# THE NUCLEAR CRYOGENIC PROPULSION STAGE

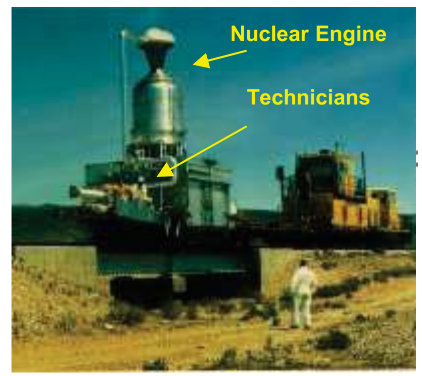
**PRESENTED AT**
**SPACE 2014**

**August 4, 2014**

# NTP Facts

The mass of a toy marble equals the mass of uranium providing the NTP energy for the entire Mars Mission

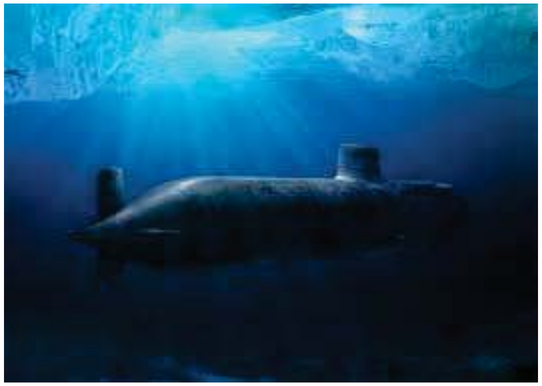
Standing next to an NTP engine before launch for one year is less radiation than diagnostic x-rays



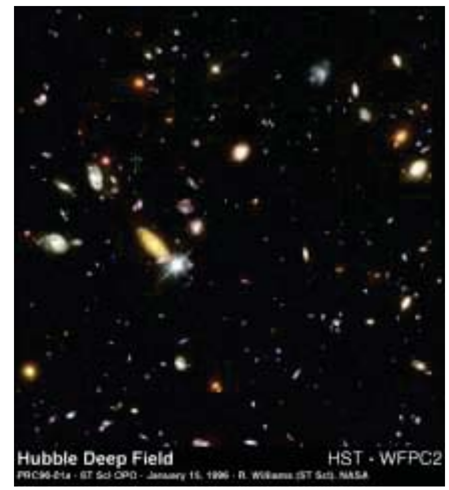


NTP ground test regulations allow annual public dose to be 25% of what comes from all annual food you eat (e.g., bananas, potatoes, etc.), or 20 hours of plane flight

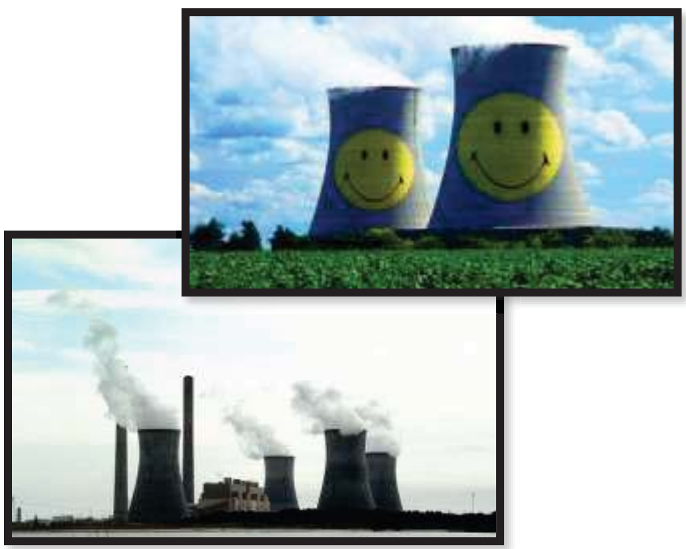
# NTP Facts (Cont'd)



Crews of nuclear submarines have lower radiation exposure than the general public above the water




NTP provides faster trip times to Mars & exposes the astronauts to less galactic cosmic radiation



NTP reactor fission products from the entire Mars mission is about equal to products formed after ~10 minutes of runtime from a nuclear power plant

# NTP Facts (Cont’d)

Using NTP saves up to 4 SLS launches for a human to mars mission and saves $B’s, shortens total launch schedule, and increases chances of mission success

NERVA prototype flight engine was ready to be fabricated based on successful NTP ground test demonstrations in 1960’s. Current TRL for new fuel ~4

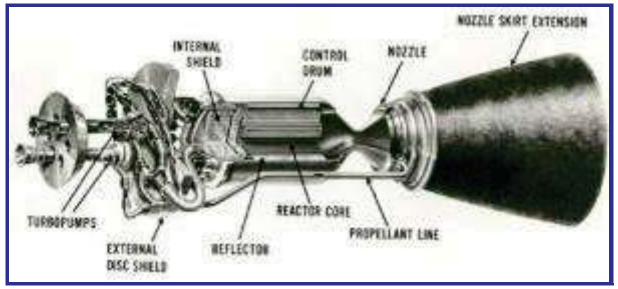

Low enriched uranium (LEU) design has much lower security costs/risks

**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.**

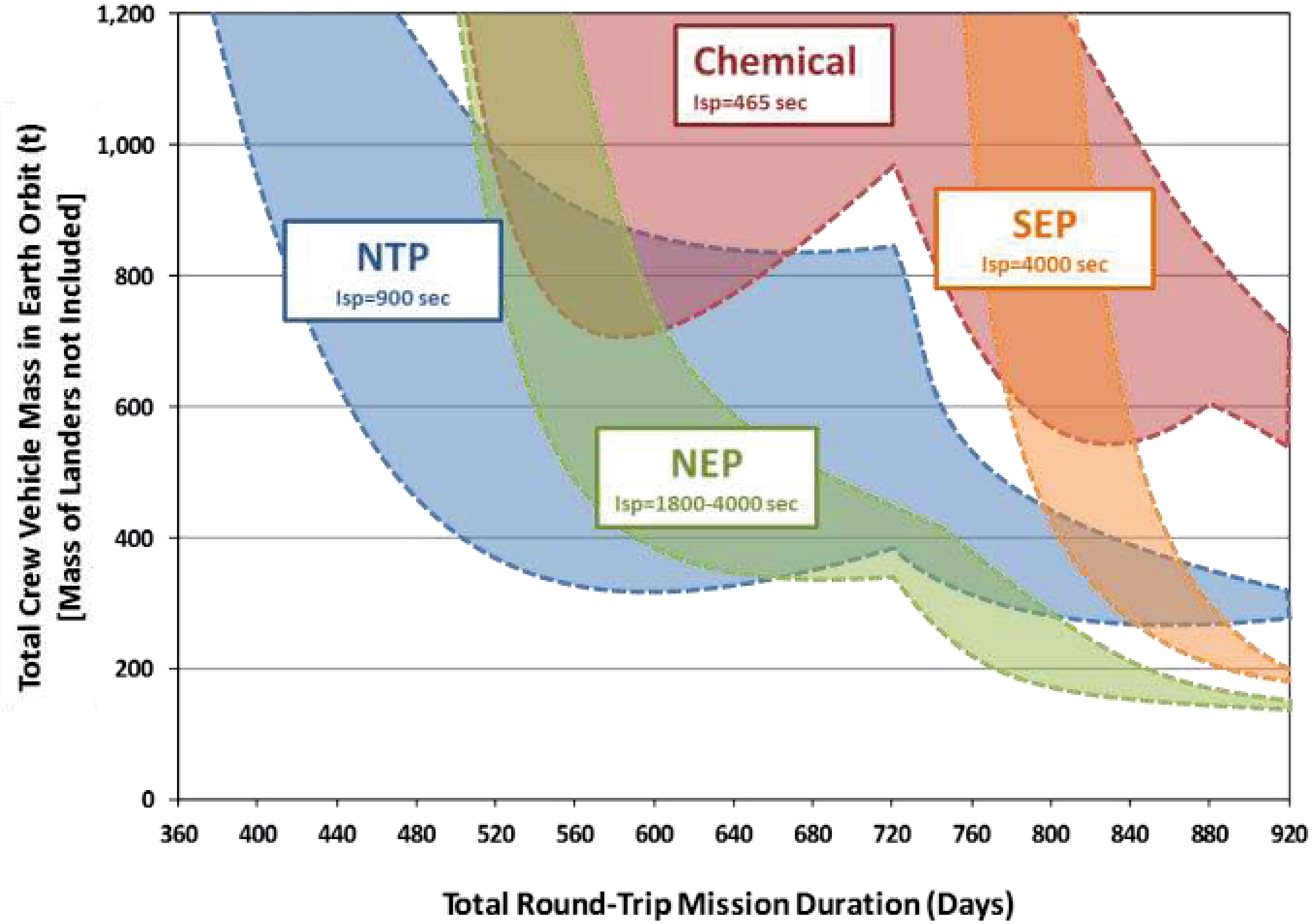
Excerpt from the 'Special Message to the Congress on Urgent National Needs'
**President John F. Kennedy**
**Delivered in person before a joint session of Congress May 25, 1961**

# *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***

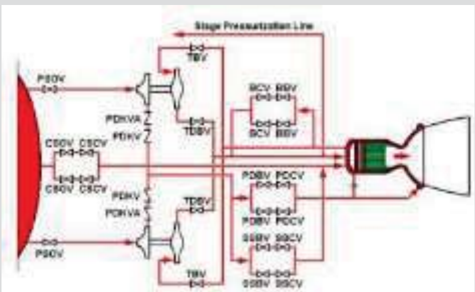
# Nuclear Cryogenic Propulsion Stage (NCPS) Organizational Structure

***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: | Steve Clement |

***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)***

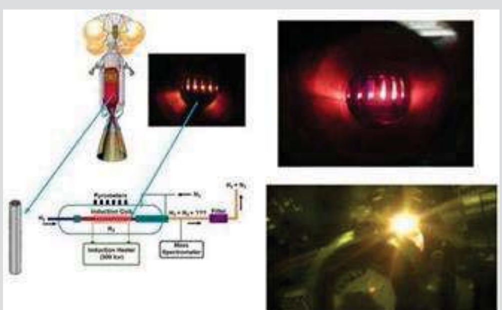
***Lead: Bill Emrich (NASA)***

***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)***



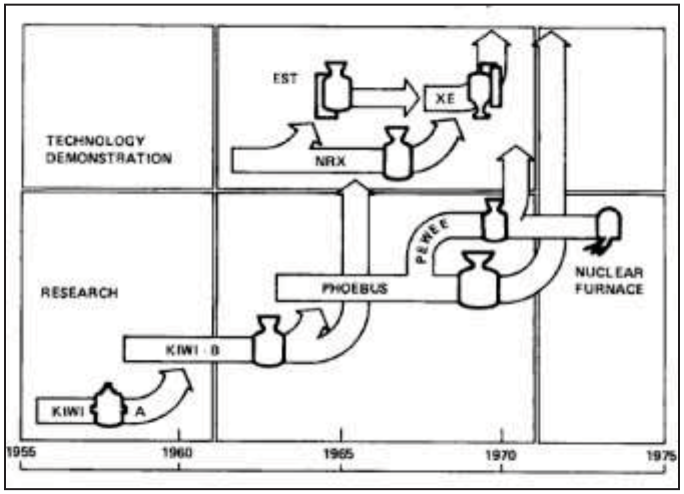
***6.0 Affordable NCPS Development and Qualification Strategy***

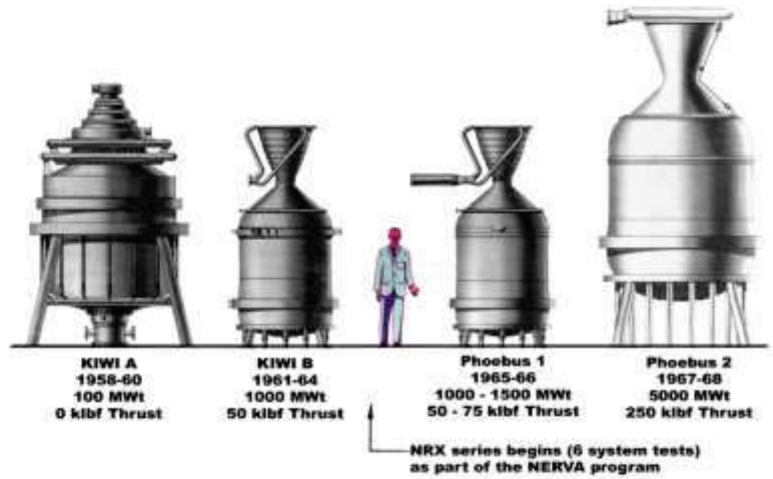
***Co-Leads: Harold Gerrish (NASA), Glen Doughty (NASA), Stan Borowski (NASA), David Coote (NASA), Robert Ross (NASA), Jim Werner (INL), Roy Hardin (NRC)***

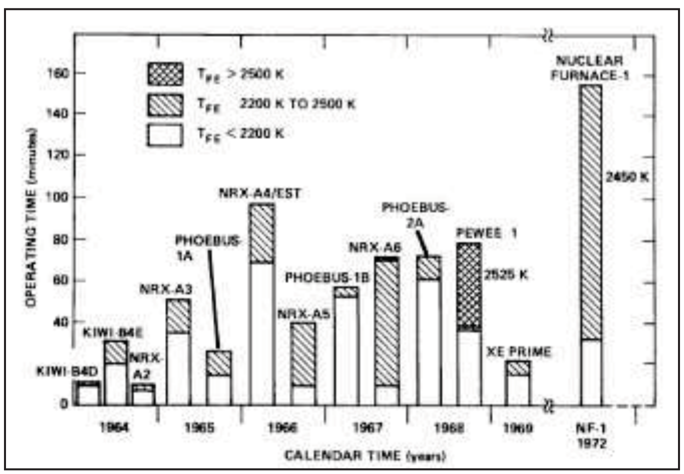
# NCPS Team FY14/15 Milestones

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

# Test Program safely accomplished in the past



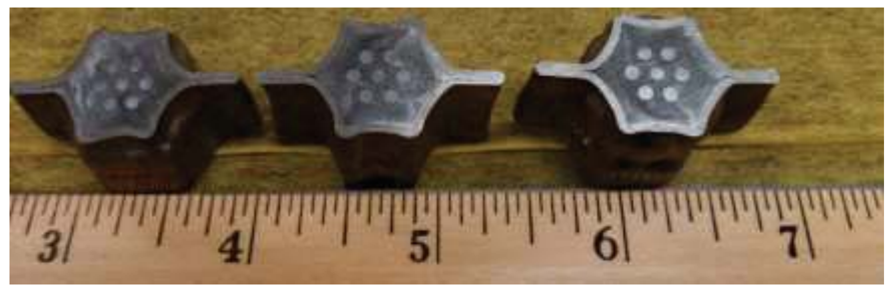




**20 NTP engines designed built and tested during Rover/NERVA**

# 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

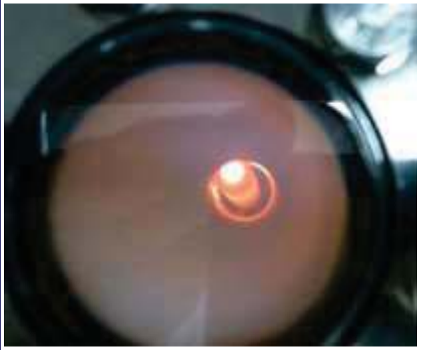
Left & above: LANL sample post fill and closeout prior to shipping

Above/Below: 7 channel W$UO_2$ 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

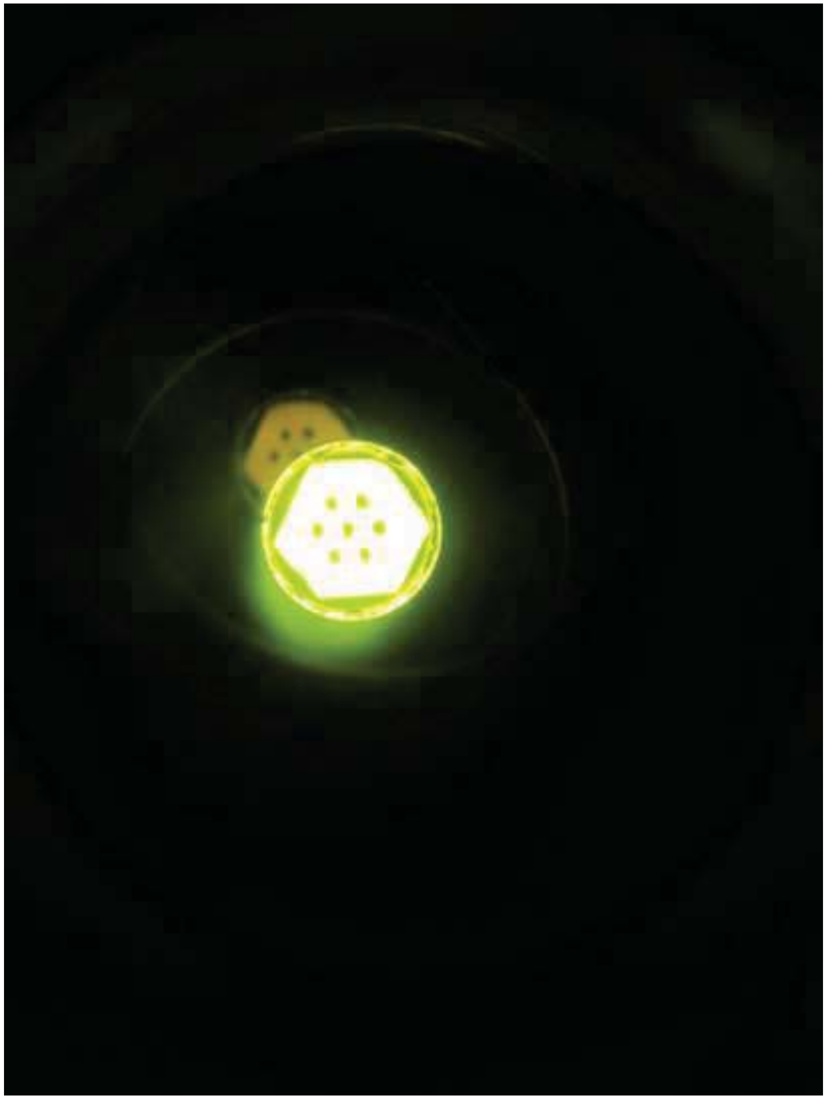
Completed CFEET system. Ready for W-$UO_2$ and $H_2$ testing



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

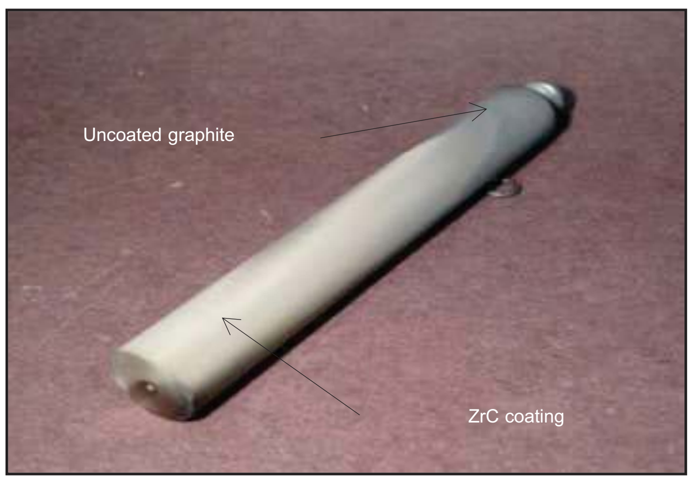


# Coated Graphite Composite Development (ORNL)

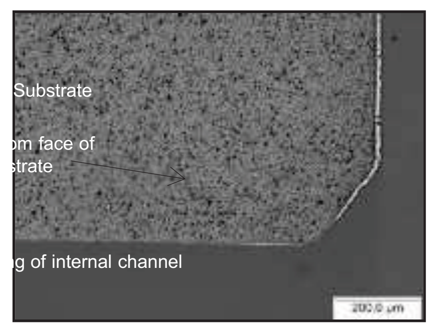

Above: Members of Oak Ridge National Laboratory fuels team with the graphite extruder; Left: Graphite extruder with vent lines installed for DU capability

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

Right: Layoff base / Graphite insert




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



# Nuclear Thermal Rocket Element Environmental Simulator (NTREES)

**NTREES Phase 1 50kW (2011)**

**NTREES Phase 2 – 1MW Upgrade (2014)**

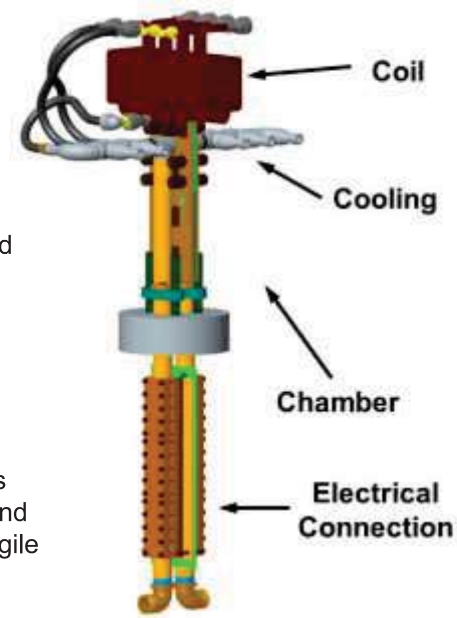
New Cooling Water System now provides 2 separate systems that cool induction coil and power feedthrough, induction heater and $H_2N_2$ mixer respectively

## 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

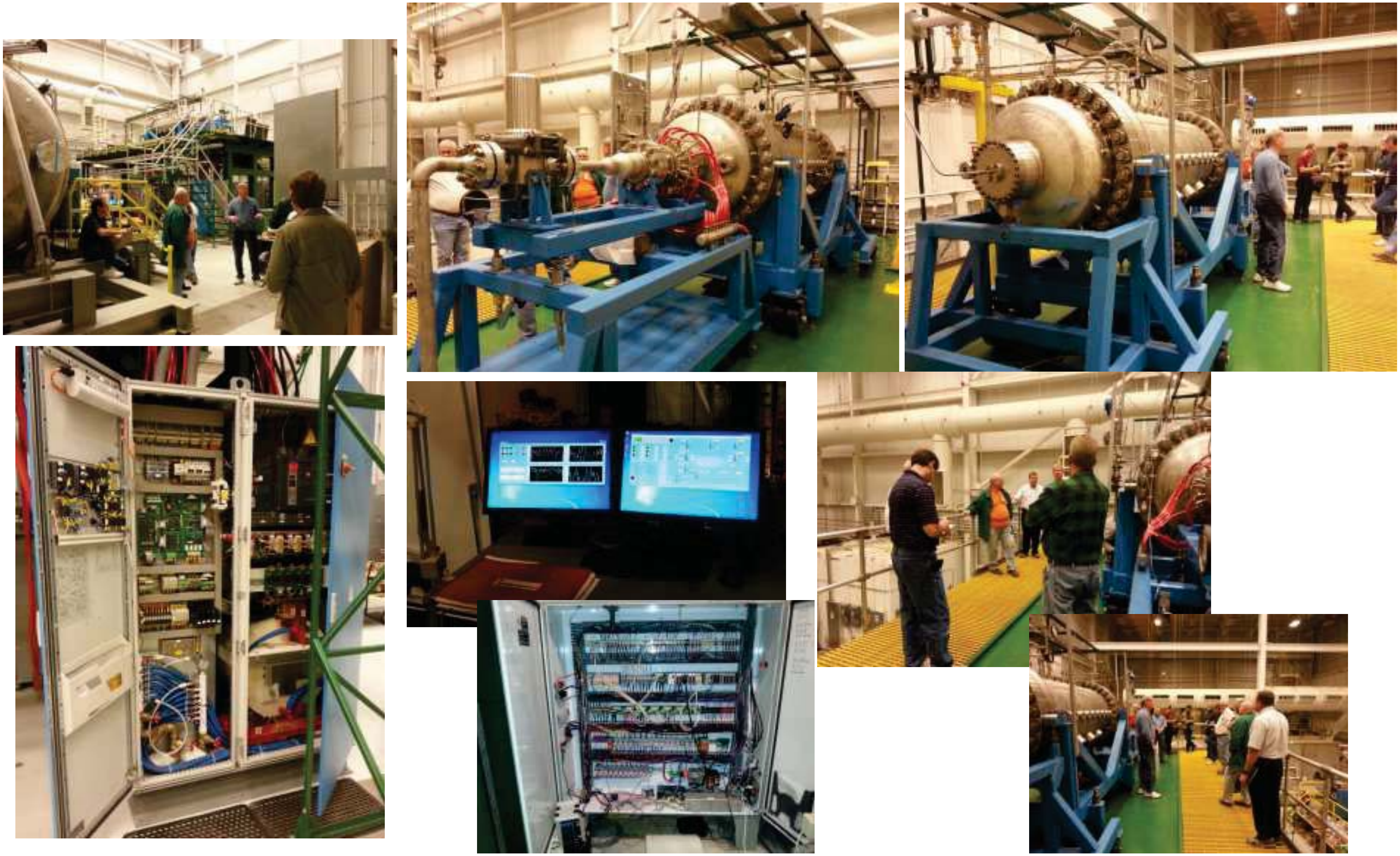
Old Coil was Uninsulated and Somewhat Fragile




Coil and Feedthrough Assembly

# NTREES 1 MW Operational Readiness Inspection

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



# What Else Needs Done?

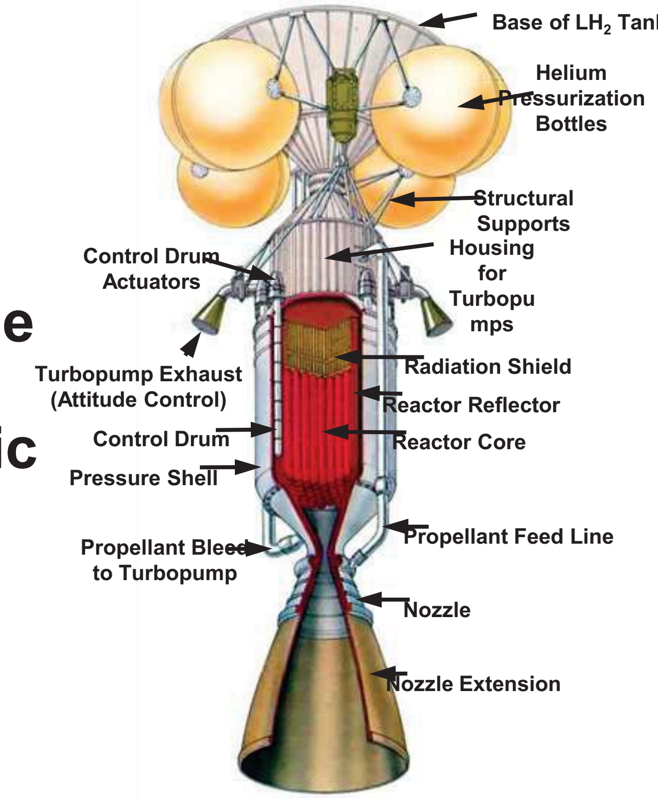
## Observations:

59 years since the start of the Rover / NERVA program

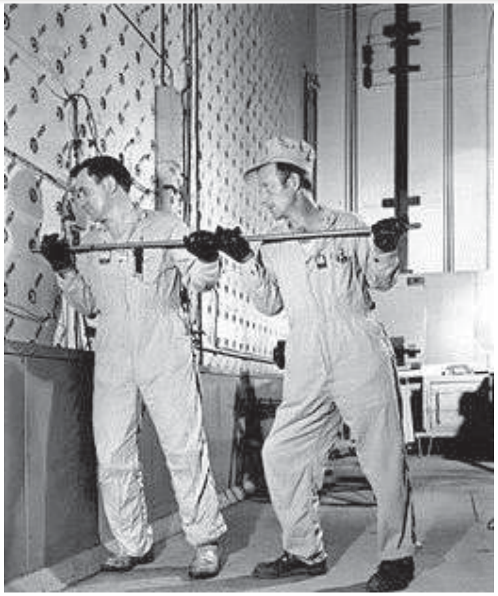
NTP programs typically cancelled because mission is cancelled, not because of insurmountable technical or programmatic issues

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




# 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.

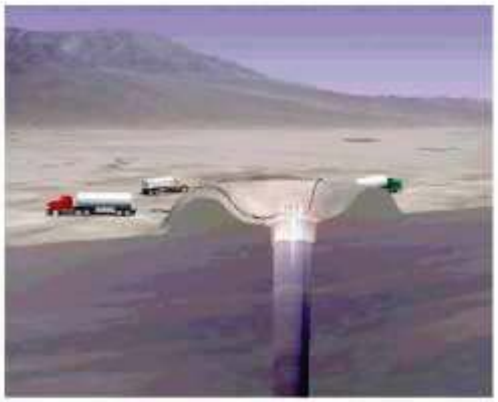
Recent successes in “space nuclear” public outreach (Mars Science Lab).

# What Else Needs Done?

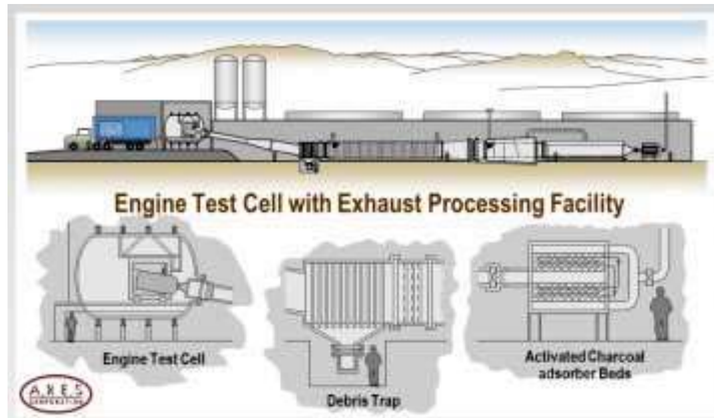
## Many Decisions will Affect Long-Term Affordability and Viability of any Potential NTP Development Program

- 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!

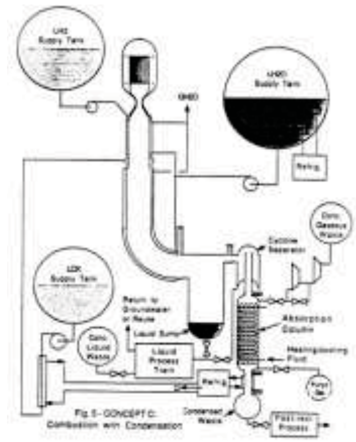
# NTP Ground Test Options



Bore hole



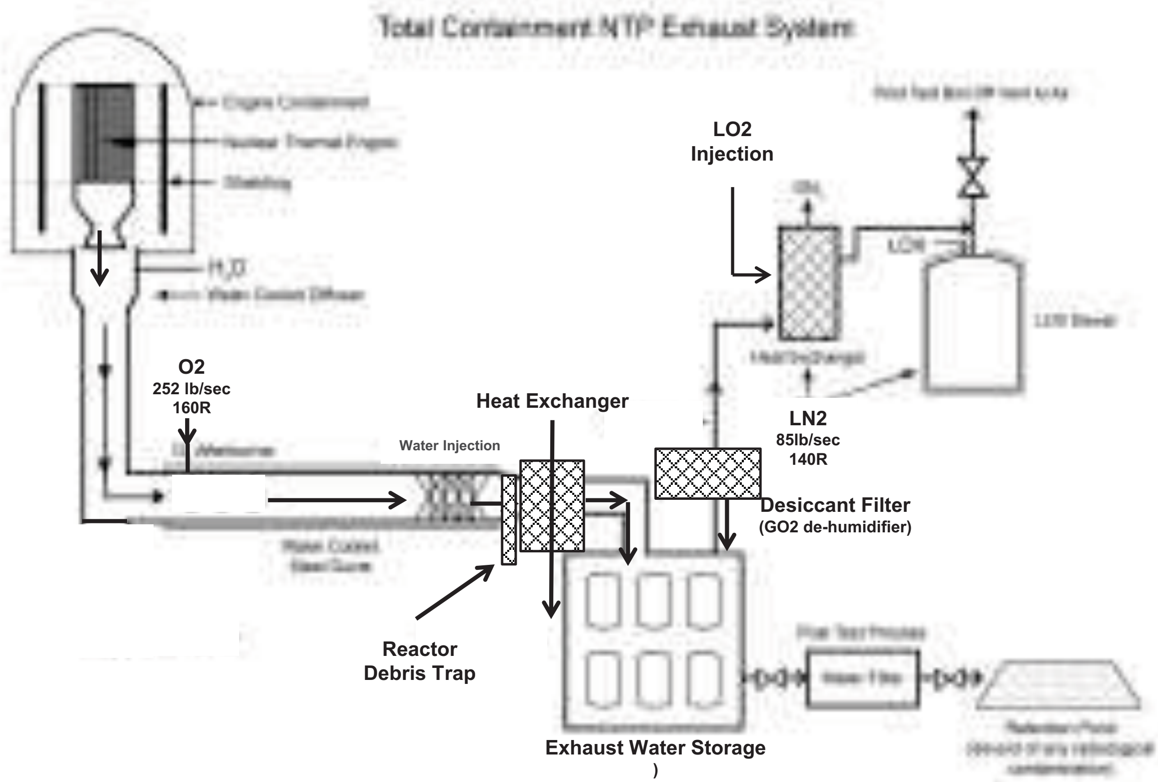

Above ground scrubber with filters



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

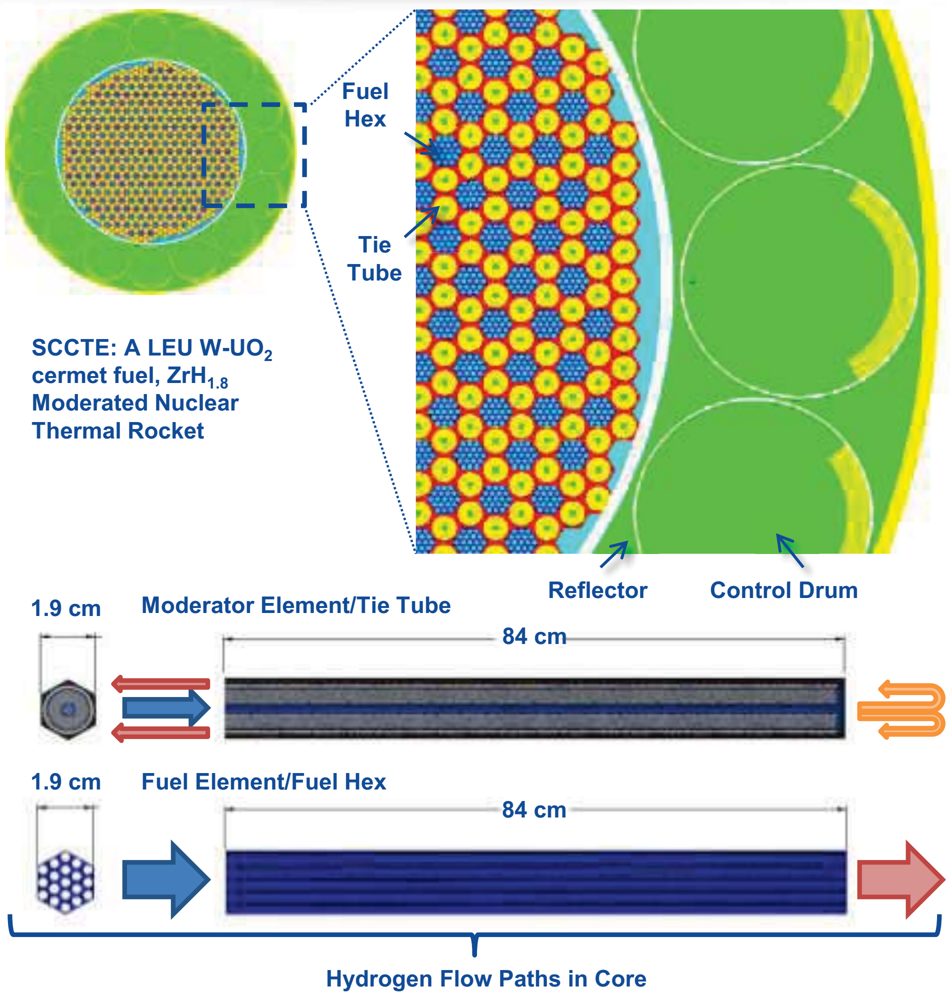
**How it works:**

- 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)




| 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** |

# Human Mars Mission Architecture & Mission Design

**Thrust**
Sensitivity Trades

- 3 x 25 klbs thrust
- 5 x 15 klbs thrust
- 2 x 50 klbs
- 3 x 30 klbs
- 1 x 75 klbs
- 1 x 100, 125, 150…
- 8 x 10 klbs

**Isp**
Sensitivity Trades

- 825-950 sec
- Isp to fit 4 launch mission
- Isp to fit 5 launch mission
- # of LV needed w/ 900 s


**Thrust/Weight**
Sensitivity Trades

- 1, 2, 3, 4, …
- Engine T/W
- Vehicle T/W

**Initial Assumptions**

- DRM 5.0 Human Mars Mission
- 3 x 25 klbs thrust
- Isp = 900 s
- Engine T/W = 3.5
- 4 re-starts
- 102 minutes total burn time
- 2033 Opposition Class (hardest case)

**Close Stack**

**Considerations affecting thrust, t/w, Isp**

**Outside NCPS influence**
- Enabling technologies
- HAT requirements
- SLS Launch Vehicle (or other)

**NCPS Task 3 & Task 6 influence**
- Fuel Element material (Isp)
- Affordable Strategy (testing limitations)

**NCPS Task 2 influences (modeling & analysis)**
- Trajectory (min delta V, minimize time)
- Boil-off estimates
- Transient operations (start, shutdown)
- Leakage
- Human Rating (engine out scenario)
- Bi-modal
- Radiation shield concept (large mass)
- Higher fidelity analysis
- Innovative efficient concepts

**New Requirements**

- 20## Human Mars Mission
- # x ## klbs thrust
- Isp = ### seconds
- Engine T/W = ##.#
- # re-starts
- ### minutes total burn time

# 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.

# Deaths by TeraWatt Hours (TWh) *

| Energy Source | Death Rate (per TWh) | Percent - World Energy /Electricity |
|---|---|---|
| Coal (electricity, heating, cooking) | 100 | 26% / 50% |
| Coal (electricity -world average) | 60 | 26% / 50% |
| Coal (electricity, heating, cooking) - China | 170 | |
| Coal (electricity) - China | 90 | |
| Coal - USA | 15 | |
| Oil | 36 | 36% |
| Natural Gas | 4 | 21% |
| Biofuel / Biomass | 12 | |
| Peat | 12 | |
| Solar (rooftop) | 0.44 | 0.2% of world energy for all solar |
| Wind | 0.15 | 1.6% |
| Hydro | 0.10 (Europe death rate) | 2.2% |
| Hydro (world including Banqiao dam failure) | 1.4 (About 2500 TWh/yr and 171,000 Banquio dead) | |
| Nuclear | 0.04 | 5.9% |

60% for coal for electricity, cooking and heating in China. Pollution is 30% from coal power plants in China for the particulates and 66% for sulfur dioxide. Mining accidents, transportation accidents are mostly from coal for electricity.

*Source: http://nextbigfuture.com/2011/03/deaths-per-twh-by-energy-source.html?m=1 5/13/2011

# Radiation Dosage Comparison

| Event | Duration | Rem | mSv | Yearly mSv |
|---|---|---|---|---|
| eating 1 banana | instantaneous | 0.00001 | 0.0001 | |
| Dental x-ray (panoramic) | instantaneous | 0.001 | 0.01 | |
| living in a stone/brick/concrete building | 1 year | 0.007 | 0.07 | 0.1 |
| public exposure limit due to NTR testing | 1 year | 0.010 | 0.1 | 0.1 |
| eating 1000 bananas | 1 year | 0.010 | 0.1 | 0.1 |
| 20 hour plane flight | 20 hours | 0.010 | 0.1 | |
| chest x-ray (2 views) | instantaneous | 0.010 | 0.1 | |
| EPA yearly release limit for nuclear power plant | 1 year | 0.1 | 1 | 1 |
| 1 mammogram | instantaneous | 0.3 | 3 | |
| Normal yearly backgroud dose to person | 1 year | 0.4 | 3.65 | 4 |
| a beach in Brazil (Guarapari) | 1 year | 17.5 | 175 | 175 |
| Ramsar Iran | 1 year | 25.0 | 250 | 250 |
| No observable effects | instantaneous | 25.0 | 250 | |
| Possible temporary blood effects | instantaneous | 25.0 | 250 | |
| Radiation worker one-year dose limit | 1 year | 5.0 | 50 | 50 |
| Space Shuttle Mission 41-C | 8 day @ 460 km orbit | 0.6 | 6 | 255 |
| Apollo 14 | 9 day mission to moon | 1.1 | 11 | 446 |
| Skylab 4 | 87 day mission @ 473 km orbit | 17.8 | 178 | 747 |
| ISS mission | 6 month | 16.0 | 160 | 320 |
| Estimated Mars Mission (in space) | 3 year | 120.0 | 1200 | 400 |
| Estimated Mars Surface | 1 day | 0.1 | 0.67 | 245 |
| Astronaut career limit (female age 25) | 5 years | 100.0 | 1000 | 200 |
| Astronaut career limit (male age 55) | 20 years | 400.0 | 4000 | 200 |
| 50 km NW of Fukashima accident (March 16 & 17) | 1 day | 0.4 | 3.6 | 1314 |
| Severe radiation poisoning | instantaneous | 200.0 | 2000 | |
| Extremely severe radiation poisoning | instantaneous | 400.0 | 4000 | |
| Fatal dose of radiation poisoning | instantaneous | 800.0 | 8000 | |
| People have survived (possibly) | instantaneous | 1000.0 | 10000 | |
| contact with Chernobyl explosion reactor core steam | 10 minutes | 5000.0 | 50000 | |