Development and Utilization of Nuclear Thermal Propulsion

presented by

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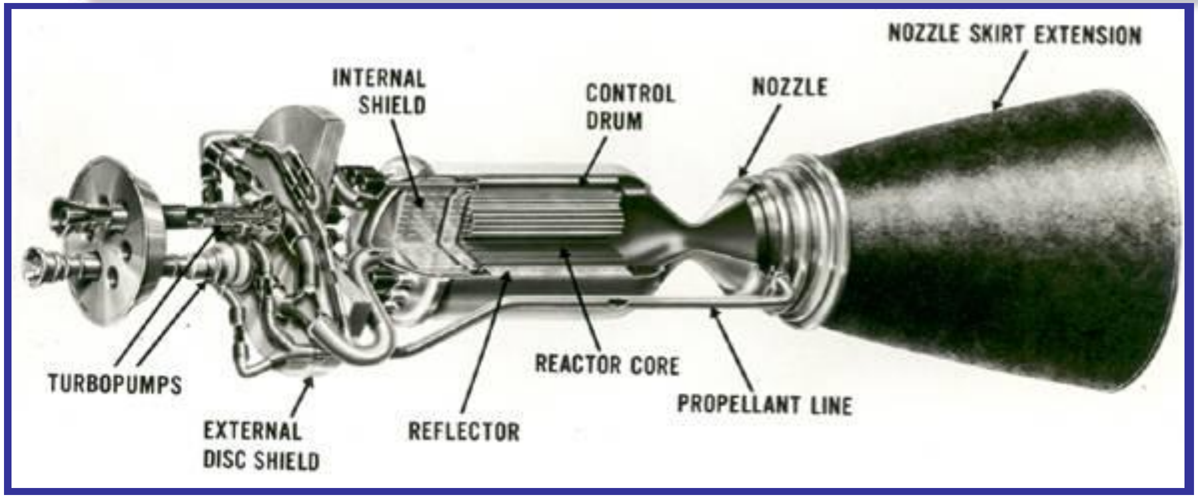
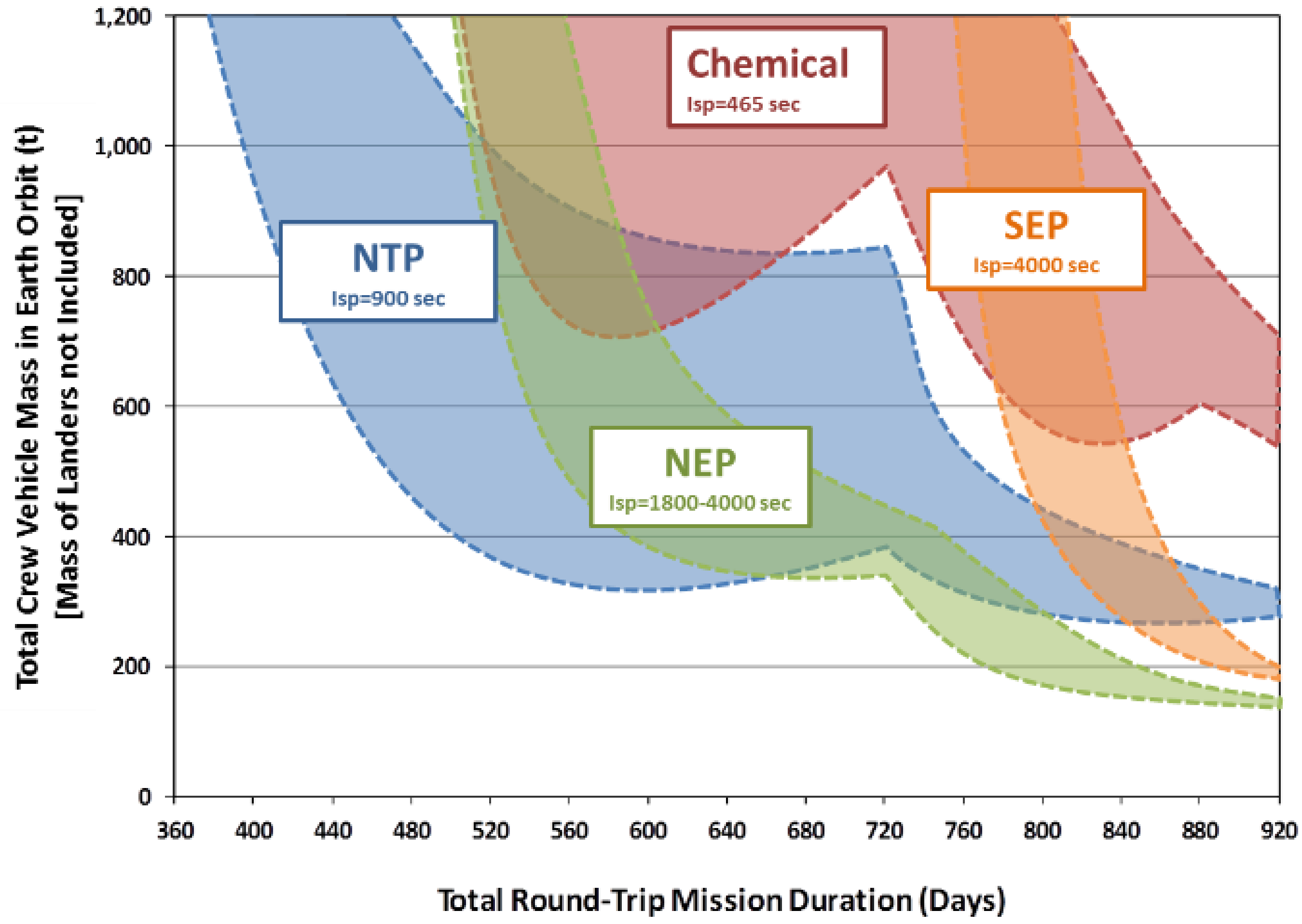
Nuclear Thermal Propulsion (NTP)



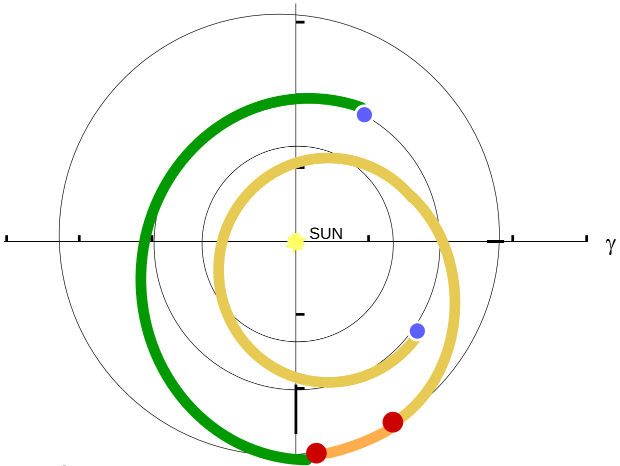
- Nuclear thermal propulsion (NTP) is a fundamentally new capability
  - Energy comes from fission, not chemical reactions
  - Virtually unlimited energy density
- Even first generation NTP offers significant benefits:
  - 2/3 mass from Earth to Orbit vs Conventional Chemical stage (No Liquid Oxygen)
  - 40 percent reduction in time to destination - Mars (Reduces in-space exposure time to GCR and zero-g)
  - Significant order of magnitude increase in launch window over conventional approach (Month instead of days – Allows flexibility)
- Advanced nuclear propulsion systems could have extremely high performance and unique capabilities
- First generation NTP could serve as the “DC-3” of space nuclear power and propulsion

Why is Nuclear Thermal Propulsion (NTP) considered for Human Missions to Mars?

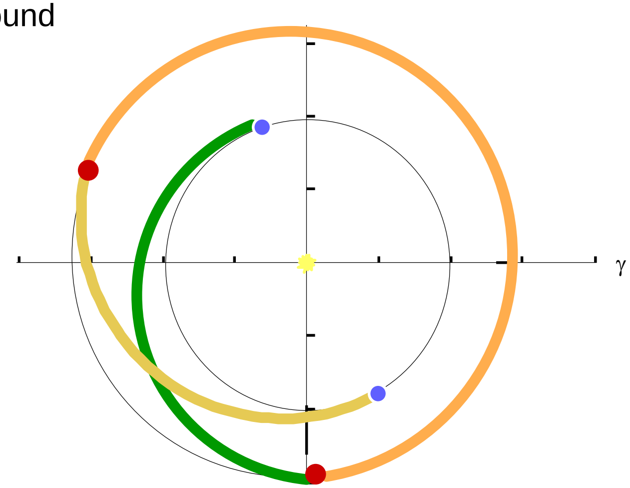


Drake, B. G., "Human Mars Mission Definition: Requirements & Issues," presentation, Human 2 Mars Summit, May 2013

Why is Nuclear Thermal Propulsion (NTP) considered for Human Missions to Mars?



Outbound
Surface Stay
Inbound



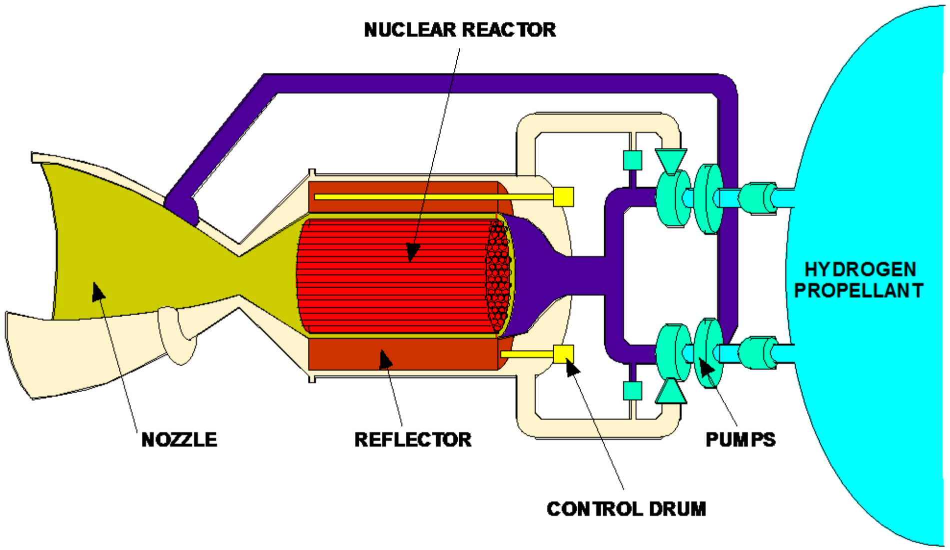
- **Opposition-Class Mission Characteristics**
  (Used in "90-Day" / SEI Mars Studies)
  - Short Mars stay times (typically 30 - 60 days)
  - Relatively short round-trip times (400 - 650 days)
  - Missions always have one short transit leg (either outbound or inbound) and one long transit leg
  - Long transit legs typically include a Venus swing-by and a closer approach to the Sun (~0.7 AU or less)
  - This class trajectory has higher ΔV requirements

  NOTE: Short orbital stay missions will likely be chosen for initial human missions to Mars and its moons, Phobos and Deimos

- **Fast-Conjunction Class Mission Characteristics**
  (Used in DRM 4.0 and DRA 5.0 Studies)
  - Long Mars stay times (500 days or more)
  - Long round trip times (~900 days)
  - Short "in-space" transit times (~150 to 210 days each way) ***Question: Can we go faster?***
  - Closest approach to the Sun is 1 AU
  - This class trajectory has more modest ΔV requirements than opposition missions

How Does NTP Work?

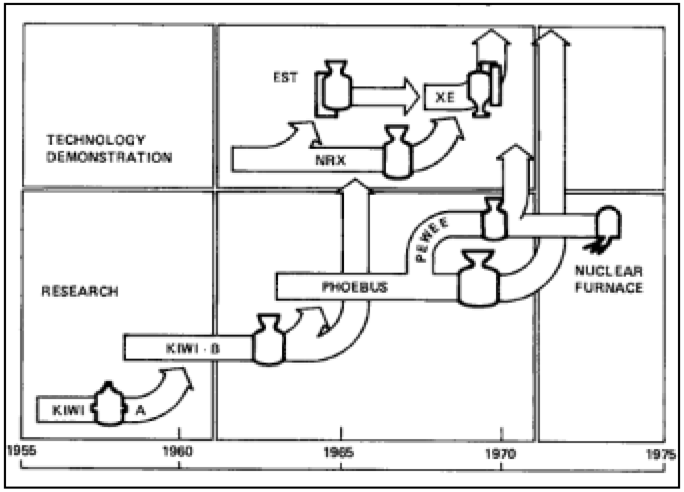
- Propellant heated directly by a nuclear reactor and expanded/accelerated through a nozzle
- Low molecular weight propellant – typically Hydrogen
- Thrust directly related to thermal power of reactor: 150,000 N ≈ 675 MW_{th} at 900 sec
- Specific Impulse directly related to exhaust temperature: 830 - 1000 sec (2300 - 3100K)
- Specific Impulse improvement over chemical rockets due to lower molecular weight of propellant (exhaust stream of O_2/H_2 engine actually runs hotter than first generation NTP)

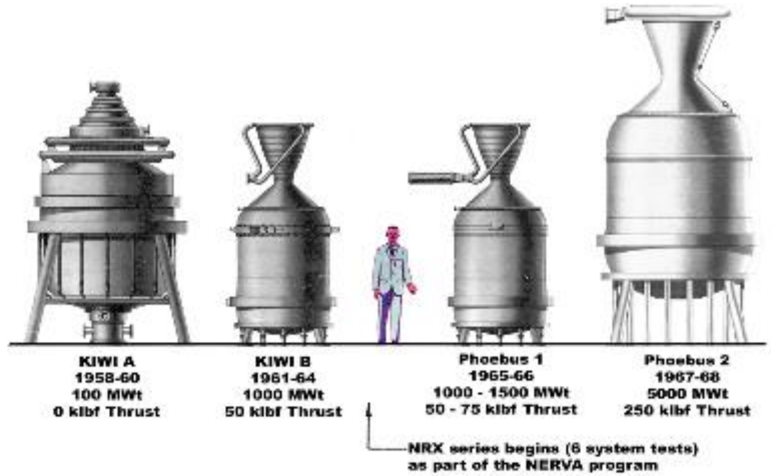


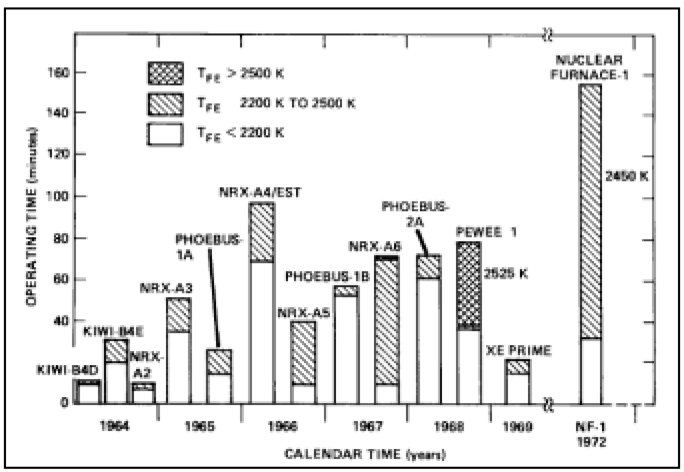
Major Elements of a Nuclear Thermal Rocket

NERVA Nuclear Thermal Rocket Prototype

Significant Interest in NTP for over 60 Years







Why has NTP never been developed and utilized?

NTP in the 21st Century? Observation 1

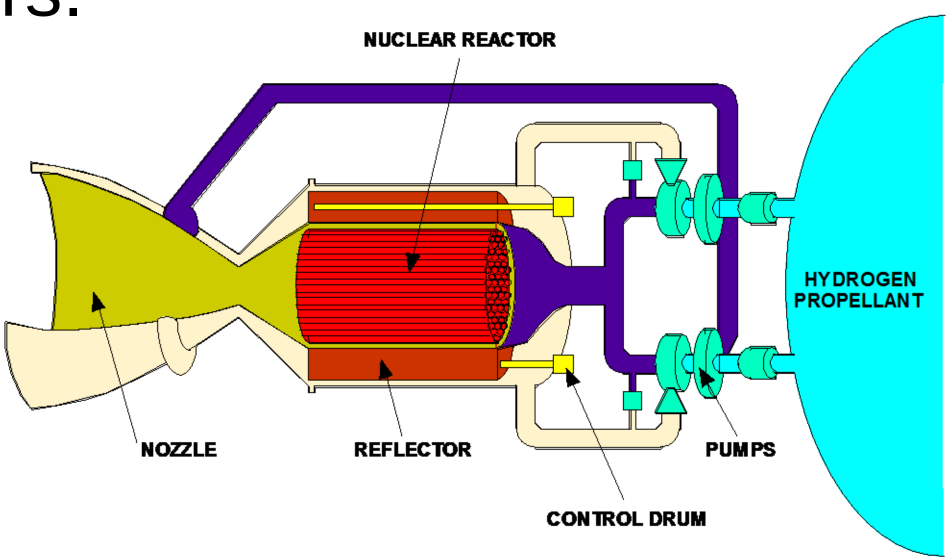
- NTP was originally considered of use on ICBMs, and then for the 2nd stage of a lunar rocket.
- By the end of the Rover/NERVA program, NTP was the leading propulsion system candidate for human Mars missions.
- Other potential initial uses for NTP have never “stuck”. NTP could be strongly enhancing for numerous potential missions.

Observation:

A reference initial role for NTP should be carefully chosen, and the development program focused on enabling that initial role. If the initial role for NTP is supporting human Mars missions, the development program should focus on systems that could fulfill that role.

NTP in the 21st Century? Observation 2

NTP systems are unique, and the capability to develop NTP does not exist within a single company or government agency. To be affordable and viable an NTP development program must be flexible and designed to facilitate involvement from industry, universities, NASA, the Department of Energy, and others.



NTP in the 21st Century? Observation 3

Current US policy strongly discourages the use of highly enriched uranium (HEU) in civilian applications. Low enriched uranium (LEU) NTP systems should be considered to significantly reduce security-related cost, schedule, and programmatic impacts, and to avoid generating opposition based on non-proliferation concerns.

2012 White House Fact Sheet: “The United States is committed to eliminating the use of HEU in all civilian applications, including in the production of medical radioisotopes, because of its direct significance for potential use in nuclear weapons, acts of nuclear terrorism, or other malevolent purposes.”

2016 *Reducing the Use of Highly Enriched Uranium in Civilian Research Reactors*

NTP in the 21st Century? Observation 4

If possible, any required ground nuclear testing should be designed to eliminate radiation exposure to the public and the planned release of radionuclides. Although extremely safe radiation exposure limits have been set (and could be easily complied with), the planned release of any radioactivity from an NTP ground test could generate significant public opposition.

NTP in the 21st Century? Observation 5

If possible, dual-use fuels and other components should be utilized. For example, a fuel form could be chosen with the potential for enabling both NTP and advanced space fission power systems. A fuel form with commonality to ongoing nuclear fuel development programs (e.g. “Accident Tolerant Fuels”) could be chosen, although that could result in reduced performance.

NTP in the 21st Century? Observation 6

Nuclear testing can be extremely expensive, and it is important to have high confidence in the success of a nuclear test before that test is performed. Non-nuclear testing should be performed to the extent that it is beneficial. Ongoing advances in analytical techniques should also be employed in all aspects of an NTP development program.

NTP in the 21st Century? Observation 7

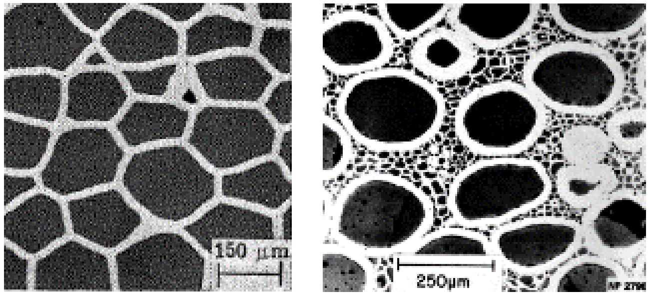
The potential benefits of NTP must be communicated. NTP can reduce earth-Mars transit times, which can benefit astronaut safety and increase the probability of mission success. NTP can also enable numerous Mars mission scenarios, including opposition class missions that could reduce the total Mars astronaut time away from earth by a factor of two (900 days down to 450 days). NTP reduces earth-to-orbit launch mass requirements and increases launch windows. Initial NTP systems could provide a stepping stone to the development of much more advanced space nuclear power and propulsion systems, capable of opening the entire solar system.

Backup

Heritage CERMET Fuel Development

- CERMET fuels consist of a W matrix with embedded ceramic UO_2 fuel particles
  - W matrix (high melting point, H_2 compatibility)
- Developed in 1960's as an alternate to the graphite fuels used in the Rover/NERVA program, and for high performance space fission power systems
  - Long operating life (>10 hrs, 2800k)
  - Multiple restart capability
  - Improved fission product retention
- Recent work builds on GE710, ANL, and NASA LeRC development programs
  - Developed extensive capabilities and processes that are no longer available (must recapture and certify)
- Significant progress made to characterize fuel
  - Fuel loss and failure mechanisms are known
  - Materials and process options to improve fuel performance are known

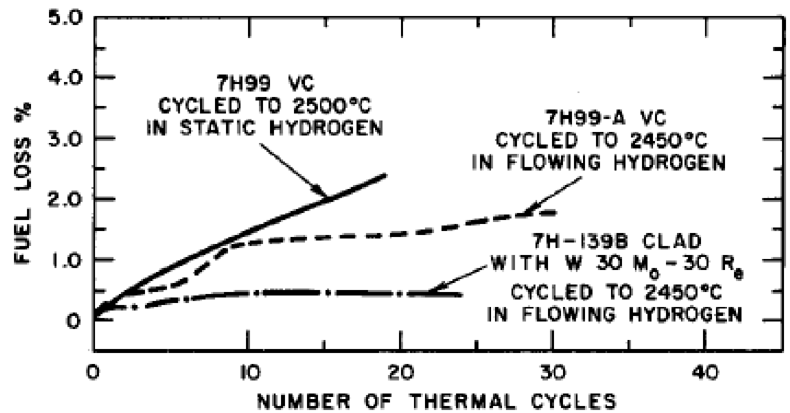
W-UO2 CERMET Samples fabricated during ANL Program



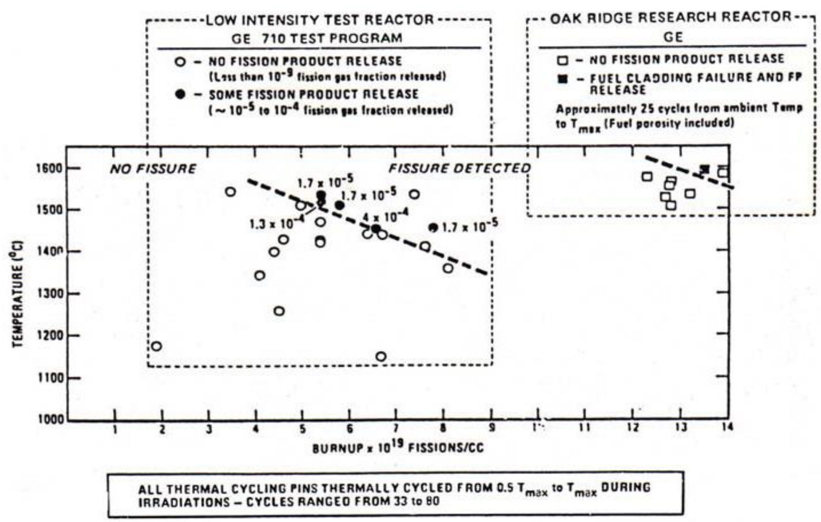
W - light phase, UO2 - dark phase

Heritage CERMET Fuel Testing

- Testing showed good thermal cyclic capability in flowing hydrogen at 2700K < 1% fuel loss for 25 cycles
- Thermal shock testing in TREAT reactor
  - >2900K, 10,000 C/sec, 30 MW/liter
  - No visible distortion or cracking
- No in-pile testing for current NTR conditions
  - Low burnup at 2800K in flowing H2
- In-pile testing during GE710 at lower temps and longer durations
  - 1600-1900K, 1000's of hours
  - Fission gas containment to burn up levels exceeding 6×10^{19} fissions/cm^3
  - Equivalent to dozens of Mars missions
  - Demonstrated capability of W-UO_2 fuels to handle high burnups



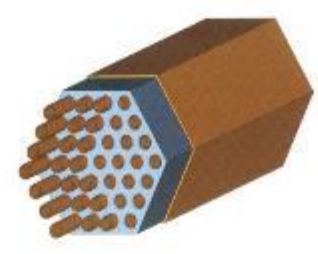
ANL Hot Hydrogen Testing of W-UO_2

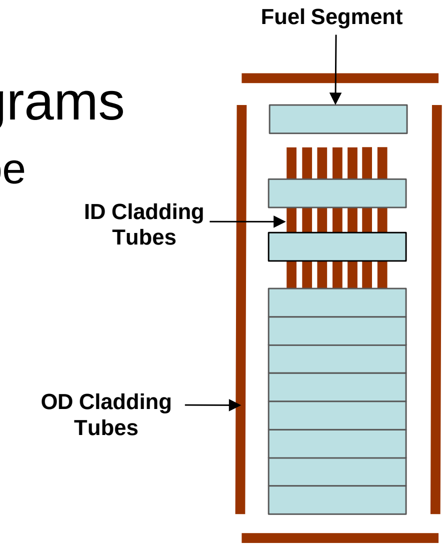


GE710 In-Pile Testing of W-UO_2

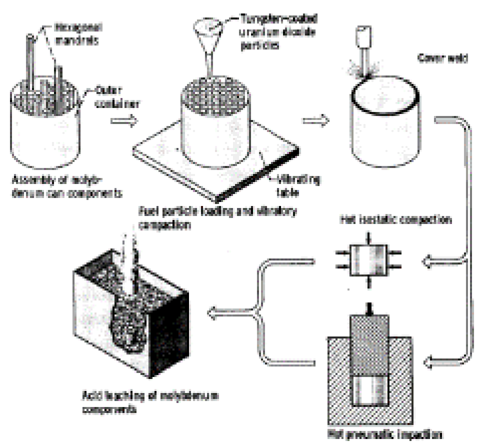
Heritage W-UO_2 Fuel Fabrication

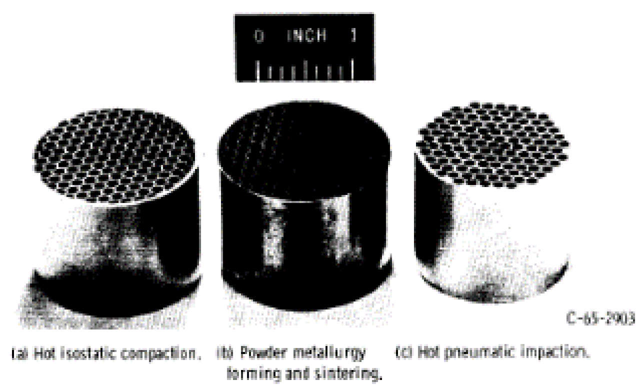
- Significant fabrication development during past programs
  - Produced dense hexagonal sections using press/sintering, HIP, and hot pneumatic impaction
  - Complete W-UO_2 fuel specification was developed for GE710
    - Includes drawings, quality standards and nondestructive inspection
    - Fabricated/tested 19, 37, & 91 channel fuel elements
- HIP process was predominant approach at end of programs
  - Less machining, fewer segments, and uniform UO_2 particle shape
  - Integral fabrication and bonding of claddings





GE710 W-UO2 Fabrication





ANL and NASA LeRC W-UO_2 Fabrication

CERMET Fuels Show Tremendous Potential For Both NTP and High Performance Space Fission Power Systems

- **But:**
  - Tungsten/UO_2 cermet reactors design have typically required large quantities of highly enriched uranium (HEU) to overcome the effects of parasitic neutron absorption in the tungsten.
  - US policy discourages the use of highly enriched uranium (HEU). A 2012 White House “Fact Sheet” states that “The United States is committed to eliminating the use of HEU in all civilian applications, including in the production of medical radioisotopes, because of its direct significance for potential use in nuclear weapons, acts of nuclear terrorism, or other malevolent purposes.”
  - Even if allowed, security requirements associated with the use of HEU could result in very significant impacts to the cost and schedule of development, qualification, and utilization of nuclear thermal propulsion (NTP) systems that use HEU.
  - The use of low enriched uranium (LEU) is internationally accepted. LEU is used in a wide variety of fission systems throughout the world, including commercial and university reactors.
- **The Potential Solution:**
  - An emerging technology may reduce the cost of “purifying” tungsten by 2 to 3 orders of magnitude. If developed, this technology could potentially enable LEU NTP in the thrust range of interest for human Mars missions.

Can NTP ground testing be affordable and viable?

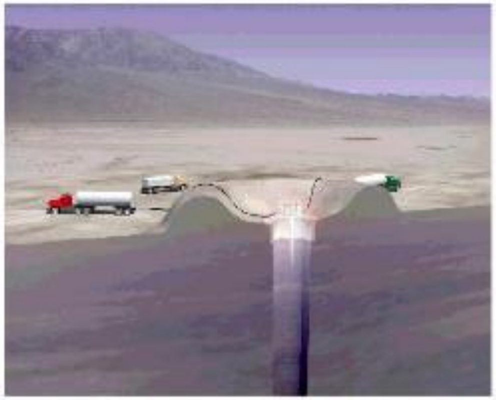
Nuclear Thermal Propulsion (NTP) offers tremendous performance potential and mission advantages for future space exploration, but it must be shown to be affordable, safe and viable to develop.

- Engine development requires a lot of ground testing.

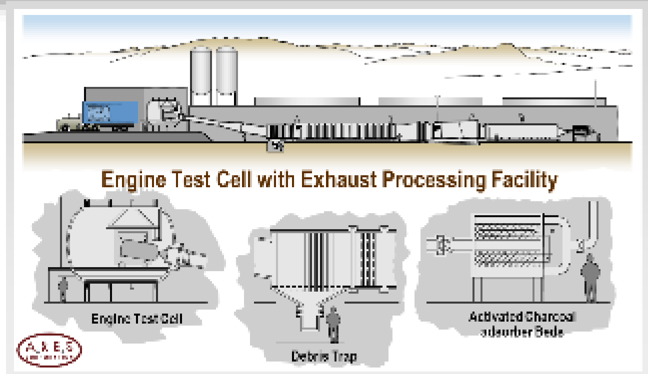
Why is NTP ground testing more difficult than chemical engines:

- Current regulations do not allow/permit open air testing of NTP as was done in the 1960's and 1970's for the Rover/NERVA program
- There is a misconception that ground testing is not possible and/or cost for ground testing would be prohibitive
- Public acceptance requires testing hazard risks to be as low as reasonably achievable (ALARA) and far below regulatory limits

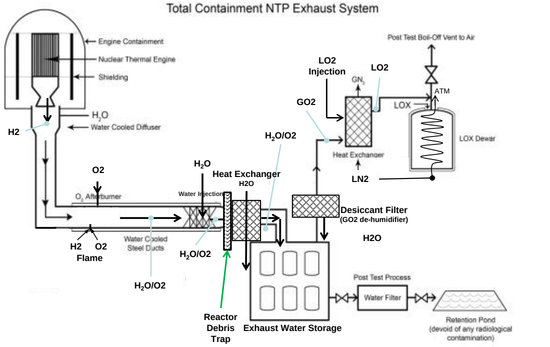
NTP Ground Test Options



Bore hole



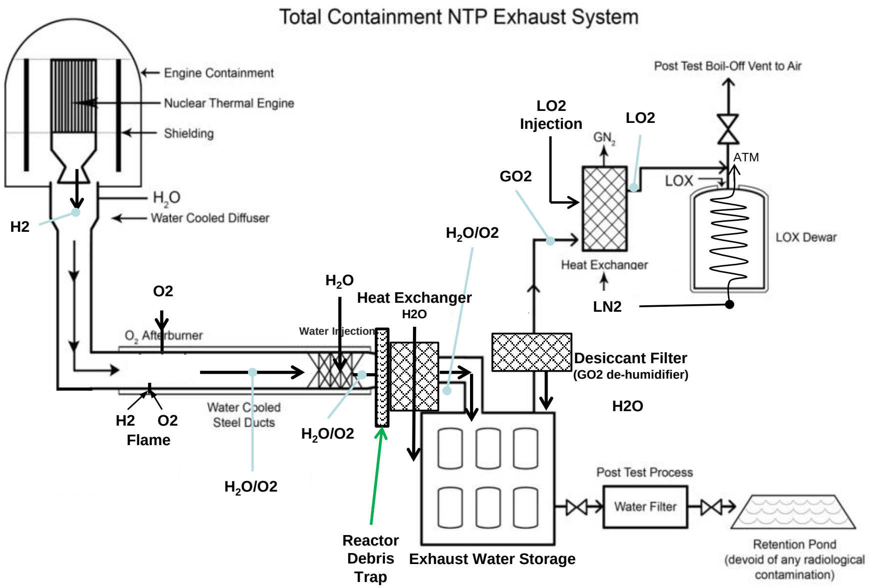
Above ground scrubber with filters



Total containment with combustion and condensation

- ♦ Bore Hole
  - Relies on permeability of desert alluvium soil to filter engine exhaust
    - Unresolved issues on water saturation effects on soil permeability, hole pressure during engine operation, and soil effectiveness in exhaust filtering
- ♦ 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 reliability and economically accomplish task

NTP Total Containment Test Facility Concept



Strategy:

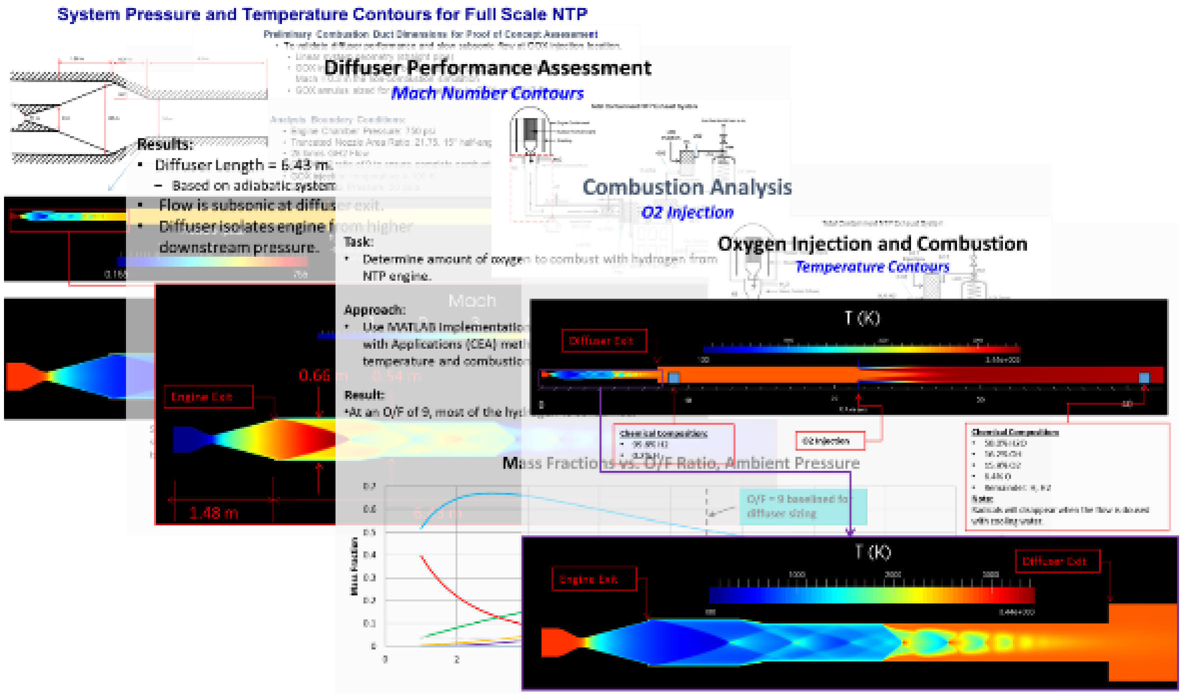
- Fully Contain engine exhaust
- Filter/drain containment vessels after test

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 LO_2
  - Products include steam, excess O_2 and potentially, a small fraction of noble gases (e.g., xenon and krypton)
- Water spray and heat exchanger dissipates heat from steam/O_2/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 LN_2 temperatures (freezes and collects noble gases) and condenses O_2.
  - LOX Dewar stores LO_2, to be drained post test via boil-off

Sample of Systems Modeling and Analysis Work Performed to Date

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



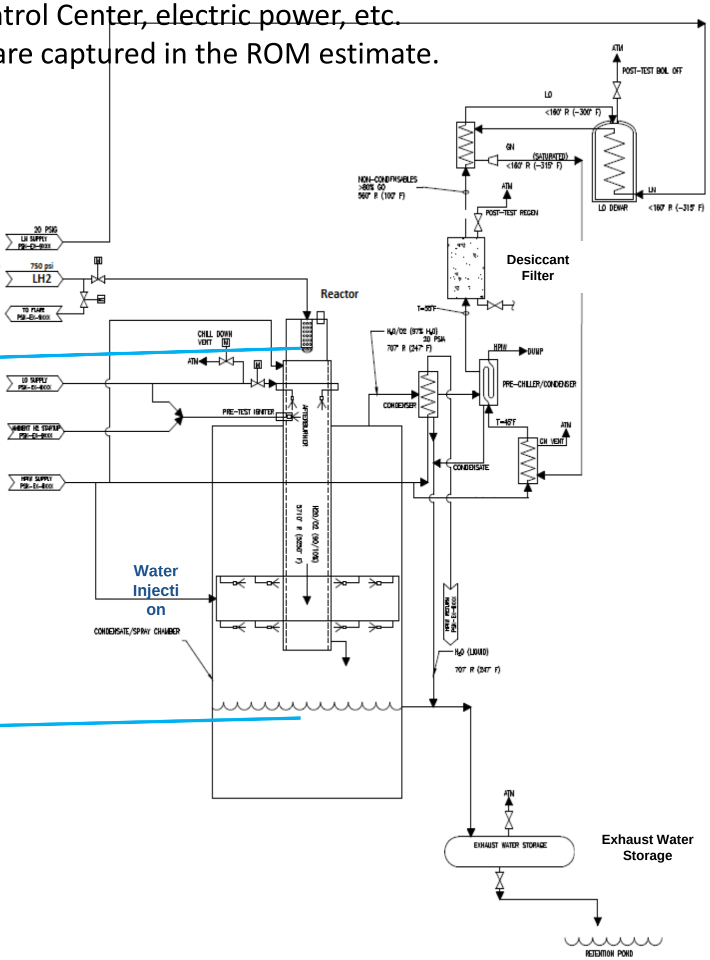
- All system operating pressures and temperatures and fluid supply and flow requirements are well within existing chemical rocket propulsion test capability and experience.

Total Engine Exhaust Containment

Conceptual System Design Layout

Facility located at SSC's A3 Test Stand

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

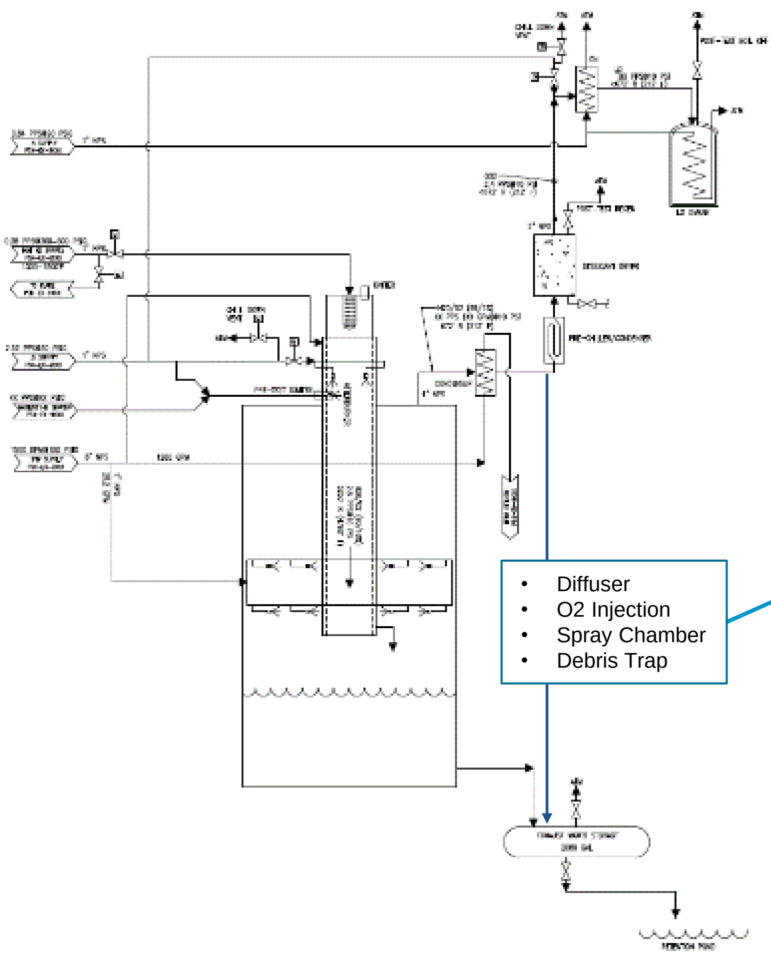


Subscale Total Containment System - Preliminary Design

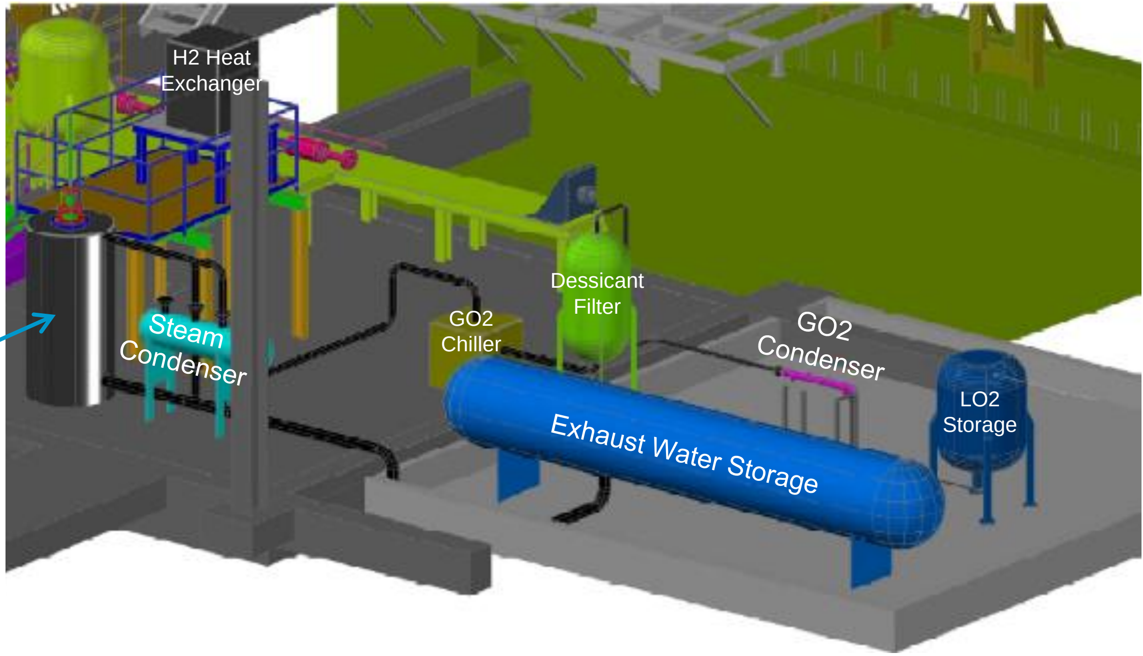
SPACE TECH'S GAME CHANGING DEVELOPMENT PROGRAM

E3 today

SSC E3 Test Facility



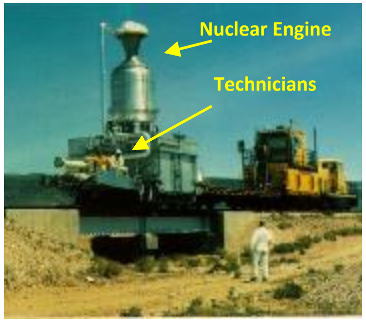
- Diffuser
- O2 Injection
- Spray Chamber
- Debris Trap



NTP Facts

- The volume of a toy marble could contain the mass of uranium providing the NTP energy for an entire Mars Mission

- Standing next to an NTP engine before launch for one year would result in less radiation dose than a diagnostic x-ray



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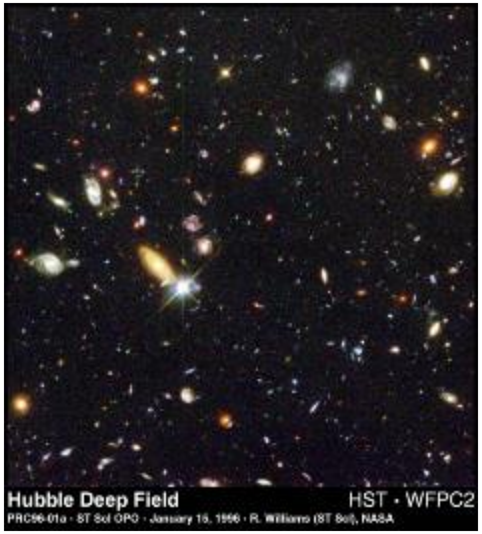
- NTP ground test regulations allow the maximum annual public dose from NTP testing to be equivalent to ~20 hours of plane flight, which is also equivalent to ~25% of the natural radiation from food.

NTP Facts (Cont'd)

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



- Using NTP for faster trip times to Mars exposes the astronauts to less galactic cosmic radiation

- NTP reactor fission products from an entire Mars mission are roughly equivalent to fission products formed during ~two weeks of runtime of a 10 MW university reactor

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

Nuclear Energy Myths

Top Ten Nuclear Energy Myths

(Source: the American Nuclear Society)

1: Americans get most of their yearly radiation dose from nuclear power plants

Truth: We are surrounded by naturally occurring radiation. Only .005% of the average American's yearly dose comes from nuclear power, 100 times less than we get from coal[1], 200 times less than a cross country flight, and about the same as eating one banana per year.[2]

2: A nuclear reactor can explode like a nuclear bomb

Truth: It is impossible for a reactor to explode like a nuclear weapon; nuclear weapons contain very special materials in very particular configurations, neither of which are present in a nuclear reactor.

#3: Nuclear energy is bad for the environment.

Truth: Nuclear reactors emit no greenhouse gases during operation. Over their full lifetimes, they result in comparable emissions to renewable forms of energy such as wind and solar.[3] Nuclear energy requires less land use than most other forms of energy.

#4: Nuclear energy is not safe.

Truth: Nuclear energy is as safe – or safer – than any other form of energy available. No member of the public has ever been injured or killed in the entire 50 year history of commercial nuclear power in the U.S. In, fact, recent studies have shown that it is safer to work in a nuclear power plant than an office.[4]

#5: There is no solution for huge amounts of nuclear waste being generated.

Truth: All of the nuclear fuel generated in every nuclear plant in the past 50 years would fit in a football field to a depth of less than ten yards, and 96% of this 'waste' can be recycled.[5] Used fuel is currently being safely stored. The U.S. National Academy of Sciences and the equivalent scientific advisory panels in every major country support geological disposal of such wastes as the preferred safe method for their ultimate disposal.[6]

1. National Council on Rad Protection and Measurements No. 92 and 95
2. CDR Handbook on Radiation Measurement and Protection
3 P.J. Meier, "Life-Cycle Assessment of Electricity Generation Systems and Applications for Climate Change Policy Analysis, 2002"

http://www.ans.org/pi/resources/myths/docs/myths.pdf

4. Nuclear Energy Institute (http://www.nei.org
5. K.S. Krane, *Introductory Nuclear Physics,* John Wiley and Sons, 1988
6. *Progress Towards Geologic Disposal of Radioactive Waste: Where Do we Stand?* Nuclear Energy Agency, OECD report, 1999 (http://www.nea.fr/rwm/reports/1999/progress.pdf)

Nuclear Energy Myths, continued

Top Ten Nuclear Energy Myths
6: Most Americans Don't Support Nuclear Power
Truth: The NEI reports (Feb. 2013) that in a national telephone survey of 1,000 U.S. adults, 68 percent said they favor nuclear energy, up from 65 percent in September 2012, while 29 percent opposed. Those strongly favoring nuclear energy outweigh those strongly opposed by more than a two-to-one ratio, 29 percent versus 13 percent.
7: An American "Chernobyl" would kill millions of people.
Truth: A Chernobyl –type accident could not have happened outside of the Soviet Union because this type of reactor was never built or operated here. The known fatalities during the Chernobyl accident were mostly first responders.[8] Of the people known to have received a high radiation dose, the increase in cancer incidence is too small to measure due to other causes of cancer such as air pollution and tobacco use.
#8: Nuclear waste cannot be safely transported.
Truth: Used Fuel is being safely shipped by truck, rail, and cargo ship today. To date, thousands of shipments have been transported with no leaks or cracks of the specially designed casks.[9]
#9: Used nuclear fuel is deadly for 10,000 years.
Truth: Used nuclear fuel can be recycled to make new fuel and byproducts.[10] Most of the waste from this process will require a storage time of less than 300 years. Finally, less than 1% is radioactive for 10,000 years. This portion is not much more radioactive than some things found in nature, and can be easily shielded to protect humans and wildlife.
#10: Nuclear energy can't reduce our dependence on foreign oil.
Truth: Nuclear generated electricity powers electric trains and subway cars as well as autos today. It has also been used in propelling ships for more than 50 years. That use can be increased since it has been restricted by unofficial policy to military vessels and ice-breakers. In the near term, nuclear power can provide electricity for expanded mass-transit and plug-in hybrid cars. Small modular reactors can provide power to islands like Hawaii, Puerto Rico, Nantucket and Guam that run their electrical grids on imported oil. In the longer-term, nuclear power can directly reduce our dependence on foreign oil by producing hydrogen for use in fuel cells and synthetic liquid fuels.

7. Perspectives on Public Opinion, NEI publication, June 2008
8. Chernobyl Forum reports 20 year findings, offers recommendations, Nuclear News, Oct-05
9. DOE Fact Sheet (http://ocrwm.doe.gov/factsheets/doeymp0500.shtml)
10. K.S. Krane, *Introductory Nuclear Physics,* John Wiley and Sons, 1988

*Source: http://www.ans.org/pi/resources/myths/docs/myths.pdf