a typical microstructure and image of a net shape consolidated CERMET part. The part is a 19 hole configuration that had uniform shrinkage during consolidation and good tolerance on the flow channel geometry.



a) **b)**

FIGURE 6. a) Micrograph of a W/60 vol% ZrO_2 CERMET with integral W claddings; b) Consolidated W/40 vol% HfN CERMET sample.

The nature of this initial task is rapid materials and process screening as a precursor to the detailed development that will be required to fully optimize and qualify a CERMET fuel. CERMET materials and processes were demonstrated at a subscale level in previous efforts, but there are significant technical and programmatic challenges for key technologies. Some of the materials and process approaches being developed to maximize performance are the size of the fuel particles and resultant shape in the consolidated part, CVD tungsten coating of spherical UO_2 particles prior to consolidation, complete surface cladding of the elements with tungsten, and additions of small amounts of fuel particle and matrix stabilization materials such as ThO_2, Y_2O_3, or Gd_2O_3.

Significant work is also being done at Oak Ridge National Laboratory (ORNL) to recapture Rover/NERVA graphite composite fuel materials. Various graphite based fuels consisting of UO_2, UC_2, (U, Zr)C particles in a graphite matrix, or pure carbides were tested in the Rover/NERVA program. The materials were successfully demonstrated in full scale nuclear test engines. However, the fuel materials and fabrication technologies are not currently available. The NCPS task is focused on developing the graphite composite extrusion and ZrC coating capabilities. The composite fuel matrix is a carbide-based ceramic fuel composition consisting of uranium carbide, zirconium carbide and graphite materials. Subscale matrix samples are being fabricated and tested to demonstrate microstructure and properties. In parallel, coating trials are being performed on short elements for hot hydrogen testing at MSFC. The goal is to validate recapture of the graphite composite fuel material including required coatings using a representative segment of a Rover/NERVA type fuel element. Figure 7 shows images of Phoebus reactor fuels from the 1960s.

FIGURE 7. Images of the Rover/NERVA Phoebus Reactor fuel.

V. NCPS Fuels Testing in NTREES

Testing in NTREES will range from short (1" – 6") segment testing using the CFEET to the testing of near-prototypic fuel elements. A primary goal of the testing is to demonstrate adequate fuel performance and to increase confidence in fuel system designs (e.g. materials, coatings, geometries) prior to potential nuclear testing. CERMET and graphite composite samples will be thermal cycle tested in a static and flowing environment. Several iterations of testing will be performed to evaluate fuel mass loss impacts from density, microstructure, fuel particle size and shape, chemistry, claddings, particle coatings, and stabilizers. Initial subscale testing will be performed in the CFEET system. The CFEET test samples will be approximately 0.5" diameter x 3" length for solid slug and prototypic 7-hole channel configurations. Testing of solid slugs will be performed to baseline performance prior to introducing geometric variables.

The 7-hole channel configuration (Figure 8) was chosen for CFEET screening to rapidly evaluate thermal cyclic affects on prototypic geometries from surface vaporization, diffusion/migration, and cracking. Testing has shown that fuel mass loss is significantly impacted by thermal cycling and geometry. The prototypical geometry will be much more susceptible to cracking induced migration and volatilization of the exposed fuel particles. The fuel materials and forms such as coated particles, claddings, and stabilizers being evaluated on this effort have all been demonstrated to control fuel migration and loss. The initial screening is not to determine or characterize specific modes of fuel loss or mechanisms. The intent is to verify performance improvements of the materials and processes prior to expensive full scale fabrication and testing. Post test analysis will include weight percent fuel loss, microscopy (SEM, EBSD, and EDS), and dimensional tolerance and cracking.

Subsequent testing of full scale fuel elements will be performed in NTREES. The test samples will be based on Rover/NERVA fuel element designs and ANL 200MW (or other) cermet fuel element designs. The goal is to benchmark performance in NTREES for comparison to future materials and process improvements, alternate fabrication processes, and other fuel materials of interest. The iterative materials and process development, CFEET screening, and NTREES testing will continue through FY12-14 NCPS effort with numerous subscale and full scale element testing milestones.

NTREES testing will also be designed to create as realistic of an environment as possible. Parameters such as hydrogen temperature and fuel element axial power profile can be readily matched with those predicted for an actual nuclear system. Differences in heat deposition between RF heating and nuclear heating are being quantified to allows any desired adjustments in test design to be made.

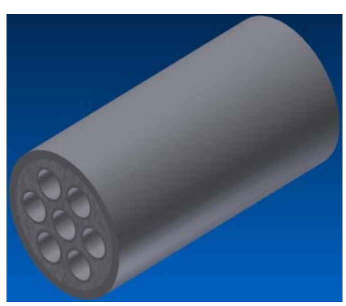


FIGURE 8. CFEET Sample Configuration.

VI. Affordable NCPS Development and Qualification Strategy

Devising an affordable strategy for developing and qualifying an NCPS is key to enabling the potential use of such a system. The development and qualification strategy must take into account all potential cost drivers, including costs associated with safety, security, and environmental considerations.

One potential strategy is to design an NTR potentially capable of supporting human Mars or other ambitious missions. To rapidly gain operational experience, the NTR could then be run "de-rated" (in terms of operating temperature, operating time, or power density) to support less demanding near-term missions. The NTR would be incorporated into an NCPS suitable for use with the launch vehicle chosen for each given mission. The NCPS could use one or more NTRs, depending on mission requirements.

Lessons learned have been acquired from the J-2X rocket engine program, ARES 1-X Test Flight Program, and X-43A Flight Demo Program. The major factors from the lessons learned include the following: follow NASA standards unless deviation has concurrence from the chief engineer and safety officer, start with low safety factors and evolve, upfront involvement from Safety Mission Assurance (including Risk Management) and Systems Engineering Integration, test development engines to the extremes and test two certification engines for flight with double the burn duration and double the number of start-ups.

It has also been determined that the design, development, test, and evaluation (DDT&E) approach and requirements for NTP will take advantage of those used for liquid rocket engines (LRE) and solid rocket motors (SRM). LRE's are hot fired many times to assure the design and manufacturing workmanship. SRM's have a very limited full scale motor firing and rely on subscale tests and manufacturing process checks. NTP engines can't be started up for acceptance testing like the LRE, which is another similarity with SRM.

Human rating the NTP for future human missions will require the following design characteristics: Fault avoidance by designing out the failure modes, design with sufficient margin to be robust, design redundancy capability in the system to be tolerant of failures, and provide detection capability to detect, warn, and provide other systems to activate or respond to avoid loss of crew scenarios.

The NTP test topology is shown in Figure 9. Past NTP development programs had extensive testing involving a ground test complex with a special reactor to test fuel elements, a nuclear furnace for material characterization, and critical assemblies to test reactor physics. To save time and money, the current plans are to avoid having a nuclear furnace and fuel element reactor. The focus will be on non-nuclear testing of the fuel elements, followed by specimen irradiation testing using existing facilities, and using an existing reactor for sub-element testing. Final fuel element testing will take place at the full scale ground test facility.

The Rover/NERVA engine tests in the past released the unfiltered hydrogen propellant directly into the open air. Although such testing was successful and posed no hazard to the public, a programmatic decision has been made to filter or confine hydrogen that has been heated in the core during a test prior to releasing the hydrogen to the open air. NCPS full scale engine tests facilities would have an exhaust filter to ensure that any radioactivity potentially released would be within regulatory limits.

One filtering concept being investigated involves using bore holes at the Nevada Nuclear Security Site (or other appropriate site) to filter the hydrogen propellant after it exits the thrust chamber. The bore holes at the NNSS are about 1200 feet deep and 8 feet in diameter. The soil is made of alluvium. Current soil analysis indicates permeability will allow the hydrogen exhaust gas to rise up through the soil while trapping any radioactive particulates that could potentially be present in the hydrogen. Back pressures in the bore hole up to 35 psi could be present in a full scale NTP engine test and affect the coupling of the engine to the bore hole. More investigations are underway. The Subsurface Active Filtering of Exhaust (SAFE) concept is shown in Figure 10.

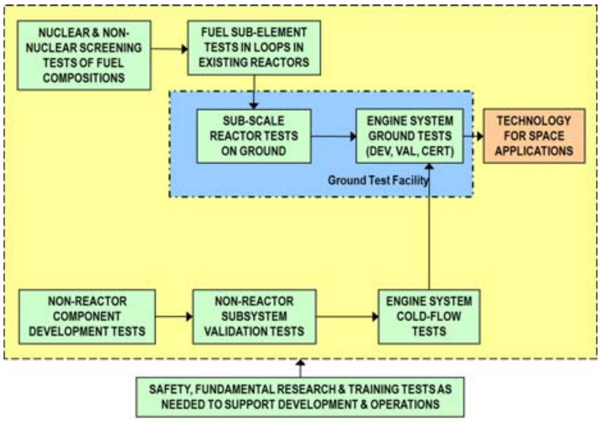


FIGURE 9. NTP Test Topology.

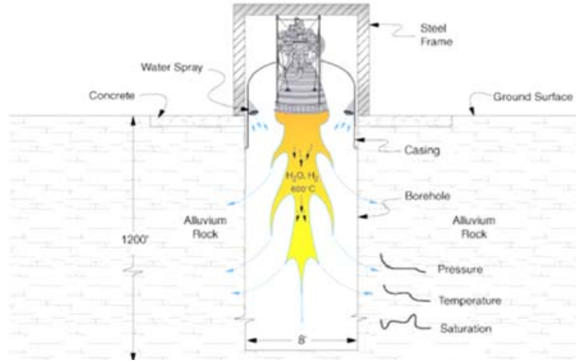


Figure 10. SAFE bore hole concept for full scale NTP testing[3].

In addition to ground testing a full scale NTP engine, a flight demonstration is being investigated to help qualify the engine system and possibly used by a potential customer for a science mission. One potential flight demonstration option could be to use a full-size (~25 klbf) engine operating at either rated or de-rated conditions to gain experience with the actual engine system that could potentially be used to support human Mars missions. A flight demonstration would also allow operation of a high area ratio nozzle, which is truncated for ground testing. Advanced instrumentation and robotics is being investigated to use on the NTP flight demonstration for inspection of the major engine components. Figure11 shows similar instrumentation already developed and used in conjunction with space shuttle return to flight.

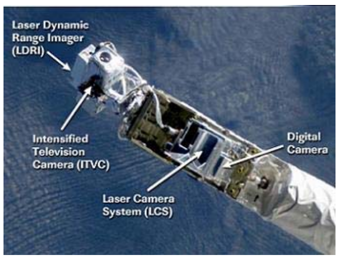


FIGURE 11. JSC Robotic Instrumentation.

A flight demonstration would also demonstrate the capability of the launch facilities to launch fission systems. Although the US has had tremendous success in launching nuclear systems, launch processing for fission systems may be different than launch processing for radioisotope systems. A nuclear safety review and launch approval process is required and shown in Figure 12. The launch approval process could take up to 5 years to complete and needs to be accounted for in the overall development plan. Both strategies for ground testing and flight demonstration appear to show promise.

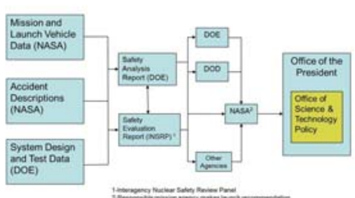


FIGURE 12. Nuclear Safety Review and Launch Approval Process.

VII. CONCLUSION

The potential capability of NTP is game changing for space exploration. A first generation NCPS could provide high thrust at a specific impulse above 900 s, roughly double that of state of the art chemical engines. Near-term NCPS systems would provide a foundation for the development of significantly more advanced, higher performance systems. John F. Kennedy made his historic special address to Congress on the importance of space on May 25, 1961, “First, I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth…” This was accomplished. John F. Kennedy also made a second request, “Secondly … accelerate development of the Rover nuclear rocket. This gives promise of some day providing a means for even more exciting and ambitious exploration of space, perhaps beyond the Moon, perhaps to the very end of the solar system itself.” The investment in the Rover nuclear rocket program provided the foundation of technology that gives us assurance for greater performing rockets that are capable of taking us further into space. Combined with current technologies, the vision to go beyond the Moon and to the very end of the solar system can be realized with space nuclear propulsion and power.

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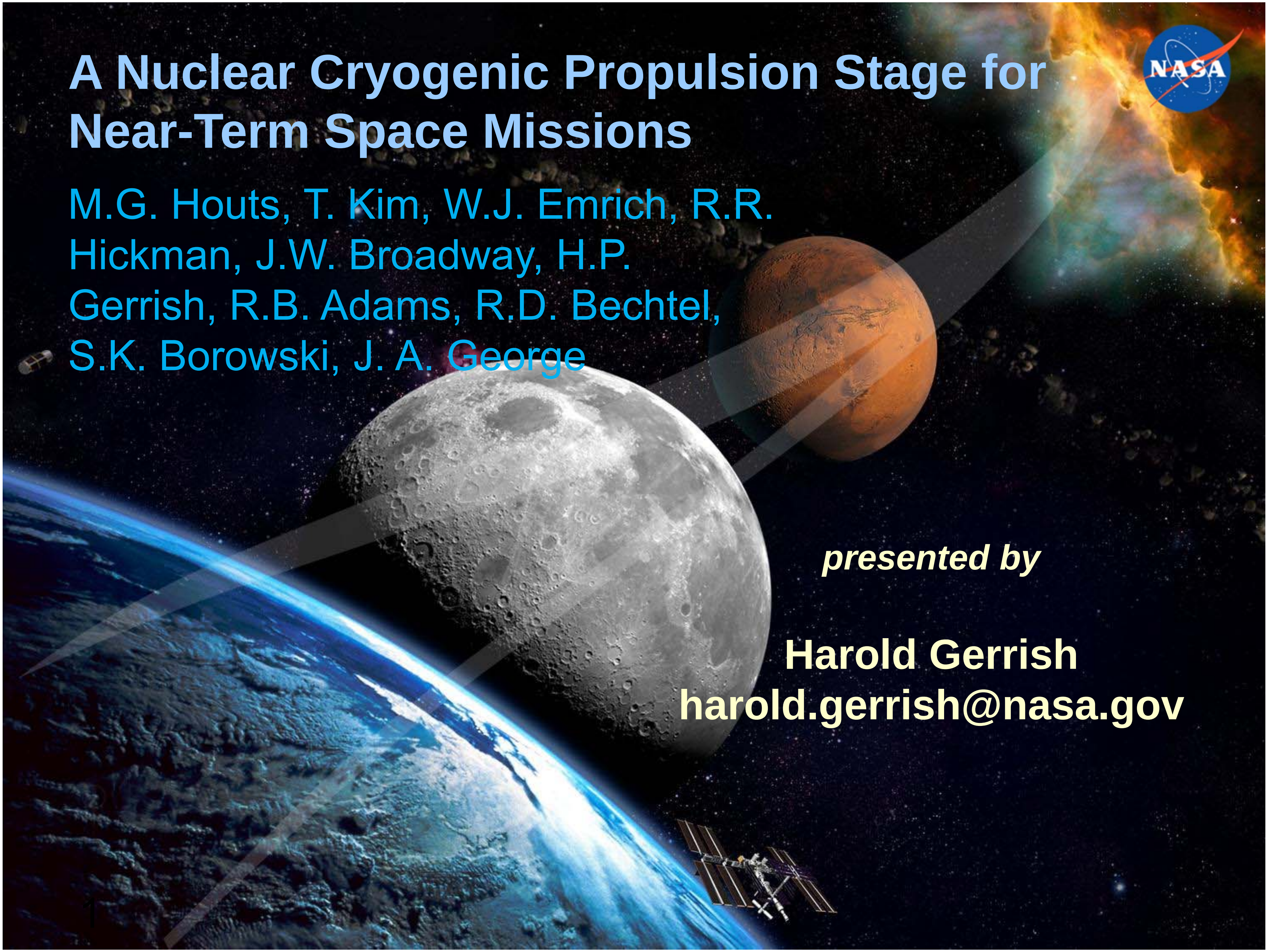

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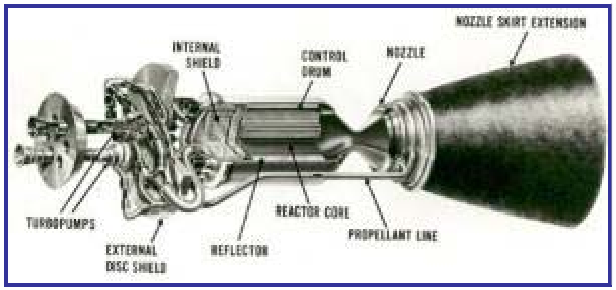
Nuclear Cryogenic Propulsion Stage (NCPS)



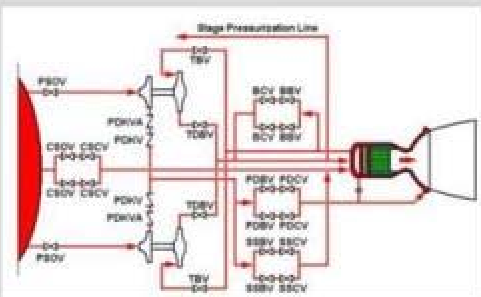
- **Nuclear thermal propulsion (NTP) is a fundamentally new capability**
  - Energy comes from fission, not chemical reactions
  - Virtually unlimited energy density
- **Initial systems will have specific impulses roughly twice that of the best chemical systems**
  - Reduced propellant (launch) requirements, reduced trip time
  - Beneficial to near-term/far-term missions currently under consideration
- **Advanced nuclear propulsion systems could have extremely high performance and unique capabilities**
- **The goal of the NCPS project is to establish adequate confidence in the affordability and viability of the NCPS such that nuclear thermal propulsion is seriously considered as a baseline technology for future NASA human exploration missions**

Nuclear Cryogenic Propulsion Stage (NCPS) Organizational Structure

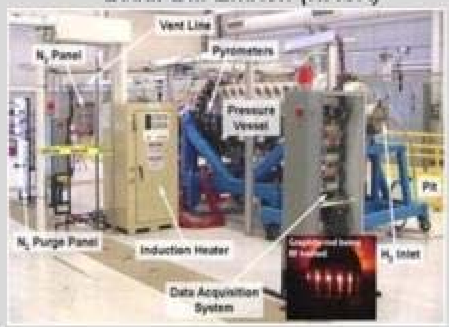
1.0 NCPS Project Management

Project Manager:	Mike Houts (MSFC)
DOE Lead:	Ryan Bechtel
GRC Lead:	Stan Borowski
JSC Lead:	John Scott

2.0 Pre-conceptual Design of the NCPS & Architecture Integration
Co-Leads: Tony Kim (NASA), Stan Borowski (NASA), David Poston (LANL)

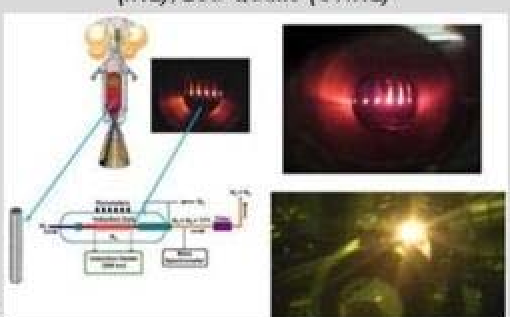


3.0 High Power (≥ 1 MW) Nuclear Thermal Rocket Element Environmental Simulator (NTREES)
Lead: Bill Emrich (NASA)



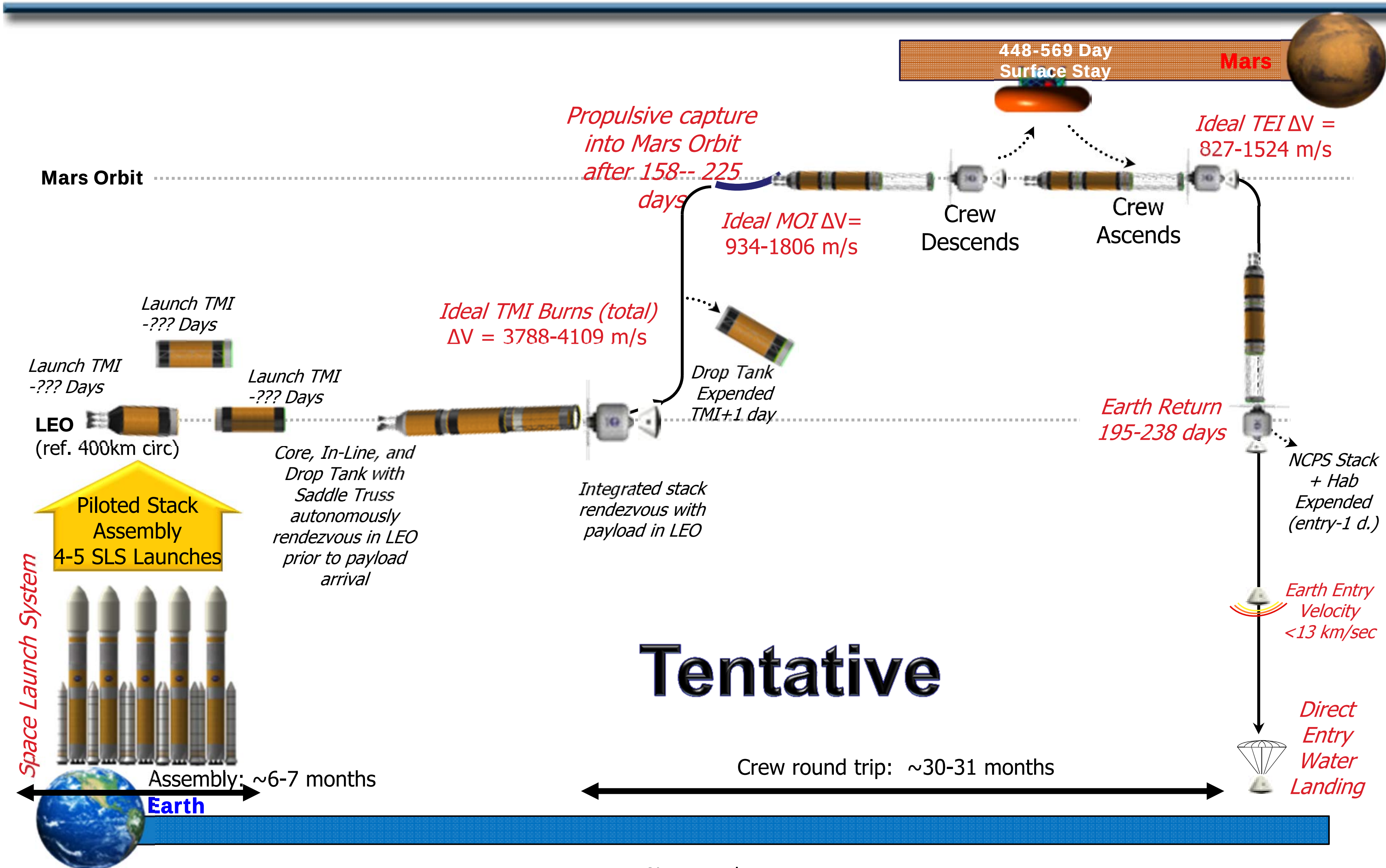
4.0 NCPS Fuel Design / Fabrication
Co-Leads: Jeramie Broadway (NASA), Shannon Bragg-Sitton (INL), Lou Qualls (ORNL)

5.0 NCPS Fuels Testing in NTREES & CFEET
Co-Leads: Bill Emrich (NASA), Robert Hickman (NASA), Shannon Bragg-Sitton (INL), Lou Qualls (ORNL)



6.0 Affordable NCPS Development and Qualification Strategy
Co-Leads: Harold Gerrish (NASA), Stan Borowski (NASA), Shannon Bragg-Sitton (INL)

Mission Profile



Not to scale

2037 NTP Mission/Architecture Stack BBC
(Baseball card as of 2/14/2013)

Nuclear Thermal Propulsion -- Mars Piloted Stack

Design Constraints / Parameters:

- # Engines / Type: 3 / NERVA-derived
- Engine Thrust: 25 klbf (Pewee-class)
- Propellant: LH2
- Specific Impulse, Isp: 900/nom. - TBD/max sec
- Tank Material: Aluminum-Lithium
- Truss Material: Composite
- RCS Propellants: NTO / MMH
- RCS Thruster Isp: 328 sec (Fregat Isp)
- Passive TPS: 0.75" SOFI + 60 layer MLI
- Active CFM: ZBO Brayton Cryo-cooler
- I/F Structure: Stage / Truss Docking Adaptor w/ Fluid Transfer

2037 Trajectory Constraints / Parameters:

- TMI ΔV1: 1934 m/s (1813-1936)
- TMI ΔV2: 2084 m/s (1976-2172)
- MOI ΔV: 934 m/s (1029-1806)
- TEI ΔV: 1475 m/s (827-1524)
- Outbound time: 212 days (158-225)
- Stay time: 489 days (448-569)
- Return time: 220 days (195-238)
- TMI, MOI & TEI: 1% ΔV Margin/FPR/other
- TMI Gravity Losses: 389 m/s total, f(T/W_0)
- MOI & TEI g-losses: Additional 1%
- Post-TMI RCS ΔVs: 180 m/s (>>7 burns)
- Tank Masses (C, I, D) Details In MEL

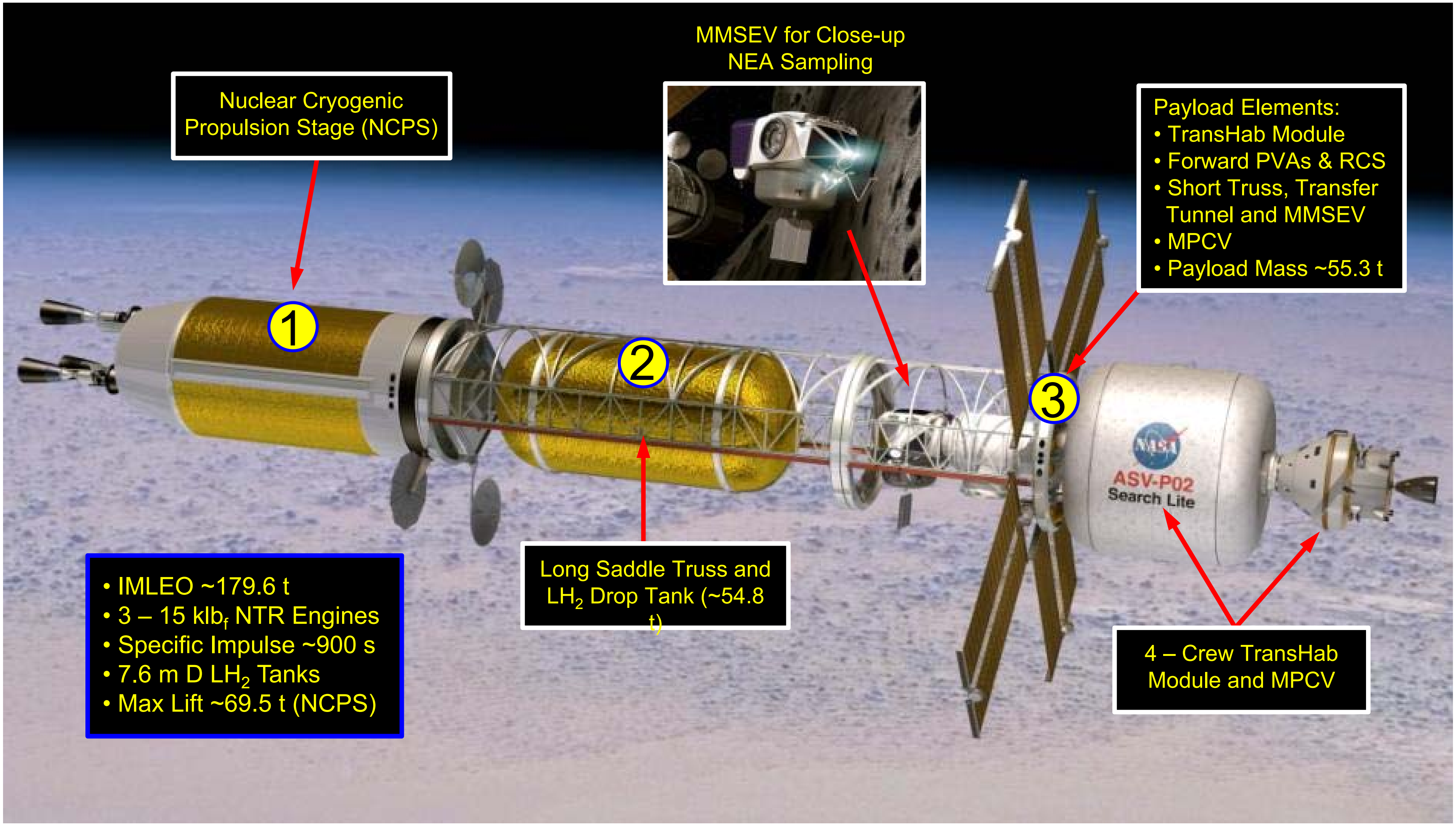
Description:

NTP system consists of 3 elements: 1) core propulsion stage, 2) in-line tank, and 3) integrated saddle truss and drop tank assembly that connects the propulsion stack to the crewed payload element for the Mars 2037 mission. Each element is delivered to LEO (407 km circ) fully fueled on an SLS LV (178.35.01, 10-m O.D. / 9.1-m 25.2 m cyl. §). They are sized for an SLS capability of ~100 mt. The stage uses three 25.1 klbf engines w/ either a NERVA-derived or ceramic-metallic (CerMet) reactor core. It also includes RCS, avionics, power, long-duration CFM hardware (e.g., COLDEST design, ZBO cryo-coolers) and AR&D capability. Saddle trusses use composite material & the LH2 drop tank employs a passive TPS. I/F structure includes fluid transfer & electrical.

v2/14/2013

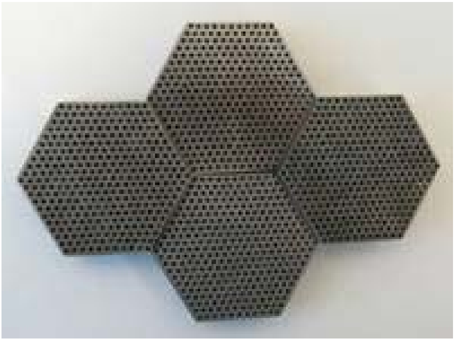
2037 Core stage (C)	Feb.14 final
Engine Isp, sec	900
Inert Mass, mt	44.99
Three 25 klbf NTP Engines	12.32
Three External Radiation Shields	6.45
Tank m_inert (w/ everything else)	26.22
Usable LH2 Mass, mt	41.64
RCS Usable Prop Load, mt	17.05
Boil-off to ullage, mt	0.20
Stage wet mass total, mt (on pad)	**103.68**
Stage Length, m (engines, RCS, I/F)	~22.2
Approx. Effective LH_2 PMF / λ	0.48
2037 In-line Tank (I)	
Inert Mass, mt (w/ everything)	28.59
Usable LH2 Mass, mt	66.40
RCS Usable Prop Load, mt	5.51
Stage wet mass total, mt (on pad)	**100.50**
Engine Isp, sec	900
Stage Length, m (incl. RCS & I/F)	~21.2
Approx. Effective LH_2 PMF / λ	0.70
Saddle Truss & Drop Tanks, $1^1/_2$ (D)	
Inert Mass, mt	38.35
Saddle Trusses (w/ everything)	7.73
Drop Tanks (w/ everything)	30.61
Usable LH2 Masses mt	103.30
RCS Usable Prop Loads, mt	8.58
Boil-off, mt	1.54
Stage wet mass total, mt (on pad)	**151.76**
Engine Isp, sec	900
Stage Length, m (incl. RCS & I/F)	~33
Approx. Effective LH_2 PMF / λ	0.73
Payload Mass Total (on pad)	**80.48**
Deep Space Hab (stocked)	51.85
MPCV (CM+SM, no prop)	14.49
Payload RCS/Truss/Canister	14.14
Mars stack interim total	**436.43**
Start-up/Shut-down LH2, mt (4-burns)	3.96
Crew, mt	0.79
Less mass exp. prior to TMI, mt	(25.95)
Total TMI- Stack Mass, mt	**411.26**

Reusable NTR Asteroid Survey Mission to 2000 SG344 in 2028 Uses Clustered 15 klb$_f$ Engines and 3 – "70 t-class" SLS Launches



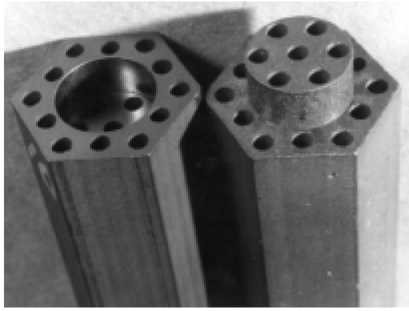
NCPS Task 4 - Fuel Design / Fabrication

- **Goals**
  - Mature CERMET and Graphite based fuel materials
  - Develop and demonstrate critical technologies and capabilities
- **Objective**
  - Team (Department of Energy National Laboratories and NASA centers) optimize manufacturing processes to develop an NTP fuel material
  - Fabricate CERMET and graphite composite fuel element samples with depleted uranium fuel particles
  - Complete mechanical and thermal property testing to develop an understanding of the process/property/structure relationship
  - Perform full scale element testing of CERMET and graphite fuels



331 Channel Hex Demo (MSFC)

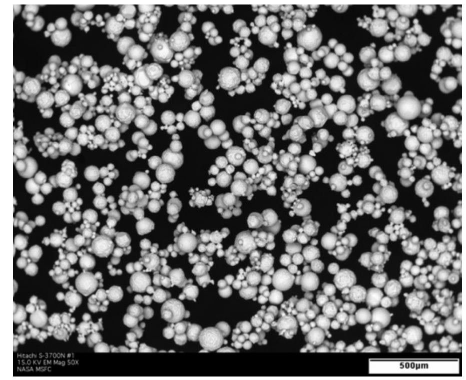
19 Channel HIP Demo (MSFC)



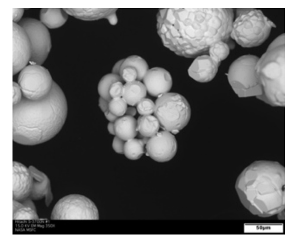
Graphite Composite Fuel Element (Rover/NERVA)

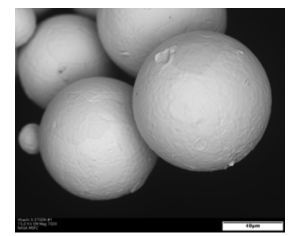
Oak Ridge National Laboratory Sol-Gel Development

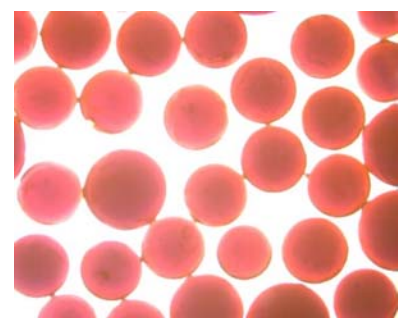
- Currently have a qualified process for 300µm TRISO fuel particles
- Completed a study to deliver fine spherical particles
  - No system modifications; varied system parameters
  - Understand smallest particles achievable
  - Understand yields and distributions
- Delivered ~140g of spherical dUO_2 particles to MSFC
  - ~50g, <75µm
  - ~90g, +75/-150µm
  - ~2g, +150/-212µm
- Results
  - Good spherocity and density
  - Able to produce finer particles but high distribution
  - Agglomeration of fine particles to larger during sintering
  - Only contamination found was from Al_2O_3 boat used during sintering
- Second phase to produce 3kg of 100+/-25µm particles
  - Switch to a smaller needle during processing
  - Obtain tighter distribution of particles, 100 +/-25µm
  - At last update 1.5kg complete through sol-gel and were waiting on sintering
  - Smaller needles and modified parameters are producing a tighter distribution



SEM Image 50x ORNL SG DU


SEM Image 350x ORNL SG dU

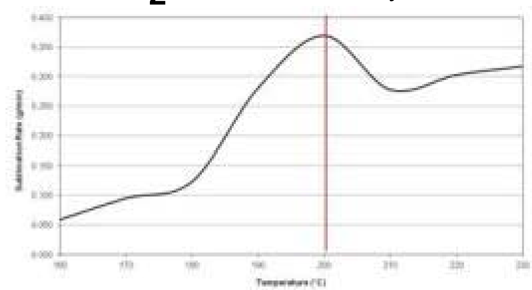

SEM Image 700x ORNL SG dU


ORNL phase II particles
Pre-sintering

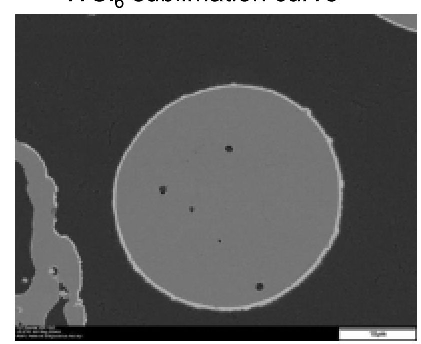
Chemical Vapor Deposition (CVD)

- **Problem: NTP fuel erosion during nominal operation**
- **Solution: Coated powders enable fuel failure tolerance**
  - Eliminate UO_2 kernel-to-kernel contact
  - Prevent H_2 propellant reduction of UO_2 fuel kernels
  - Minimize powder segregation during HIP can vibratory fill
  - Improve powder packing %TD and consequently dimensional tolerance
- **Objective: Develop lab-scale prototype to coat spherical dUO_2 powder with 40 vol% tungsten**
  - Eliminate excessive vendor cost to develop coated dUO_2
- **WCl_6 process** $WCl_6 + 3H_2 \xrightarrow{Ar,\, xs\, H_2,\, 930^\circ C} W + 6HCl + Ar + xsH_2$
  - Minimal trace contaminants compared to WF_6 process
  - Complex and corrosive solid-to-vapor reagent formation
  - Raining feed, fluidized bed reactor, H_2/Ar 10:1 ratio
- **Ongoing Efforts**
  - Completion of design upgrades
  - Optimize process variables to produce coating properties that meet service life requirements
  - Characterize coatings as a function of substrate microstructure and process variables

CVD system



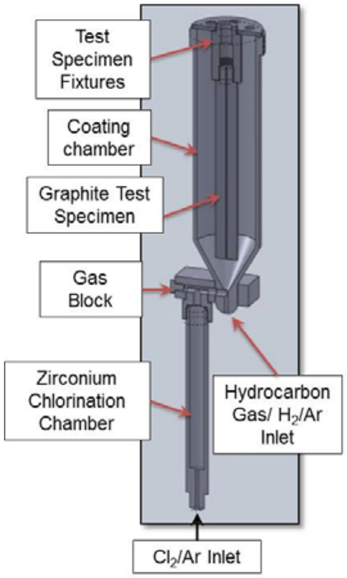
WCl_6 sublimation curve



W coated ZrO_2 (2500x)

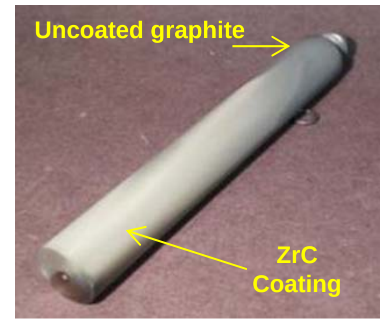
Chemical Vapor Deposition (CVD)

ORNL Graphite Composite FE: Coating Development

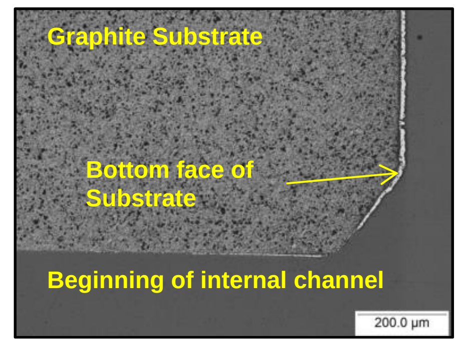


CVD particle Coating furnace

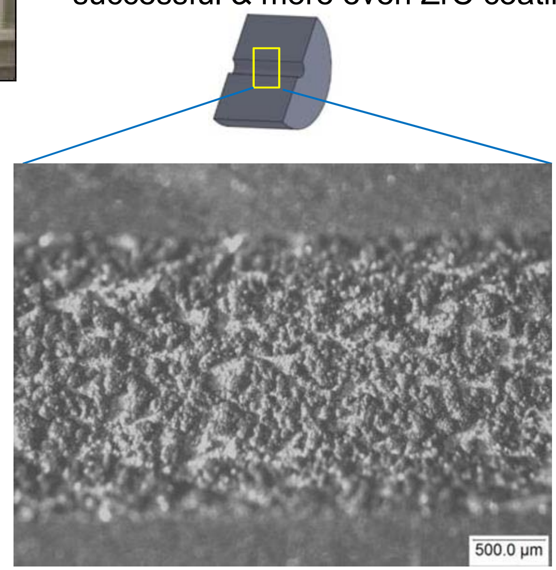
- Initial ZrC coating only present in first few hundred microns
- Redesign of furnace resulted in successful ZrC deposit of internal channel
- ZrC growth rate higher than nucleation rate – created 'islands of ZrC and incomplete coverage
- Increased flow rates resulted in successful & more even ZrC coating



Above: Test Piece highlighting ZrC Coating
Below: Coating primarily on external surface

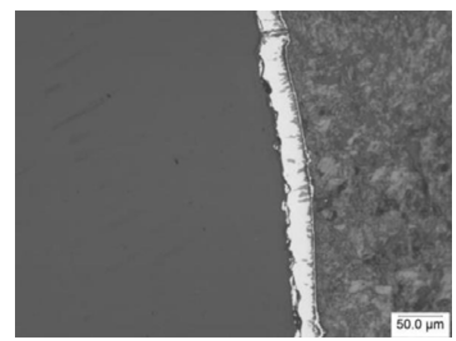


- CVD particle coating furnace uses new fixtures to hold NTP type cylindrical substrate within coating chamber
- Redesigned to force precursor gases through internal channels to ensure coating of this more critical area
- Entire assembly dropped 4" within hot zone to minimize deposition/clogging of gas block passageways
- Method scalable to allow coating of 16 inch specimens when new coating furnace arrives



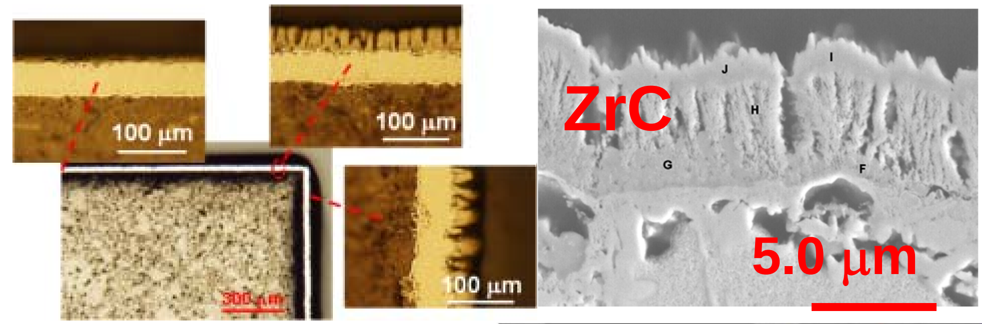
Cross Sectional image of ZrC-7 (3X)

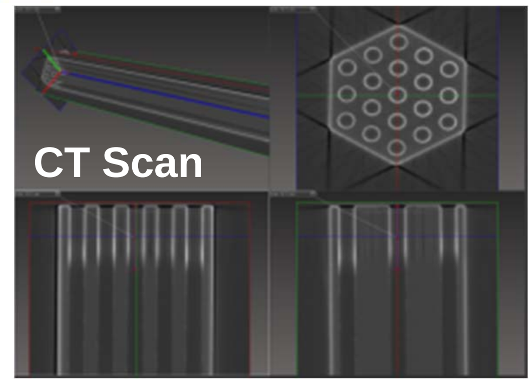
Above and Right: Improved Coating – some cracking evident but overall ZrC coating is good



Cross section perpendicular to bore axis (200X)

- ♦ **CVD process optimization studies are on-going**
- ♦ **First attempts to deposit a multilayer coating on disk specimens had mixed results**
- ♦ **First trial runs to coat the inner surfaces of coolant passages of 6” long specimens resulted in limited coating (CT scan)**



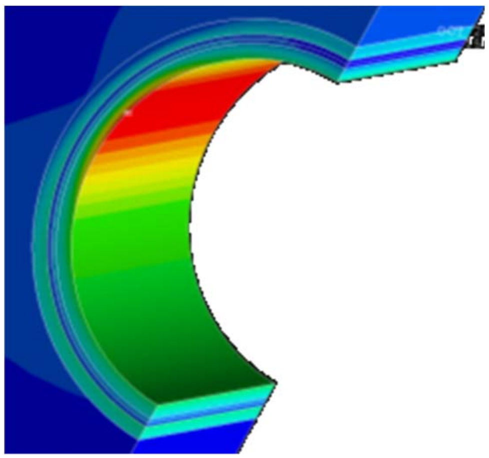


- Experimental diffusion studies at 1773 K revealed that the extent of diffusion is limited. However, calculations predict extensive diffusion above 2073 K. Monte Carlo simulation studies of hydrogen diffusion in the coatings are underway.

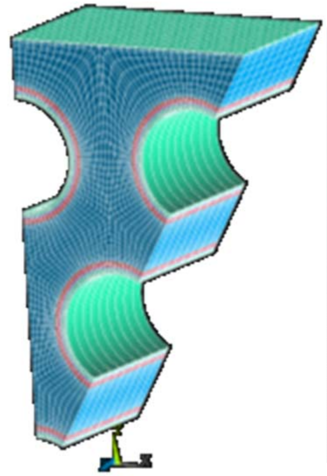
- Thermal cycling tests conducted on thick hot pressed layers (> 700 µm) between 690 and 1895 K did not lead to debonding even after 8 cycles.

Coating Architectures

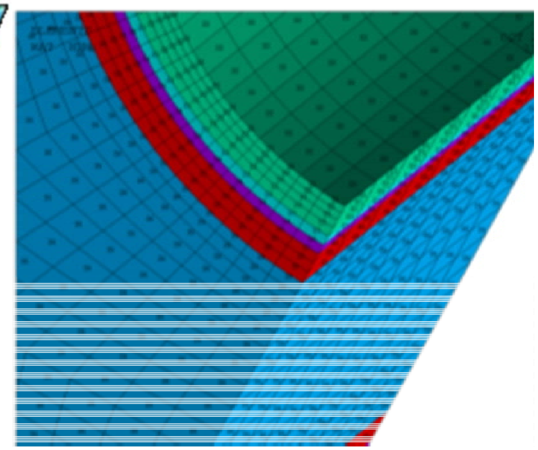
- **Thermal / stress simulation of multi-layer coating architectures**
- **Graphite - based fuels**
- **Test cases:**
  - Cool down to room temperature
  - 1500 K operating condition
- **Layers in compression and tension due to CTE variations.**



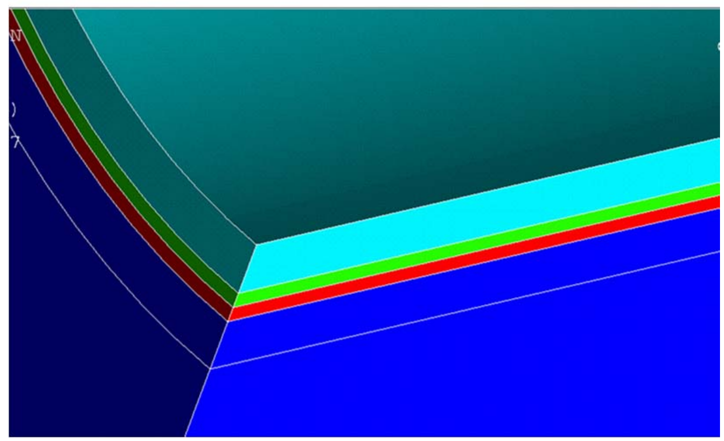
1500K Operating



Simulate section of fuel element



Coating layer detail



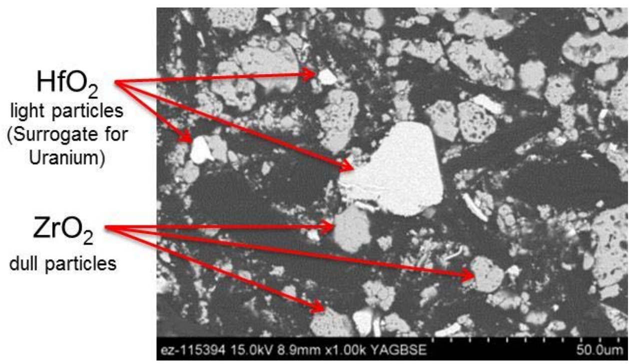
Room Temperature

Fuel Element Development & Testing

ORNL Graphite Composite FE: Extrusion Development

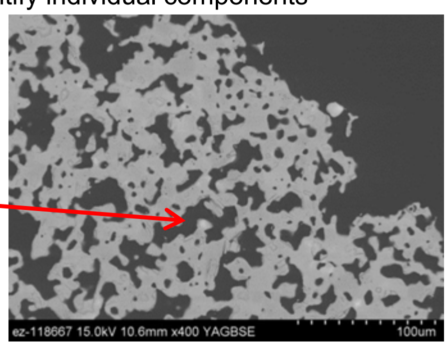
- Made compact blends prior to extruder setup and performed initial analysis
- Prior to heat treatment SEM confirmed that particles are distributed & in close proximity
- Post heat treatment SEM showed carbide network on outer sample surface – network may exist throughout sample
- Blends are developed for initial extrusion tests
- Initial extrusions will be surrogate blends 2-6” in length
- Longer extrusions will require a specially designed layoff table

Initial Extrusion runs – went very well

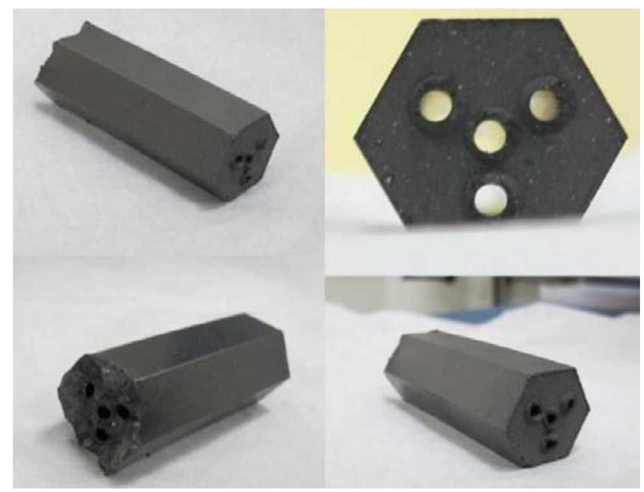


Pre-Heat Treatment: Backscattered SEM image and EDS used to identify individual components

Light color indicated Hafnia (surrogate for Uranium) rich area



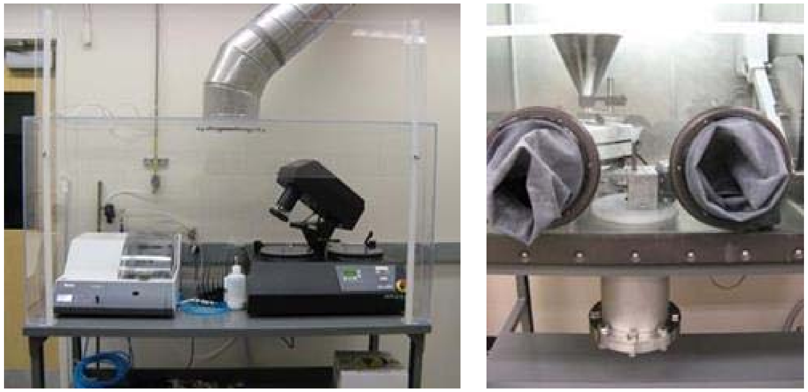
Extruder setup is complete



Initial Extrusion Trial using blend of carbon-matrix & Hafnia
0.75” across flat
0.125” coolant channel

NCPS CERMET Reference Design

MSFC CERMET FE: HIP Development



Above: Upgraded HIP processing equipment for W-UO2 samples

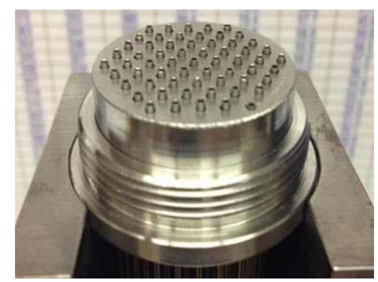
Top view of the chemical etching system configured to etch a 7-channel fuel element. The 7-channel fuel elements will be tested in CFEET.

Complete front view of a 61-channel etch component just prior to the brazing process. This component will be used to chemically etch the coolant channels in a uranium dioxide-tungsten fuel element.

- Will complete three HIP cycles by 6/30/13
  - W/ZrO2 prototypic element welded & ready for powder fill
  - Initial W/UO2 slug HIP can welded and ready for fill
  - W/UO2 7 channel CFEET sample is in work
- HIP can filling glove box modification complete
  - Extension chamber added for full scale HIP can filling
  - Integrated tooling and vibratory packing
- Performing trial HIP cycles to understand HIP ops
- Completed HIP processing procurements
  - Surface grinder for post HIP can removal
  - Sample saw for full scale element post HIP can cutting

MSFC ANL 200MW Demo HIP can

Top view of a 61-channel etch component just prior to the brazing process, showing the channel head and etch tubes positioned in the brazing assembly.

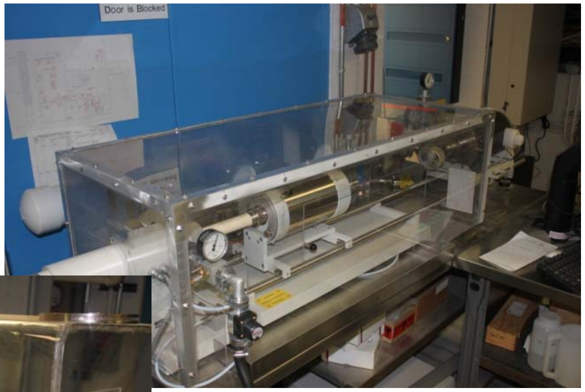


Above: 61 channel head with modified tooling to prevent bending in the tubes. Will use braze foil instead of braze paste.

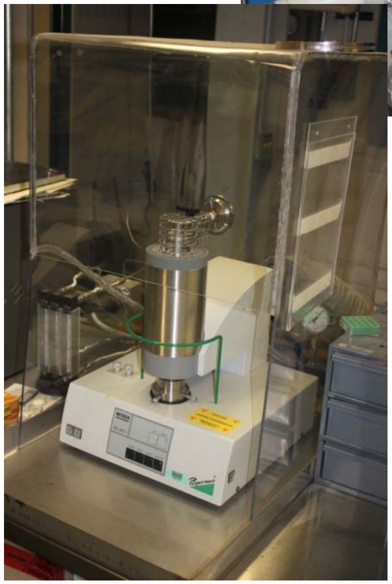
Extensive Diagnostic / Characterization Capability at DOE National Laboratories (example below from INL)

Thermal Characterization Suite Analysis of Sintered Specimens

- **Dilatometer, thermal expansion, 2000^oC**
- **Differential Scanning Calorimeter (DSC), heat capacity, 1200^oC**
- **Laser Flash Analyzer, thermal diffusivity, 1200^oC**
- **Combination of measurements allows thermal conductivity calculation**
- **Equipment modified for radioactive samples**



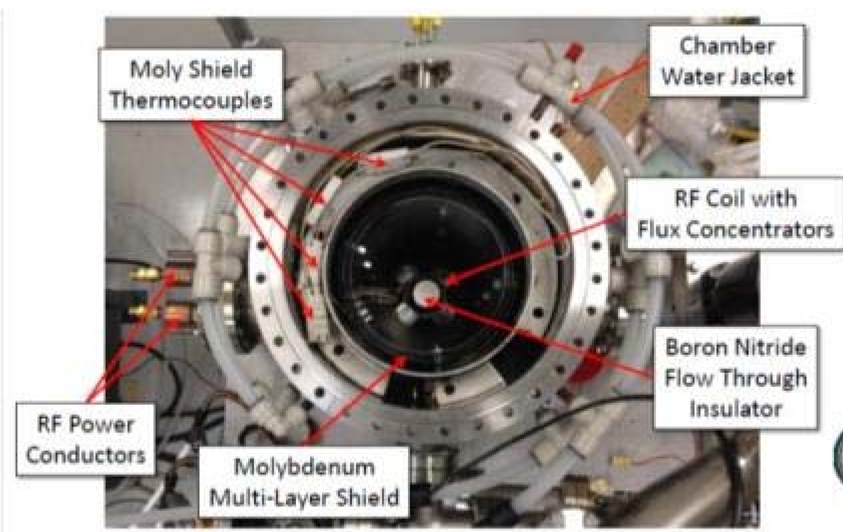
Dilatometer


DSC

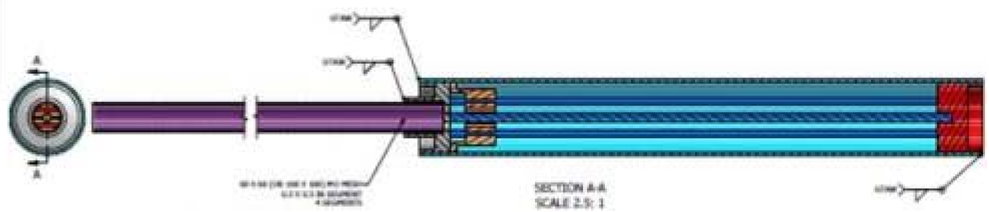
Laser Flash

Compact Fuel Element Environment Test (CFEET) System

- **Developed for affordable, rapid screening**
  - Slug and 7-hole samples (0.5” OD x 1-6” length)
- **Numerous system modifications**
  - Vacuum, cooling water, RF coil, data acquisition, H_2 feed, and sample support
- **Initial testing with 15 kW RF power supply**
  - Operational tests using W-Re-HfN CERMET
  - Tested to failure in vacuum at 2840 K
  - Primary heat loss from thermal radiation

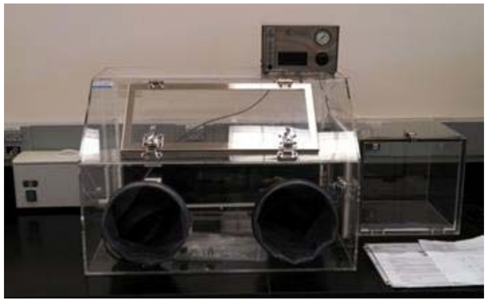


Pre/Post test W-Re-HfN CERMET



CFEET & CVD Optimization

MSFC CERMET FE: System Upgrades



Above: WCl6 Glove box

Above: Optimized CVD System
Left: CVD System Front Panel

CVD System

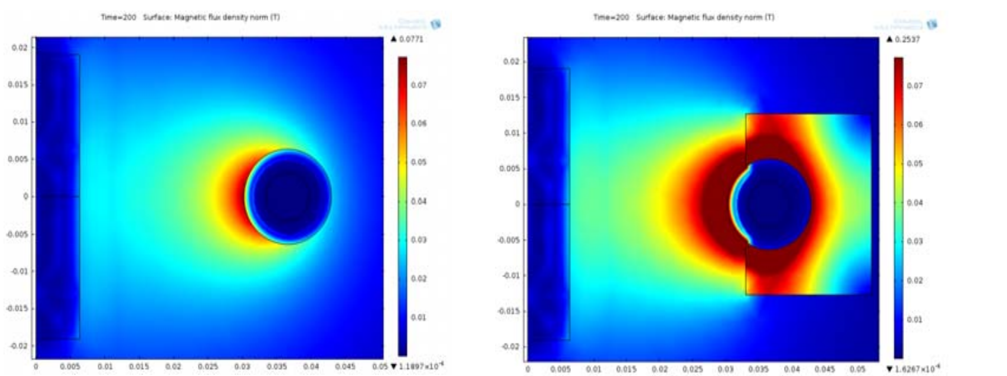
- Redesigned system layout for usability and safety
- MSFC Safety in final review process for updated procedures
- Completed subsystem checks on heaters, controllers and valves
- Procured a new tabletop acrylic glove box for WCl6 handling
  - WCl6 very reactive and corrosive if moisture is present
  - Glove box will prolong component life and reduce corrosion in the system

CFEET System 50 Kw Upgrade

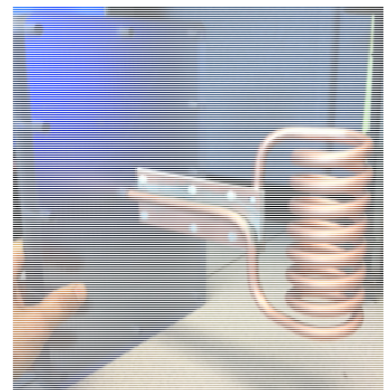
- Redesigned chamber and containment for dU
- Redesigned and optimized coil
- Completed ops checks on the following subsystems:
  - Burnstack T/C and solenoid valve controller
  - Mass flow controller
  - Vacuum pump isolation valves and interlocks
  - Vacuum Pump
- Begin checkout testing 6/4/13

CFEET Coil Optimization

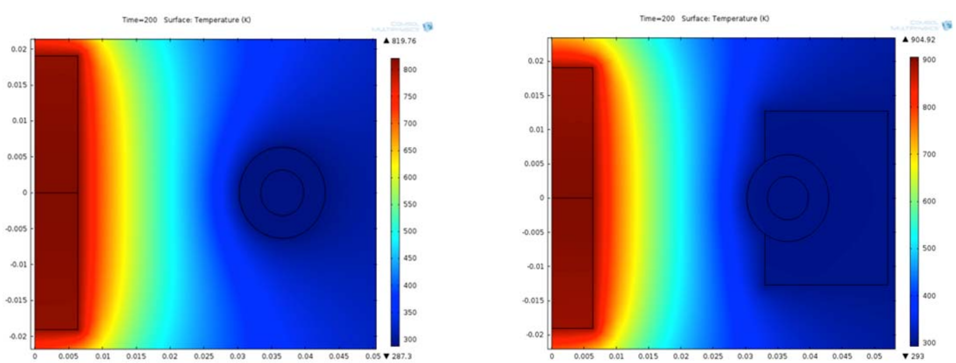
- Completed in-house coil analysis, design and fabrication
  - Evaluated coil diameter, shape, # of turns
  - Evaluated flux concentrator need, materials and submersion of coil



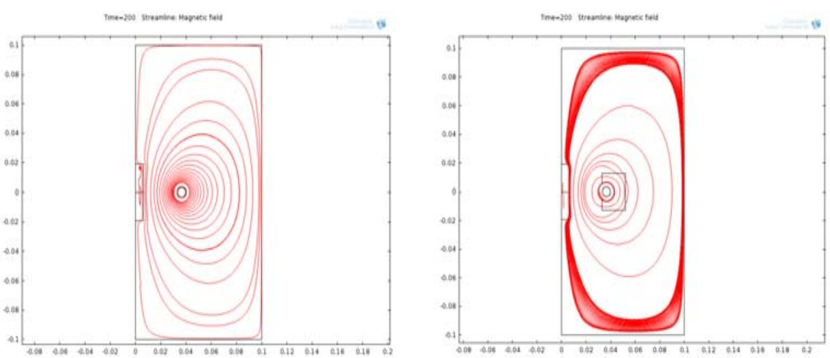
Magnetic flux density without the concentrator (left) and with the concentrator (right)



CFEET coil (left) and installed into the chamber (right)

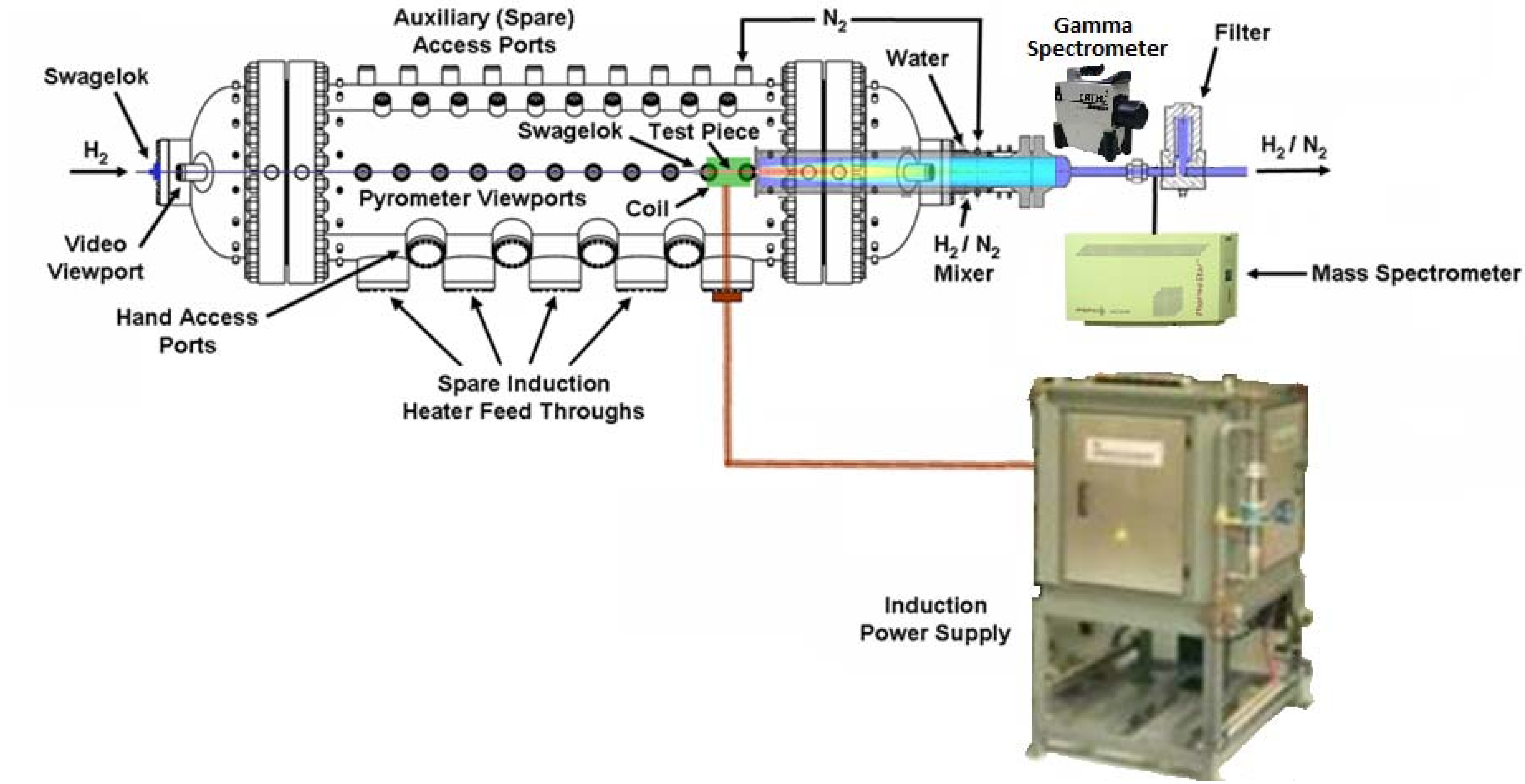


Model of one turn of the coil at 20kW power. Sample energy increased 11% with concentrator (right)



These images show the effect of concentrator on the flux density. With the concentrator the magnetic lines are forced out and coalesce more effectively on the sample (right)

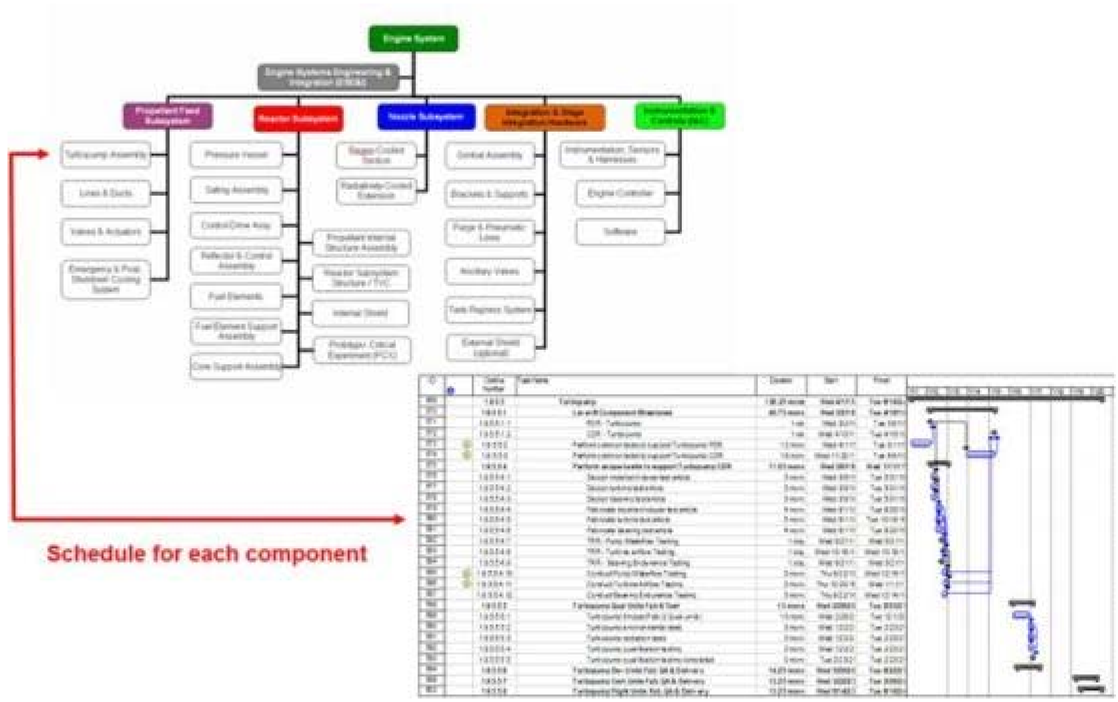
NTREES Hardware Test Chamber and Induction System



Current NTREES Configuration in 4205/101

Task#6 Affordable Development Strategy

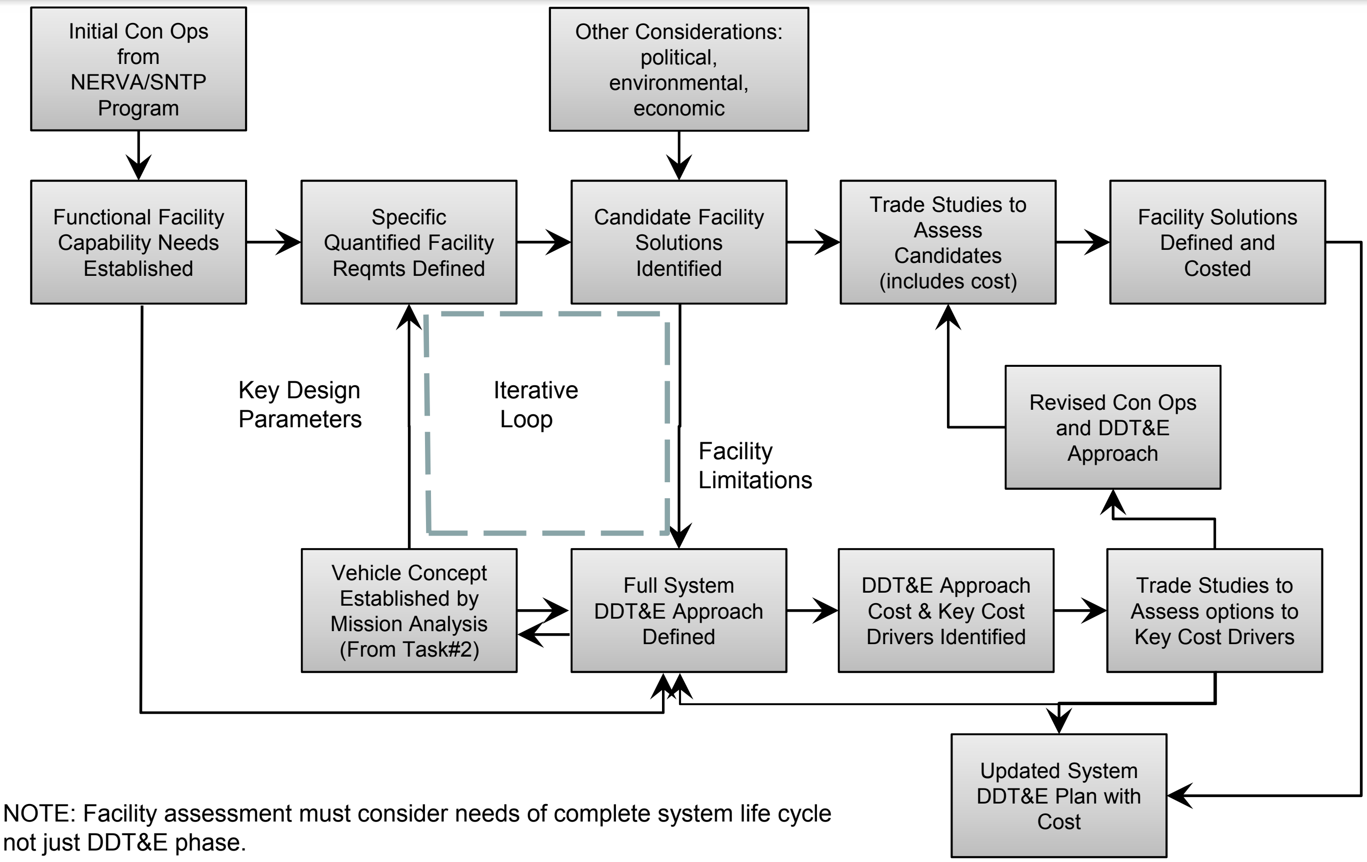
- **Determine an affordable development and qualification strategy, including a strategy for nuclear testing of the NCPS, with an estimated cost and schedule:**
  - Innovative Approach
  - Schedule
  - Cost
  - Sensitivities
  - Open Issues



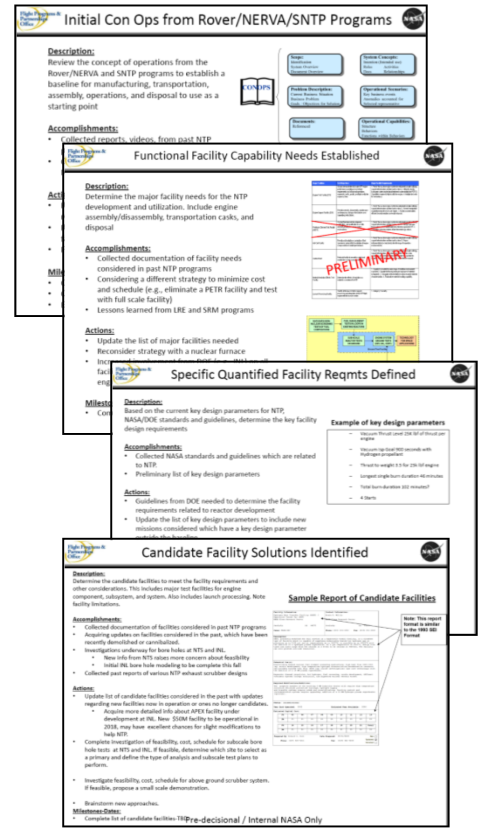
Example of WBS Breakdown

Goal-First cut by end of FY13

Affordable Development Plan Logic Flow



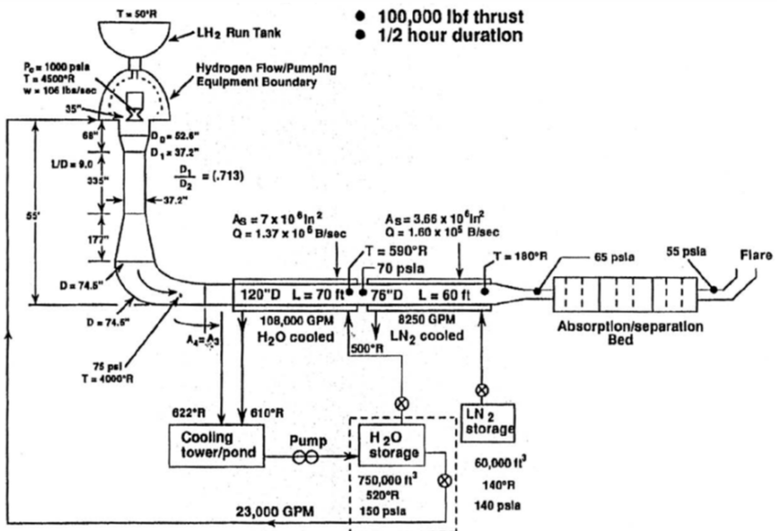
NOTE: Facility assessment must consider needs of complete system life cycle not just DDT&E phase.

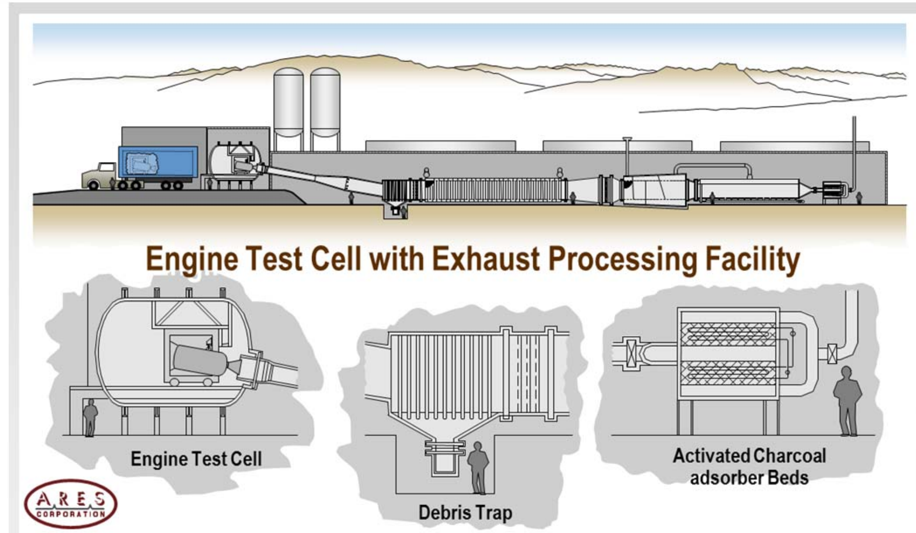


Examples of block definitions

- Defined the objectives, accomplishments, and actions for each block
- Identifying many open issues for each block which need to be worked.
- Prioritizing the actions and open issues for each block to best determine what to focus on with limited time and procurement funds

Above Ground Exhaust Scrubber Facility





- Investigating past reports to determine the following:
  - Optimum test stand configuration. Can modern technologies make it any better?
  - Compare past cost breakdown estimates to notice sensitivities, similarities or significant differences. Determine which test facility sections are the main cost drivers (e.g., engine test cell, controls, etc.)
  - Acquire facility design and cost breakdowns from other similar scale ground test facilities already constructed
- Referencing past EIS's to help identify the regulations and guidelines for past NTP facility designs. (e.g., National Emission Standards for Hazardous Air Pollutants (NESHAP 40 CFR61.90)

President John F. Kennedy …

- **First, I believe that this nation should commit itself to achieving the goal, before this decade is out, of landing a man on the Moon and returning him safely to the Earth.…**
- **Secondly, an additional 23 million dollars, together with 7 million dollars already available, will accelerate development of the Rover nuclear rocket. This gives promise of some day providing a means for even more exciting and ambitious exploration of space, perhaps beyond the Moon, perhaps to the very end of the solar system itself.**

Excerpt from the 'Special Message to the Congress on Urgent National Needs'
President John F. Kennedy
Delivered in person before a joint session of Congress May 25, 1961