THE NUCLEAR CRYOGENIC PROPULSION STAGE

PRESENTED AT

PROPULSION AND ENERGY 2014
JULY 29, 2014

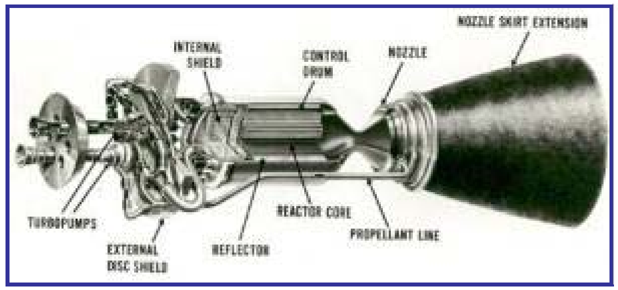
Michael G. Houts
Tony Kim
William J. Emrich
Robert R. Hickman
Jeramie W. Broadway
Harold P. Gerrish
Glen Doughty
Anthony Belvin
Stanley K. Borowski
John Scott

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.**

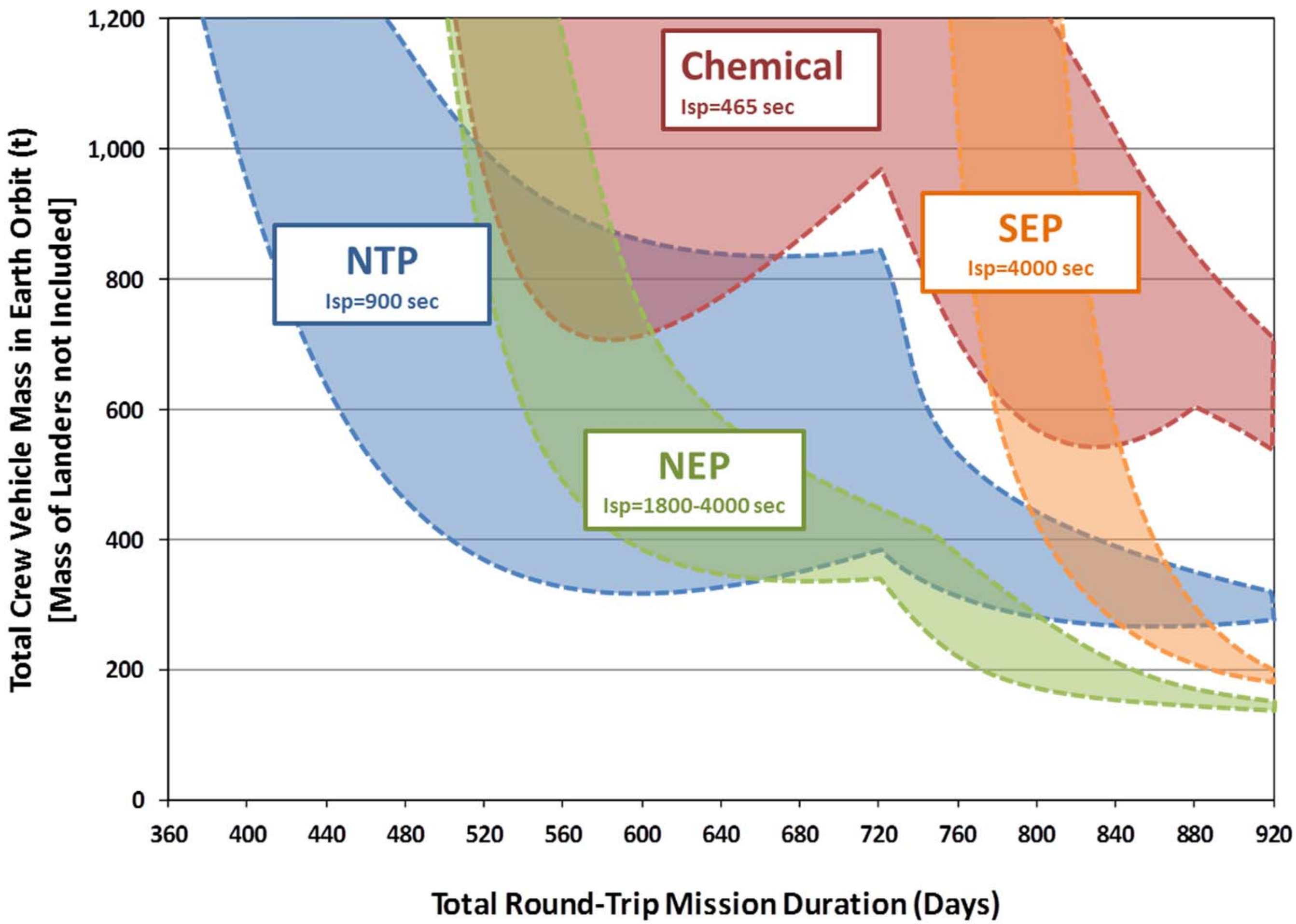
Excerpt from the 'Special Message to the Congress on Urgent National Needs'
President John F. Kennedy
Delivered in person before a joint session of Congress May 25, 1961

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**

Why is NTP considered for Human Missions to Mars?



Drake, B. G., “Human Mars Mission Definition: Requirements & Issues,” presentation, Human 2 Mars Summit, May 2013

Shorter Trip Times reduce exposure to Galactic Cosmic Radiation

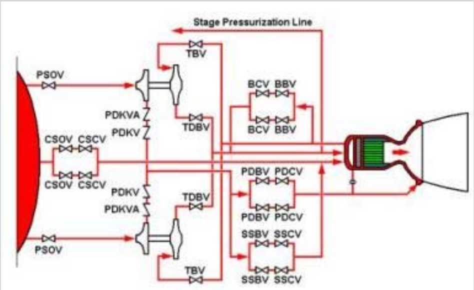
Nuclear Cryogenic Propulsion Stage (NCPS) Organizational Structure

1.0 NCPS Project Management

Project Manager:	Mike Houts (MSFC)
GRC Lead:	Stan Borowski
JSC Lead:	John Scott
DOE - NE75 Lead:	Anthony Belvin
DOE - NNSA Lead:	Jerry McKamy

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)

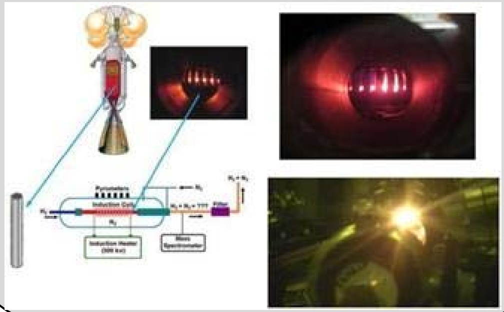
Lead: Bill Emrich (NASA)

4.0 NCPS Fuel Design / Fabrication

Co-Leads: Jeramie Broadway (NASA), Lou Qualls (ORNL), Jim Werner (INL)

5.0 NCPS Fuels Testing in NTREES & CFEET

Co-Leads: Bill Emrich (NASA), Robert Hickman (NASA), Lou Qualls (ORNL), Jim Werner (INL)



6.0 Affordable NCPS Development and Qualification Strategy

Co-Leads: Harold Gerrish (NASA), Glen Doughty (NASA), Stan Borowski (NASA), David Coote (NASA), Robert Ross (NASA), Jim Werner (INL), Roy Hardin (NRC)

NCPS Team FY14/15 Milestones

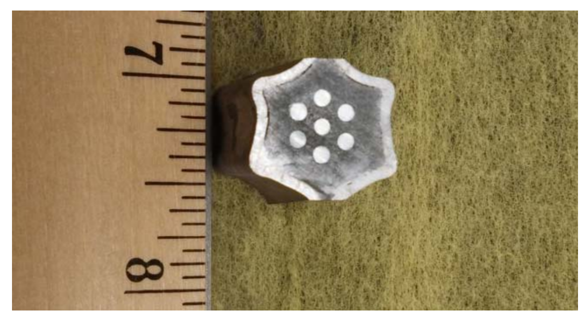
1. Fabricate short (~3") cermet fuel element and test in CFEET, 2/14/14
2. Extrude 16" graphite element and coat multiple internal channels of ~16" graphite specimen, 6/30/14
3. Fabricate representative, partial length (~16"), cermet fuel element with prototypic depleted uranium loading and test in NTREES, 8/4/14
4. Fabricate representative, partial length (~16"), coated graphite composite fuel element with prototypic depleted uranium loading, 9/1/14
5. Complete initial NTREES testing of ~16" coated graphite composite fuel element with prototypic depleted uranium loading, 11/1/14
6. Provide an initial NASA/DOE-NE75 recommendation on down selection of leader and follower fuel element types (Cermet vs. graphite composite), 12/15/14

W/UO_2 CERMET Fuel Element Fabrication: 7 Channel Element with Depleted Uranium

Above left/right: 7 channel W-UO_2 FE during HIP process

Left & above: LANL sample post fill and closeout prior to shipping

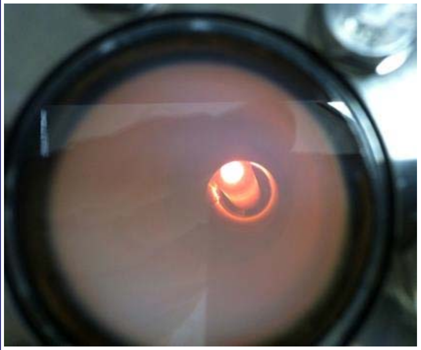
Above/Below: 7 channel WUO_2 fuel element post HIP and cross sections



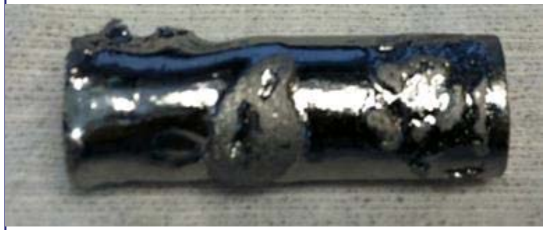
Short, 7 Channel W/UO_2 Element Fabricated and Tested in Compact Fuel Element Environmental Tester (CFEET)

CFEET System 50 kW Buildup & Checkout

Completed CFEET system. Ready for W-UO_2 and H_2 testing

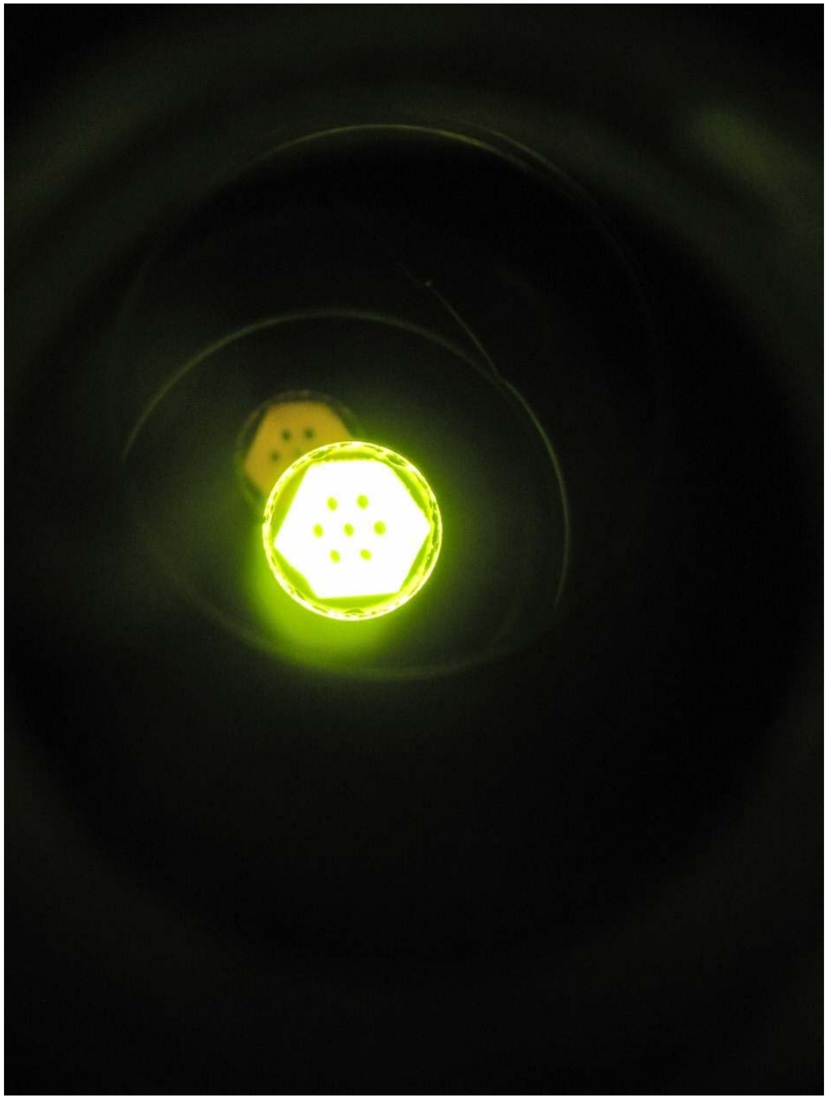


Left: View looking down into the CFEET chamber during shakeout run 1. BN insulator and bright orange sample inside



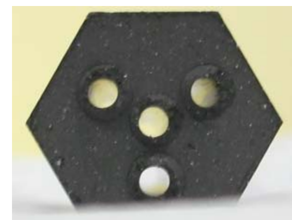
Above/left: Pure W sample post shakeout run 2. Sample reached melting point (3695K) and was held in place by the BN insulator.

Initial Testing of Short W/UO_2 Element

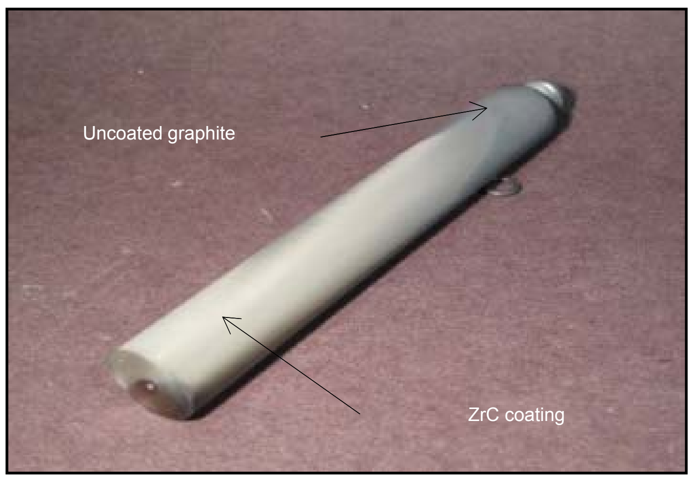


Coated Graphite Composite Development (ORNL)

Above: Members of Oak Ridge National Laboratory fuels team with the graphite extruder; Left: Graphite extruder with vent lines installed for DU capability

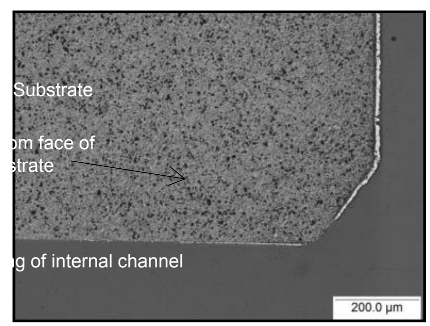


Above and Left: Extrusion samples using carbon-matrix/Ha blend .75” across flats, .125” coolant channels

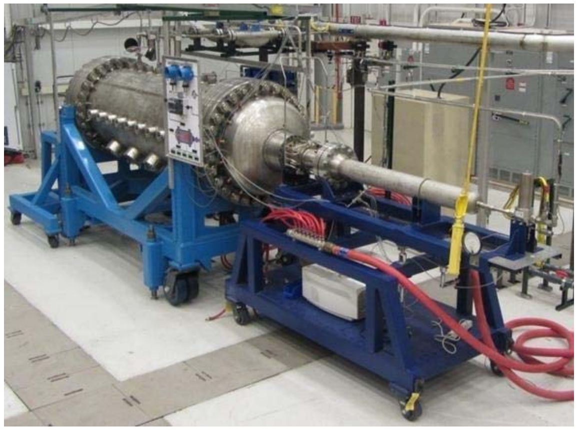


Above: Test Piece highlighting ZrC Coating
Right: Coating primarily on external surface

Right: Layoff base / Graphite insert



Nuclear Thermal Rocket Element Environmental Simulator (NTREES)



NTREES Phase 1 50kW (2011)

NTREES Phase 2 – 1MW Upgrade (2014)

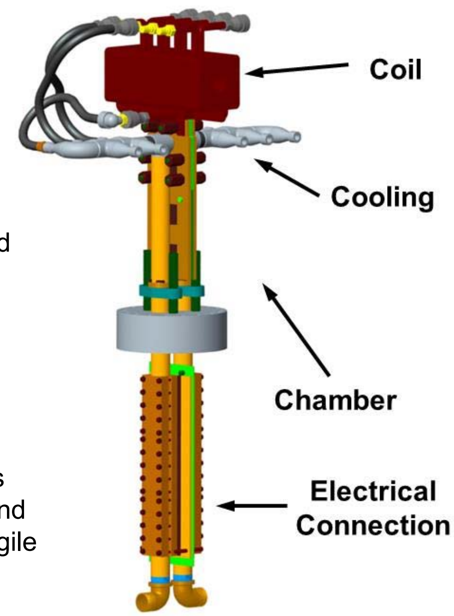
New Cooling Water System now provides 2 separate systems that cool induction coil and power feedthrough, induction heater and H_2N_2 mixer respectively

General Description:

- Water cooled ASME coded test vessel rated for 1100 psi
- GN_2 (facility) and GH_2 (trailer) gas supply systems
- Vent system (combined GN_2/GH_2 flow)
- 1.2 MW RF power supply with new inductive coil
- Water cooling system (test chamber, exhaust mixer and RF system)
- Control & Data Acquisition implemented via LabVIEW program
- Extensive H_2 leak detection system and O_2 monitoring system
- Data acquisition system consists of a pyrometer suite for axial temperature measurements and a mass spectrometer
- “Fail Safe” design

New Coil is Heavily Insulated and Rugged

Old Coil was Uninsulated and Somewhat Fragile

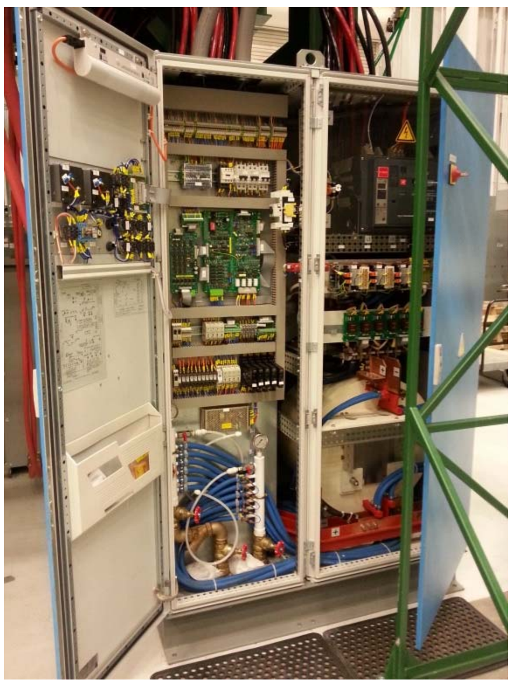
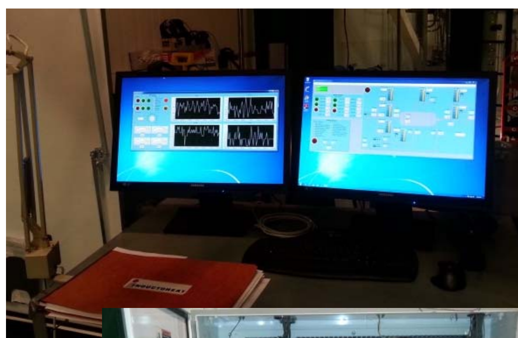
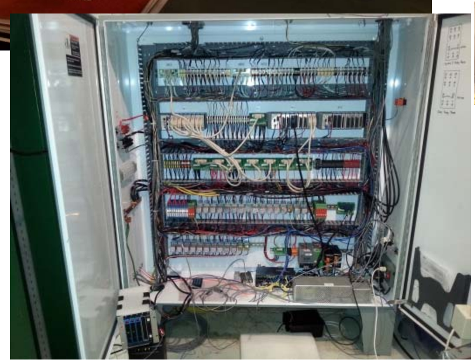


Coil and Feedthrough Assembly

NTREES 1 MW Operational Readiness Inspection

NTREES Walk-thru for ORI Board: 1/30/14



What Else Needs Done?

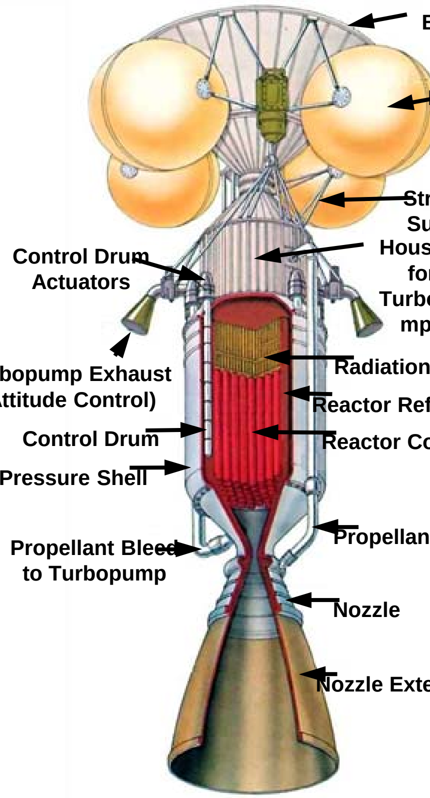
Observations:

59 years since the start of the Rover / NERVA program

NTP programs typically cancelled because mission is cancelled, not because of insurmountable technical or programmatic issues

Programmatic constraints, technical capabilities, available facilities, mission needs, etc. all continually change

Need to devise an optimal approach to developing a 21st century NTP system



What Else Needs Done?

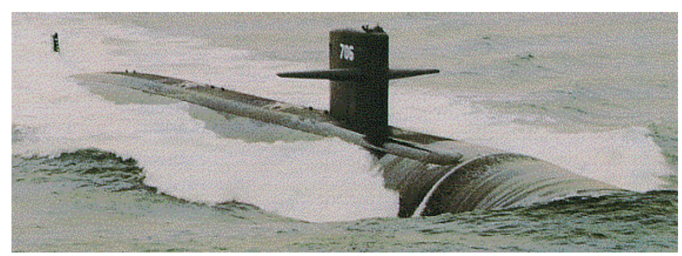
Options Have Changed Since 1955

Tremendous advances in computational capabilities (nuclear and non-nuclear).

Increased regulation and cost associated with nuclear operations and safeguards.

Extensive development of non-nuclear engine components. Extensive experience with various types of nuclear reactors.

Recent successes in “space nuclear” public outreach (Mars Science Lab).

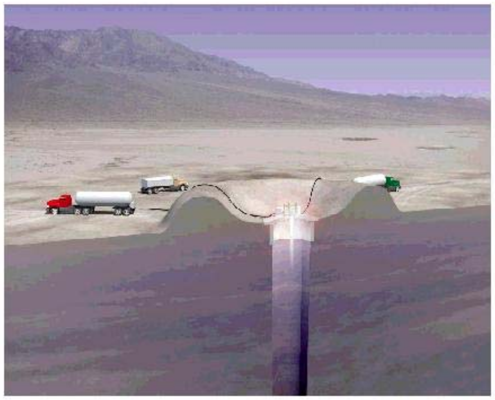


What Else Needs Done?

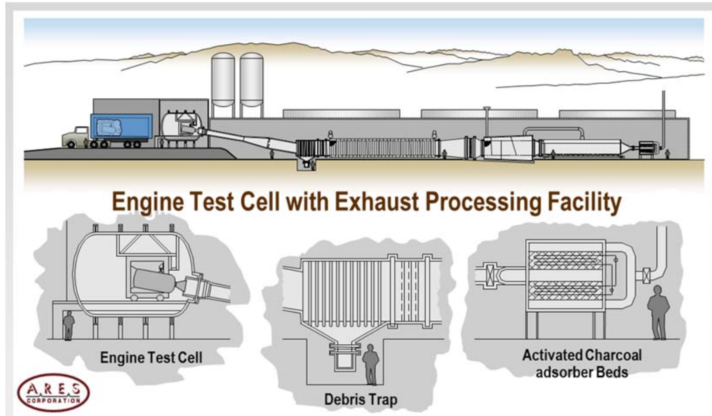
Many Decisions will Affect Long-Term Affordability and Viability of any Potential NTP Development Program

- **Balance between computational and experimental work.**
- **Flight qualification strategy / human rating**
- **Low-enriched uranium vs highly-enriched uranium**
- **Unscrubbed, scrubbed, or fully contained exhaust during ground testing.**
- **Choice of facility for any required testing (i.e. NCERC, NASA center, industry, etc.**
- **Many others!**

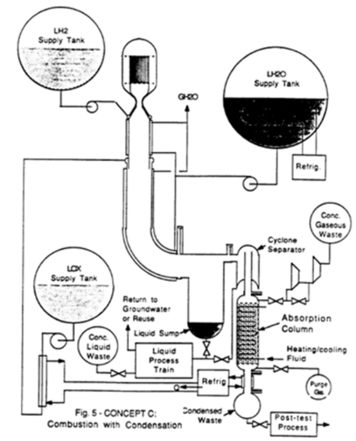
NTP Ground Test Options



Bore hole



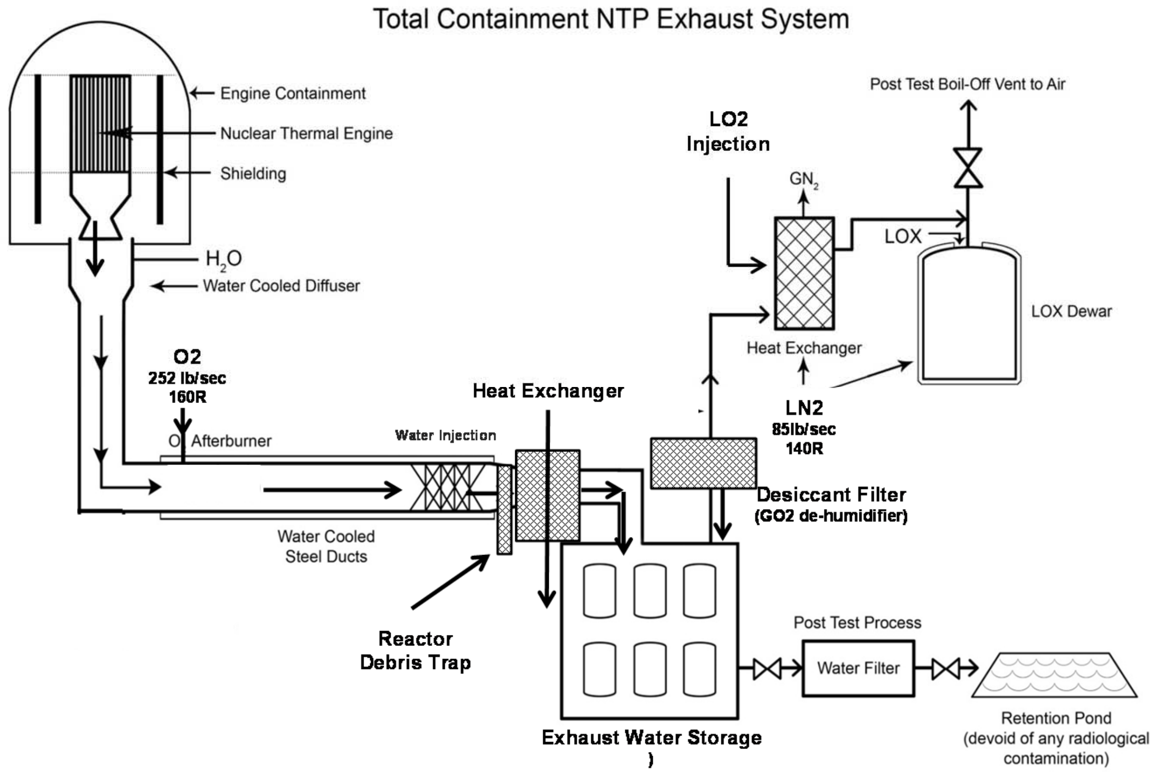
Above ground scrubber with filters



Total containment with combustion and condensation

- ♦ Bore Hole
  - Relies on permeability of desert alluvium soil to filter engine exhaust
    - Reports from Nevada Test Site show significant effects of water saturation, turbulent flow rate, hole depth, and pressures on soil permeability.
- ♦ Above Ground Scrubber
  - 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
- ♦ Total Containment
  - Engine hydrogen exhaust is burned at high temperatures with oxygen and produces steam to be cooled, condensed, and collected for controlled processing and disposal
    - All analyses to date indicate system will reliably and economically accomplish task

NTP Total Containment Test Facility Concept



Strategy:

- Fully Contain engine exhaust
- Slowly drain containment vessels after test

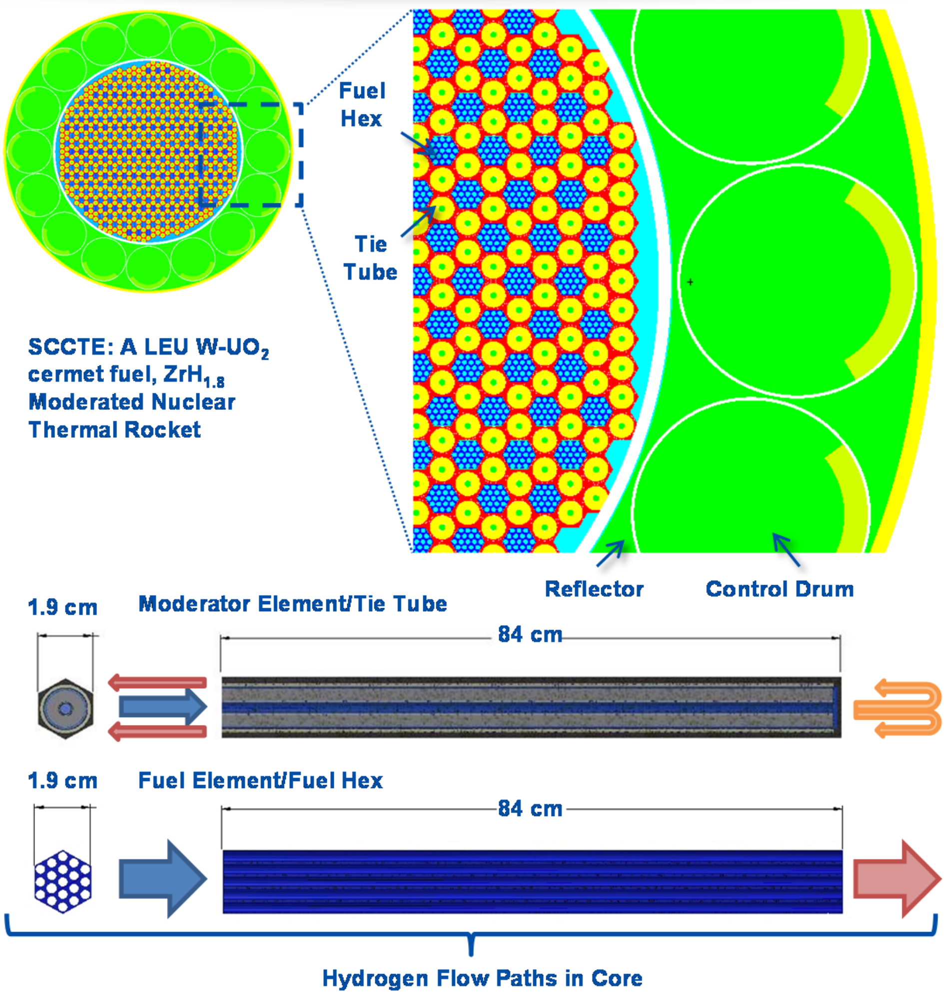
How it works:

- 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 O_2 and a small fraction of noble gases (e.g., xenon and krypton)
- Heat exchanger and water spray dissipates heat from steam/O2/noble gas mixture to lower the temperature and condense steam
- Water tank farm collects H_20 and any radioactive particulates potentially present in flow. Drainage is filtered post test.
- Heat exchanger-cools residual gases to LN2 temperatures (freezes and collects noble gases) and condenses O2.
- LOX Dewar stores LO_2, to be drained post test via boil-off

Low Enriched Uranium (LEU) NTR - Example

Space Capable Cryogenic Thermal Engine

(Baseball Card as of 6/20/14, Rev. 0.2.2)



SCCTE: A LEU W-UO_2 cermet fuel, $ZrH_{1.8}$ Moderated Nuclear Thermal Rocket

Reactor System Performance	
Core power (MW)	558.2
Core average fuel power density (MW/l)	18.50
Max Fuel Temp. (K)	2850.0 K
U-235 Enrichment (a%)	19.75
U-235 inventory (kg)	31.86

Engine System Interface Information			
Interface Point	Flow Rate (lbm/s)	Pressure (psia)	Temp. (R)
Core inlet	29.0	543.2	432.3
Core outlet	29.0	449.9	4927.7

Power Deposition	
Tie Tubes (MW)	16.19
Radial Reflector (MW)	2.56
Other Non-Fuel Components (MW)	3.00

Key Dimensions	
Total Reactor Length (fuel + axial reflector) (cm)	99.24
Total Reactor Dia. (core+ vessel+radial reflector) (cm)	99.67
Core Dia. (cm)	64.00
Core Length (cm)	84.00

Reactor System Mass	
Fuel Mass (291 Elements) (kg)	430.47
Tie Tubes (680 Elements) (kg)	782.03
Radial Reflector + Control Drums (kg)	568.7
Axial Reflector (kg)	22.7
Slats + Barrel + Vessel (kg)	341.4
Internal Structure (Plate + Chamber) (kg)	436.8
Total Mass (Excluding Shield) (kg)	**2582.1**

Observations / Summary

HEOMD's AES Nuclear Cryogenic Propulsion Stage (NCPS) project is making significant progress.

Safety is the highest priority for NTP (as with other space systems). After safety comes affordability.

No centralized capability for developing, qualifying, and utilizing an NTP system. Will require a strong, closely integrated team.

Tremendous potential benefits from NTP and other space fission systems. No fundamental reason these systems cannot be developed and utilized in a safe, affordable fashion.