NUCLEAR CRYOGENIC PROPULSION STAGE. M. G. Houts[1], S. K. Borowski[2], J. A. George[3], T. Kim[1], W. J. Emrich[1], R. R. Hickman[1], J. W. Broadway[1], H. P. Gerrish[1], R. B. Adams[1]. [1]NASA Marshall Space Flight Center, MSFC, AL 35812, [2]NASA Glenn Research Center, Cleveland, OH, 44135, [3]NASA Johnson Space Center, Houston, TX, 77058

Introduction: The fundamental capability of Nuclear Thermal Propulsion (NTP) is game changing for space exploration. A first generation Nuclear Cryogenic Propulsion Stage (NCPS) based on NTP could provide high thrust at a specific impulse above 900 s, roughly double that of state of the art chemical engines. Characteristics of fission and NTP indicate that useful first generation systems will provide a foundation for future systems with extremely high performance. The role of the NCPS in the development of advanced nuclear propulsion systems could be analogous to the role of the DC-3 in the development of advanced aviation. Progress made under the NCPS project could help enable both advanced NTP and advanced NEP.

The Nuclear Cryogenic Propulsion Stage Project: The 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. The NCPS project involves a large (~50 person) NASA/DOE team supplemented by a small amount of procurement funding for hardware and experiments. In addition to evaluating fundamental technologies, the team will be assessing many aspects of the integrated NCPS, and its applicability to NASA architectures of interest.

Pre-Conceptual Design of the NCPS and Architecture Integration: The NCPS will be designed to integrate with the Space Launch System (SLS), and to leverage technologies and configurations being developed for the SLS. The NCPS design will focus on ensuring maximum benefit to human Mars mission, although the stage will have numerous other applications as well. Two leading fuel candidates for the NCPS are tungsten cermets and composite fuels, both with an extensive development history. The sensitivity of stage performance to specific impulse and engine thrust-to-weight ratio will also be assessed under this element. Both propulsion only and “bimodal” (propulsion and power) systems will be assessed under the NCPS.

Development of a High Power (~1 MW input) Nuclear Thermal Rocket Element Environmental Simulator: The development of a stable fuel form is a key risk for an NCPS. 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 at MSFC. The purpose of the NTREES facility (which also includes an arc heater and a compact hot 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 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. 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 hydrogen propellants.

The NTREES facility is licensed to test fuels containing 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. 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. The NTREES facility also includes an operational arc heater 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 is particularly useful for the preliminary vetting of material samples. A compact test chamber capable of high temperature fuel sample testing is also available at the NTREES facility.

The 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. A picture of the most recent operational NTREES primary chamber configuration is shown in Figure 1.

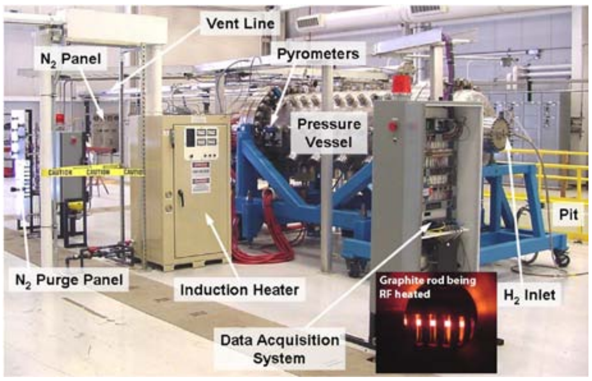


Figure 1. Nuclear Thermal Rocket Element Environmental Simulator (NTREES)

NCPS Fuel Design / Fabrication: Early fuel materials development is critical to help validate requirements and minimize technical, cost, and schedule risks for future exploration programs. NASA and DOE have demonstrated the ability to collaborate on a number of nuclear power and propulsion technology projects, and this collaboration will continue on the NCPS project.

This element will focus on tungsten cermet and composite fuels. Modern fabrication techniques (Hot Isostatic Pressing and Pulsed Electric Current) will be used to demonstrate fabrication of cermet elements with good performance potential. Composite fuel elements will also be fabricated, with emphasis on coatings to help prevent fuel loss in the hot flowing hydrogen environment and to potentially increase maximum allowable operating temperature. Other fuels developed and tested during the Rover/NERVA program [1] may also be evaluated, including carbide fuels and bead-loaded graphite fuels.

NCPS Fuels Testing in NTREES: Testing in NTREES will range from fuel sample testing (using the small chamber) 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.

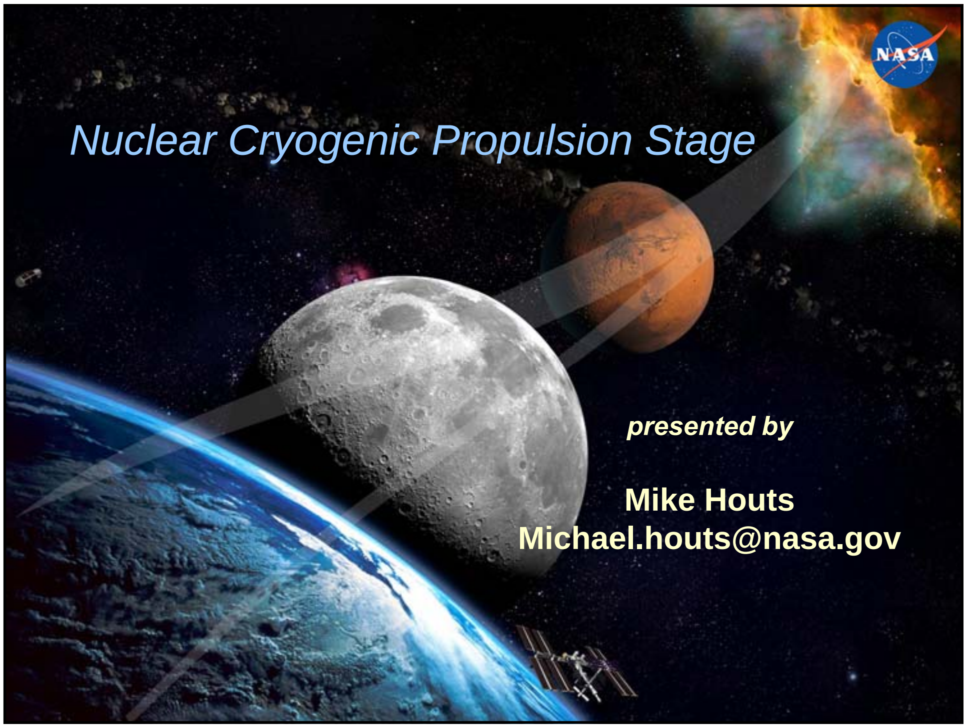
Affordable NCPS Development and Qualification Strategy: This element will focus on ensuring the overall affordability of the NCPS. Development and qualification testing of the NCPS is one potential cost driver, and at least two potential strategies will be emphasized. The first will be to utilize existing boreholes at the Nevada test site to enable flexible and affordable testing of nuclear thermal rocket engines. The second would be to utilize highly instrumented demonstration flights, including the potential for significant post-operation examination of the NCPS engine. Both strategies appear to show promise

Second Generation NCPS Concepts: Potential second generation NCPS concepts will be devised and evaluated. Modern materials and fabrication techniques may enable an NCPS capable of providing Isp in excess of 1000 s with high thrust-to-weight ratio. Radically different design approaches could yield even higher performance. The work performed under this task will devise new concepts and re-evaluate existing concepts taking into account recent advancement in materials and technologies. Concepts with high performance potential and moderate technology risk (such as ternary carbide encapsulated UC_2) will receive particular attention. Novel approaches for capitalizing on the unique attributes of fission systems will also be investigated. Such approaches include the direct use of volatiles available in space for NTP propellant. This task will also include system concepts for very high performance BNTEP.

Conclusion: The fundamental capability of Nuclear Thermal Propulsion (NTP) is game changing for space exploration. A first generation Nuclear Cryogenic Propulsion Stage (NCPS) based on NTP 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.

References:

[1] Koenig D. R. (1986) Experience Gained from the Space Nuclear Rocket Program (Rover), LA-10062-H, Los Alamos National Laboratory, Los Alamos, NM



The NCPS could serve as the "DC-3" of Space Fission Propulsion

- Initial capability superior to other options.
- Initial focus on safety, reliability, and affordability.
- Flight system development, launch, and operational experience enables
  - Establishment of design teams and design practices
  - Development of necessary materials and manufacturing capability
  - Development of components, subsystems, and integrated system
  - Development / optimization of qualification and acceptance criteria
  - Development / optimization of launch processing procedures and flow
  - Development / optimization of operational procedures
  - Increased public acceptance of technology
  - Development of much more advanced systems

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NCPS Project Work Breakdown Structure

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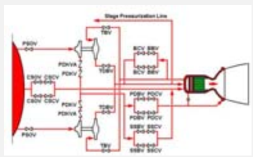
Project Manager:	Mike Houts (MSFC)	256-544-8136
GRC Lead:	Stan Borowski	216-977-7091
JSC Lead:	Jeff George	281-483-5962

2.0 Pre-conceptual Design of the NCPS & Architecture Integration
Tony Kim, MSFC 256-544-6217



4.0 NCPS Fuel Design / Fabrication
Robert Hickman, MSFC 256-544-8578
Jeramie Broadway, MSFC 256-961-1372

6.0 Affordable NCPS Development and Qualification Strategy
Harold Gerrish, MSFC 256-544-7084

3.0 High Power (≥ 1 MW) Nuclear Thermal Rocket Element Environmental Simulator (NTREES)
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5.0 NCPS Fuels Testing in NTREES
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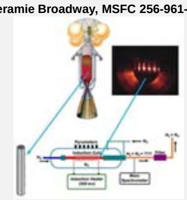

7.0 Second Generation NCPS Concepts
Rob Adams, MSFC 256-544-3464

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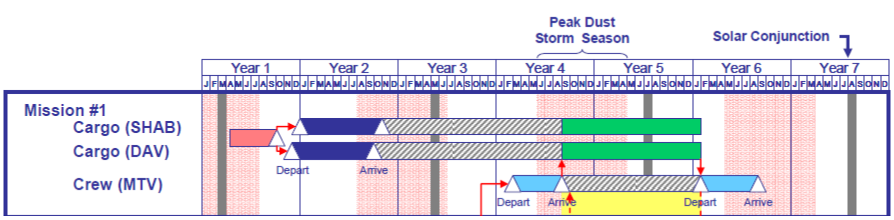
Pre-conceptual Design of the NCPS and Architecture Integration

- DRA_5
  - A mission to Mars architecture was performed in 2007.
  - This architecture was designed on a split mission concept for 3 missions. Support vehicles: surface habitat (SHAB) and descent/ascent vehicle (DAV) are sent well before the crew vehicle, Mars transfer vehicle (MTV). The first mission's timeline is shown below.



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Pre-conceptual Design of the NCPS and Architecture Integration

- DRA_5
  - This architectural study compared a Nuclear Thermal Rocket (NTR) and chemical propulsion/aerocapture options for the Mars mission
  - The NTR option required 9 launches and the chemical propulsion option required 12 launches of the Ares V vehicle. Because of the lower launch requirement, the NTR options was chosen. Furthermore if missions to explore any further than Mars are proposed, the NTR option becomes even more attractive.

NTR Option

Vehicle Assembly Timelines & ETO Delivery Manifest

	Launch Number	Launch Time Before TMI (days)	Launch Manifest	Shroud Length (m)	Launch Mass (t)
Cargo Mission (Two Vehicles)	Ares V Launches				
	1	-180	NTR TMI Core Stage 1	30.0	96.6
	2	-150	NTR TMI Core Stage 2	30.0	96.6
	3	-120	Twin In-Line LH2 Tank	30.0	93.2
	4	-90	Payload 1 (Cargo Land	30.0	103.0
	5	-60	Payload 2 (Hab Lander	30.0	103.0
		-60	TMI Window Allowance		
Total MTV Mass Delivered to Orbit					492.3
Crewed Mission	1	-150	NTR Core Stage	30.00	106.2
	2	-120	In-Line LH2 Tank	30.00	91.4
	3	-90	Truss & Drop Tank	30.00	96.0
	4	-60	Crew Payload Element	30.00	62.2
		-60	TMI Window Allowance		
	Ares I Launch (delivers astronauts to orbiting crew MTV)				
	1	-5	6 Mars Crew	n/a	0.6
Total MTV Mass Delivered to Orbit					356.4
Ares V launches:	9			Total IMLEO (t):	848.7

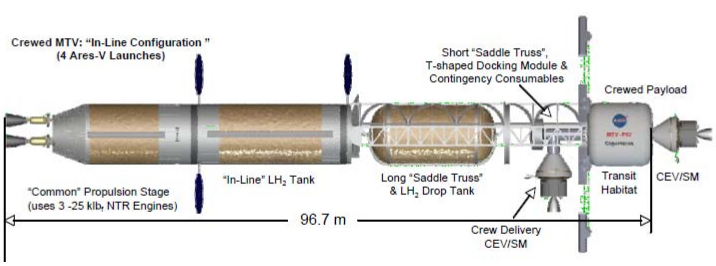
Chemical Option

Vehicle Assembly Timeline & ETO Delivery Manifest

	Launch Number	Launch Time Before TMI (days)	Launch Manifest	Shroud Length (m)	Launch Mass (t)
Cargo Mission (Both Vehicles)	Ares V Launches				
	1	-270	Reboost Module 1 Reboost Module 2	14.00	96.9
	2	-240	Payload 1 (Surf. Hab)	30.00	103.0
	3	-210	Payload 2 (Lander)	30.00	103.0
	4	-180	TMI Module 1a	16.26	103.6
	5	-150	TMI Module 2a	16.26	103.6
	6	-120	TMI Module 1b	16.26	103.6
	7	-90	TMI Module 2b	16.26	103.6
		-60	TMI Window		
Total Mass Delivered to Orbit					717.3
Crew Mission	8	-210	Transit Hab/CEV Reboost Module	17.00	99.9
	9	-180	MOI & TEI Stages	22.30	108.5
	10	-150	TMI Module 1a	16.26	108.5
	11	-120	TMI Module 1b	16.26	108.5
	12	-90	TMI Module 1c	16.26	108.5
		-60	TMI Window		
	Ares I Launches				
	1	-5	6 Mars Crew	n/a	0.6
Total Mass Delivered to Orbit					534.5
Ares V launches:	12			Total IMLEO (mt):	1,251.8

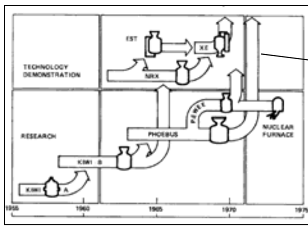
Pre-conceptual Design of the NCPS and Architecture Integration

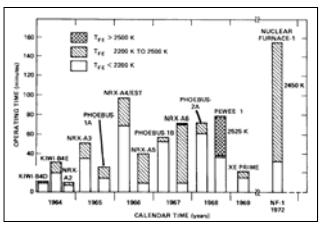
- DRA_5
  - The NTR option consisted of three 25 klbf NTR's on the MTV and support vehicles.
  - The 25 klbf engines were used because testing was assumed to be more feasible because of the smaller thrust sizes.



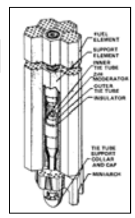
Pre-conceptual Design of the NCPS and Architecture Integration

- Quick history of the Rover\NERVA program.
  - Began in 1955 and initiated at Los Alamos National Laboratory (LANL)



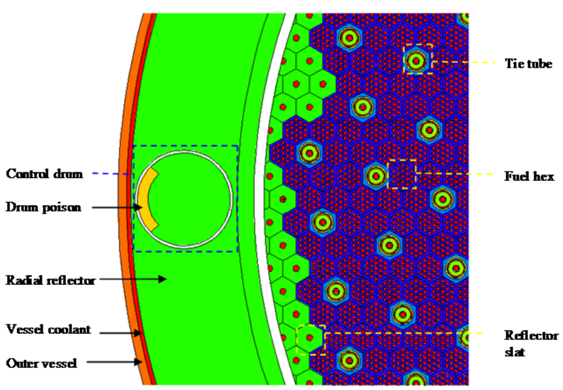


Fuel Rod Assembly

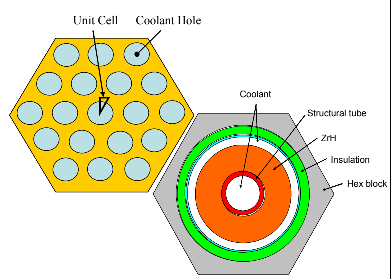


Pre-conceptual Design of the NCPS and Architecture Integration

- A more detail look at the type of designs that NTRGen/MCNP and TMSS utilized.



- Fuel is (U,Zr)-C, 5.2 wt % U
- Uranium is 93% enriched
- Control drums (18) are BeO/B4C
- Six fuel hexes per tie tube



Pre-conceptual Design of the NCPS and Architecture Integration

- Typical results for the engine balance

Tank
Inlet Press (psia) 40.0
Inlet Temp (degR) 34.0
Flowrate (lbm/s) 84.5

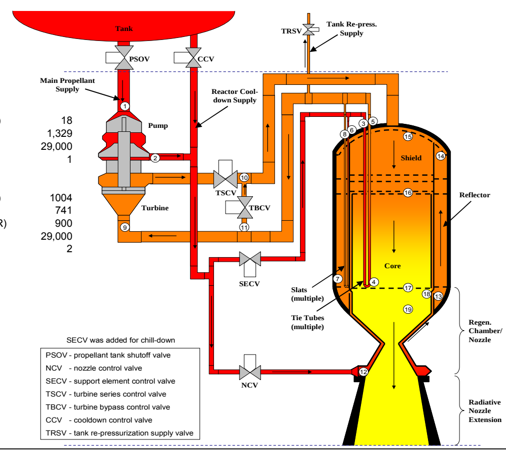
Engine System
Cycle Closed Expander
Turbine Feed Tie Tube
Pumps 1

Date 5/1/2006
Time 6:49:51 PM

Load Data

Pump
Inlet Press (psia) 18
Exit Press (psia) 1,329
Speed (rpm) 29,000
Stages 1

Turbine
Inlet Press (psia) 1004
Exit Press (psia) 741
Inlet Temp (degR) 900
Speed (rpm) 29,000
Staged 2



Performance
Thrust - Vacuum (lbf) 75,000
ISP - Actual (sec) 887
ISP - Ideal (sec) 909
Thrust/Weight w/shield 4.51
Thrust/Weight w/o shield 5.21
Pc (psia) 450
Tc (degR) 4,860

Reactor
Fuel Type Composite
Core Length (in) 52.0
Reactor Power (MW) 1668
Support Element Ratio 6:1
Flat to Flat Hex. Dim. (in) 0.750
Number of Fuel Elements 1343
Number of Support Element 260

Chamber / Nozzle
Regen. Nozzle Area Ratio 25
Total Nozzle Area Ratio 100

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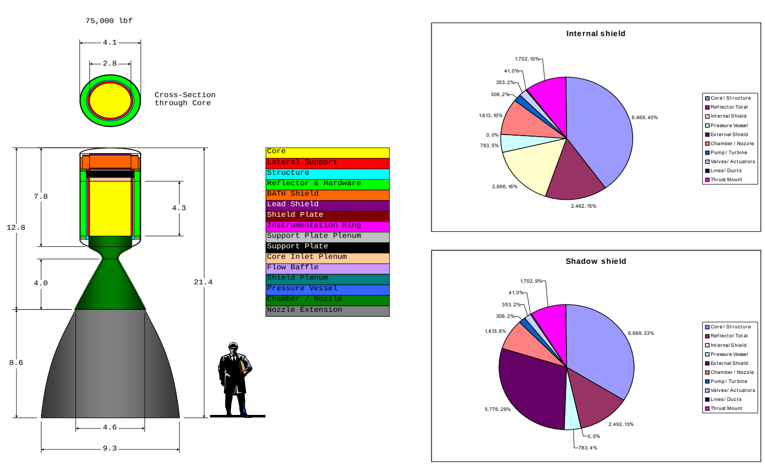
Pre-conceptual Design of the NCPS and Architecture Integration

- Total weight and size of the engine



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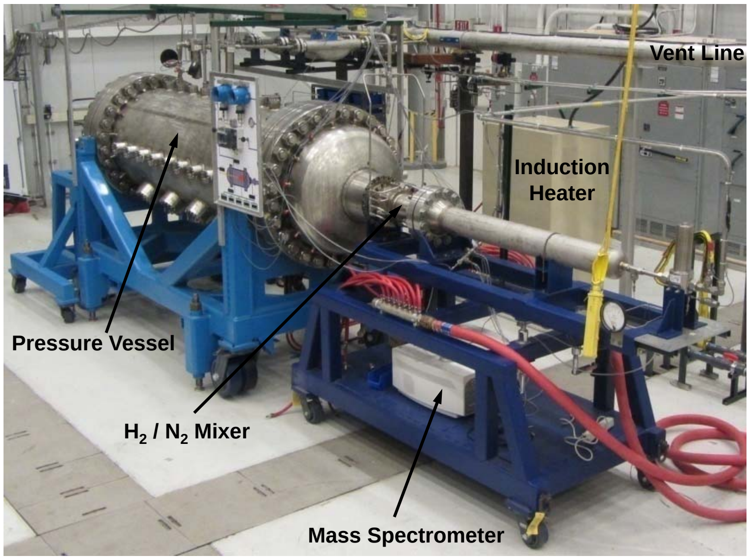
Nuclear Thermal Rocket Element Environmental Simulator (NTREES)

A key technology element in Nuclear Thermal Propulsion is the development of fuel materials and components which can withstand extremely high temperatures while being exposed to flowing hydrogen. NTREES provides a cost effective method for rapidly screening of candidate fuel components with regard to their viability for use in NTR systems

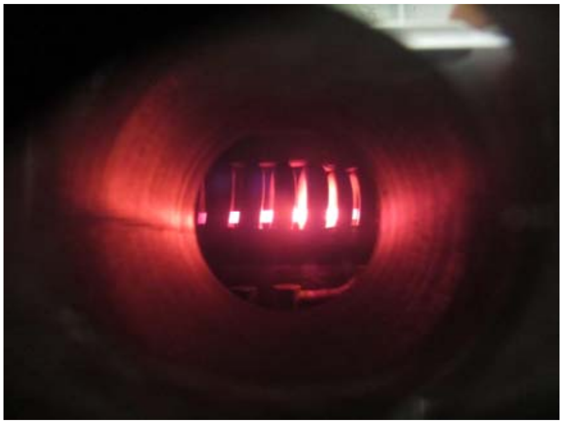
- **The NTREES is designed to mimic the conditions (minus the radiation) to which nuclear rocket fuel elements and other components would be subjected to during reactor operation.**
- **The NTREES consists of a water cooled ASME code stamped pressure vessel and its associated control hardware and instrumentation coupled with inductive heaters to simulate the heat provided by the fission process.**
- **The NTREES has been designed to safely allow hydrogen gas to be injected into internal flow passages of an inductively heated test article mounted in the chamber.**

Nuclear Thermal Rocket Element Environmental Simulator (NTREES) in 4205/101



NTREES is Currently Operational

- NTREES was successfully run with flowing hydrogen at about 2-3 gm/sec at 25 kW for several minutes until the supply hydrogen "K" bottle was depleted.
- Test article temperature was about 1100 K. Chamber pressure was 500 psi.
- A few minor problems were encountered, primarily with the DAQ system, but overall … quite successful.

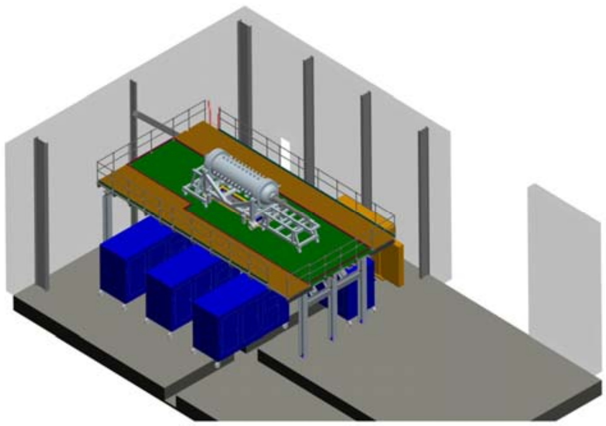


NTREES Power Upgrade Activities Continue

- NTREES induction power supply is being upgraded to 1.2 MW
- Water cooling system is being upgraded to remove 100% of the heat generated during testing
- Nitrogen system is being upgraded to increase the nitrogen flow rate to at least 4.5 lb/sec
- New piping is being installed to handle the increased flow rates
- The H_2 / N_2 mixer is being upgraded to handle the increased heat loads
- Platform is under construction to allow the new induction heater to be located underneath the NTREES pressure vessel

NTREES Platform for Power Upgrade

- Platform will allow the NTREES pressure vessel and associated components to be raised approximate 12 feet above floor level
- Induction power units will be located underneath the pressure vessel with buss bar connections feeding power directly through feed throughs to coil assemblies inside the chamber



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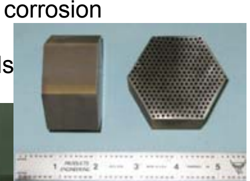
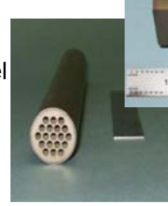
WBS 4.0 - NCPS Fuel Design / Fabrication

- Objective
  - Along with other NASA centers and DOE, optimize advanced manufacturing processes to develop an NTP fuel material
    - Idaho National Laboratory (INL)
    - Oak Ridge National Laboratory (ORNL)
  - Fabricate CERMET, graphite composite and advanced carbide fuel element samples with depleted uranium fuel particles
  - Complete mechanical and thermal property testing to develop an understanding of the process/property/structure relationship
  - Characterize samples to determine baseline material properties and evaluate fuel mass loss, matrix cracking, and other thermochemical corrosion processes
  - Develop a clear understanding of the fundamental materials impacts on fuel performance
- Key Deliverables
  - Design/Fabrication of nuclear thermal rocket fuel element segments for testing in NTREES
  - Final Report: NCPS Fuel Element Material Options





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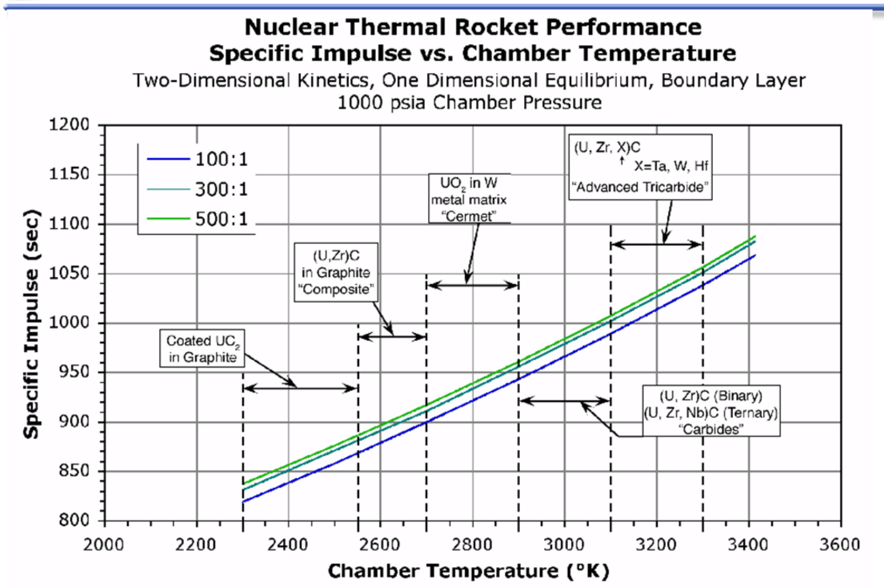
NTP Fuel Material Performance



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Fuel Material Development

- Develop/evaluate multiple fuel forms and processes in order to baseline a fuel form for NTP
  - CERMET: Hot Isostatic Pressing (HIP), Pulsed Electric Current Sintering (PECS)
  - Graphite composites
  - Advanced Carbides
- Materials and process characterization
  - Develop and characterize starting materials
    - W coated fuel particles are required for CERMETS
    - Particle size, shape, chemistry, microstructure
  - Develop and characterize consolidated samples
    - Microstructure, density, chemistry, phases
  - Optimize material/process/property relationships
    - Fuel particle size/shape vs. properties
    - Cladding composition and thickness
- Hot hydrogen testing
  - Early development to validate test approach
  - Screen materials and processes (cyclic fuel mass loss)
    - Particle size, chemistry, microstructure, and design features (claddings)

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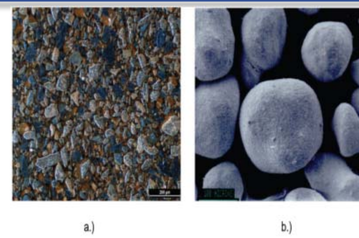
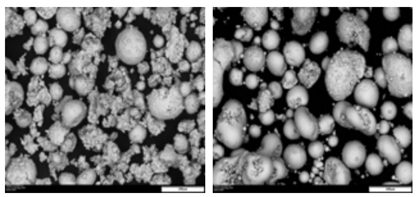
Uranium Dioxide (UO2) Particle Development

- UO2 Particle Procurement
  - Procured 2kg of dUO2
  - Particle size ranges:
    - <100um
    - 100um – 150um
    - >150um
- Plasma Spheroidization System (PSS)
  - System design complete and currently being assembled
  - Operational checkout and spheroidization trials on schedule for the end of Jan.



Y-12 Feedstock, (a) Depleted UO_2 and (b) Natural UO_2



SEM micrographs of ZrO2 powder at 250x. *(L) Pre (R) Post* Plasma Alloy and Spheroidization (PAS)

MSFC PSS assembly model

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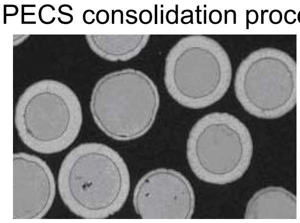
Chemical Vapor Deposition (CVD) Coated Particle Development

•MSFC Tungsten Hexachloride (WCl6) Process Development
- Redesigned and upgraded CVD system complete
- Demonstrated W coating on Al2O3 substrate
- Ongoing fluidization trails
- Reactor design optimization for fluidization

•Tungsten Hexaflouride (WF6) Process Development
- Process being developed by Ultramet
- Currently coating ZrO2 particles
- Have demonstrated 20 vol% W coating

•40 vol% W coated spherical particles required for HIP and PECS consolidation process development



SEM micrographs of spherical coated particles

Redesigned CVD System

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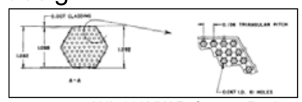
CERMET Consolidation Process Development (CEO2)

- ANL 200MW element chosen for NCPS reference design



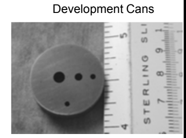
ANL 200MW Reference Design

- Hot Isostatic Pressing (HIP) process development
  - Completed HIP can designs for sample geometries being considered
  - Procured CeO2 surrogate powders currently being shperoidized

HIP Process Development Cans

- Pulsed Electric Current Sintering (PECS) Development
  - Completed pure W microstructural morphology study
  - Fabricated 7 specimens of W-40vol%CeO_2 with varying ratios of particle sizes, W vs. CeO_2 (uncoated)
    - CeO_2 encapsulated W particles when W > CeO_2 (microstructure image shown)
    - Studies ongoing for CeO_2 > W particle size
  - EDM machining investigated as a method to drill coolant channels into W-CeO_2 specimens

Hexagonal W-CeO_2 Specimen (PECS)



EDM Trials on W-CeO_2 Specimen

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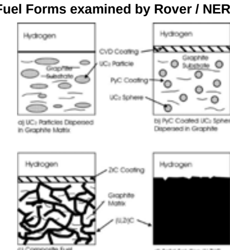
Advanced Carbide Fuel Development

- Advanced Carbides: Ceramic fuel elements fabricated from uranium carbide (UC) and 1 or more refractory metal carbides (e.g. $(U_{0.1},Zr_{0.58},Nb_{0.32})C_{0.95}$)
- Development Plan
  - Literature search regarding materials & past efforts
  - Preliminary fabrication trials planned for 2012 to assess processing & performance
  - Present focus on refractory transition metals (groups IVB – VIB, periods 4 – 6 of periodic table)
- Parameters under consideration:
  - Crystallographic phase relationships
  - Melting point/ vaporization rate
  - Diffusion characteristics
  - Thermal conductivity
  - Cost/availability
  - Thermal expansion
  - Hydrogen compatibility/reactivity
  - Neutron absorption cross-section
  - Thermal shock characteristics
  - Potential fabrication methods
- Ceramic reaction-sintered coatings (CRSC)
  - Assist in assessment of potential advanced carbide compositions
  - Assist in graphite composite fuel element coatings

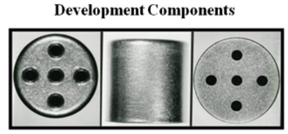
Fuel Forms examined by Rover / NERVA



Task 4.6 products closely resemble this type of fuel element

Source: Matthews, et. al; Carbide Fuels for Nuclear Thermal Propulsion; 1991

ISUS (Integrated Solar Upper Stage) Development Components



Top Side Bottom

HfB_2-HfC ceramic reaction-sintered coating applied to Poco graphite, grade AXF-5Q, via rapid high-temperature processing technique

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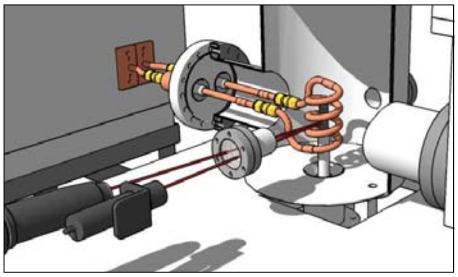
Fuel Element Thermal Cycle Testing

- CERMET Fuel Element Environmental Test (CFEET) system
  - Coupon level thermal cycle testing
  - 0.5” -6” long, 0.5” dia. samples can be thermally cycled at high temperatures quickly
  - Static environments and eventually flowing hydrogen environment (low flow rate)
  - System is assembled and going through operational checkout
  - System proven to be reliable for tests up to 1000sec and element temperatures to 2200° C
  - Looking at chamber cooling in order to reach 2800° C.



Cross section of CFEET chamber showing heating coils and sample

W/Re sample loaded into heating coil as viewed through the pyrometer viewport

NCPS Project Work Breakdown Structure

1.0 NCPS Project Management
Project Manager: Mike Houts (MSFC) 256-544-8136
GRC Lead: Stan Borowski 216-977-7091
JSC Lead: Jeff George 281-483-5962

2.0 Pre-conceptual Design of the NCPS & Architecture Integration
Tony Kim, MSFC 256-544-6217

3.0 High Power (≥ 1 MW) Nuclear Thermal Rocket Element Environmental Simulator (NTREES)
Bill Emrich, MSFC 256-544-7504

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6.0 Affordable NCPS Development and Qualification Strategy
Harold Gerrish, MSFC 256-544-7084

7.0 Second Generation NCPS Concepts
Rob Adams, MSFC 256-544-3464

WBS 6.0 - Affordable NCPS Development and Qualification Strategy

- Objective
  - Devise an affordable development and qualification strategy, including a strategy for nuclear testing of the NCPS
  - The integrated program development and test strategy will likely include fuel qualification and selection
    - Will use separate effects tests (hot H_2 and irradiation), innovative ground testing in existing boreholes at the Nevada Test Site (NTS), state-of-the-art modeling, and the development of scalable, small nuclear thermal engines for ground testing and subsequent in-space flight demonstration

- Key Deliverables
  - Yearly Reports
  - Estimated Cost and Schedule
  - Final Report: NCPS Development and Qualification Strategy

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WBS 6.1 Programmatic Considerations
WBS 6.2 Engineering Considerations

Accomplishments:

- Collected NTP development plans from 2006 NTP program at MSFC
- Collected 2011 Rational Strategy for NTP development from Sam Bhattacharyya (previously at Argonne National Labs)
- Access to development plans for SNTP and ROVER/NERVA programs
- Initiated support from the MSFC Engineering Cost Office

Next:

- Acquire J2X development plans and lessons learned. Cost office said to man rate the J2X was only an extra ~$50M.
- Acquire any other development plan suggestions
- Coordinate with the GRC cost office for the last NTP cost estimate made
- Combine development plans into one for baseline NTP. Future versions could account for bi-modal NTP development

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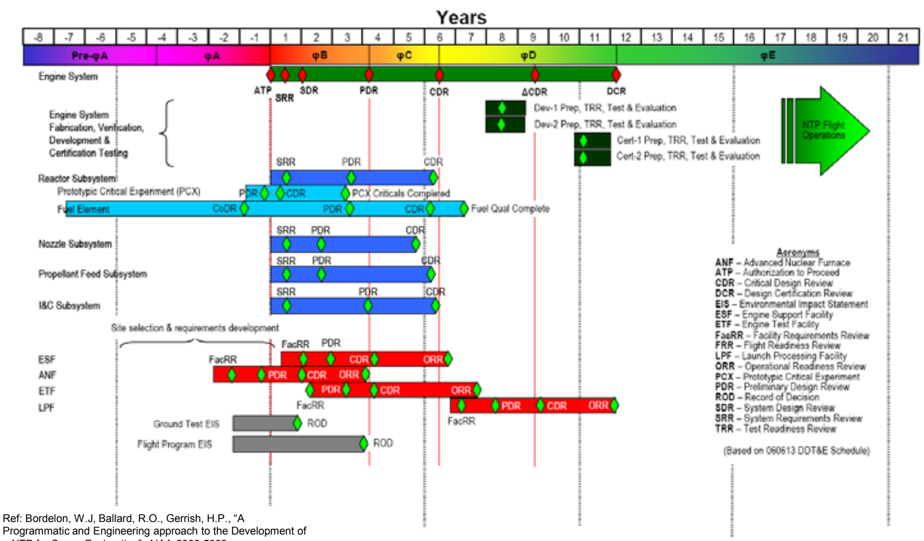
2006 NTP Development Plans



Ref: Bordelon, W.J, Ballard, R.O., Gerrish, H.P., "A Programmatic and Engineering approach to the Development of a NTP for Space Exploration", AIAA-2006-5082

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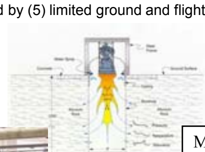
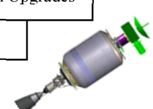
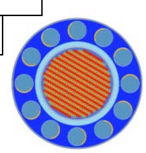
2011 Formulation of Affordable & Sustainable NTP Development Strategy

Strategy builds on wealth of past data (Rover / NERVA, GE-710, ANL, FSU programs), and use of: (1) detailed SOTA computer analysis; (2) focused non-nuclear testing (e.g., NTREES); (3) nuclear testing (e.g., ATR at INL) to validate candidate fuels, coatings & claddings; and (4) affordable SAFE ground testing; followed by (5) limited ground and flight testing of small, scalable engines

- Subsequent Missions with Upgrades
- Instrumented Protoflight Test
- Minimum Scaleable Ground Test
- Focused Nuclear testing
- Maximize non-nuclear testing
- Robust Flexible Reactor Design
- Use of SOA Design Methods
- Develop test matrix
- Benign System Requirements
- Modest Initial Mission
- Utilize large existing database







Ref: Sam Bhattacharyya, "A Rationale Strategy for NTR Development", AIAA-2011-5945, 47th JPC, San Diego, CA

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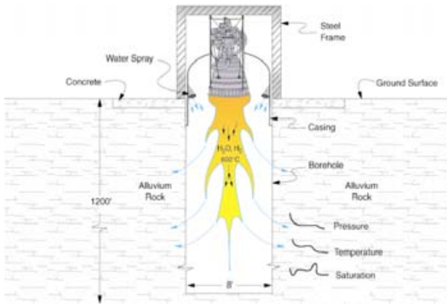
WBS 6.3 –Bore Hole Validation

Accomplishments:

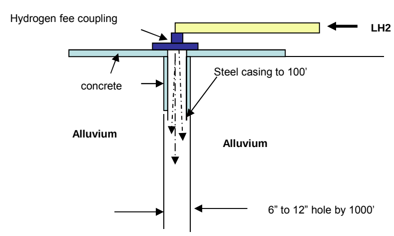
- Collected 2007 preliminary modeling results of the Nevada Test Site bore hole permeability.
- Setting up a technical review of all bore hole analysis work done in 2011. Projected date 1/31/12 at MSFC.

Next:

- Evaluate all analysis work done in 2011 to determine what analysis is still required. List all engineering concerns and what needs to be done to resolve them.
- Prepare plans for a subscale ground test demonstration to validate analysis.

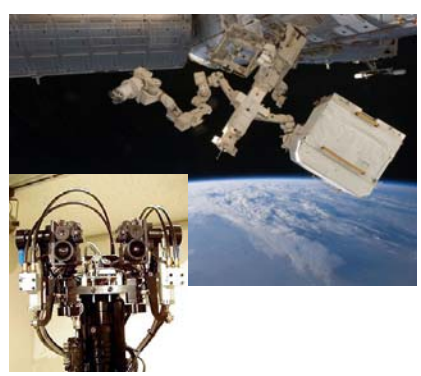


Subscale Test Example



WBS 6.4 –Demo Flight

- Assess the viability and desirability of an NCPS demo flight.
- Assess potential data gathering and analysis techniques for both the operating and post-operational phases.
- Assess impact of limits on information that could be obtained from a demo flight.



WBS 6.5 –Nuclear Stage

Accomplishments:

- Coordinated with the SLS program the draft capabilities of each SLS block (I, IA, II). The data will be used to determine how each block can be used for a nuclear cryogenic upperstage or a Mars transfer vehicle.

- Participated in SLS trade to determine the best SLS fairing length and shape. The larger the diameter and longer the length, the better for NTP.

Next:

- Stage sizing and performance trades (done under task#2)
- Collect cost and schedule from other upperstages

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Future Plans / Path Forward

- Space nuclear power and propulsion are game changing technologies for space exploration.
- The NASA NCPS project has 1 to 3 years to demonstrate the viability and affordability of a Nuclear Cryogenic Propulsion Stage.
- Participation is encouraged. Please feel free to contact the NCPS project with interest or ideas (michael.houts@nasa.gov).

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Backup

BACKUP

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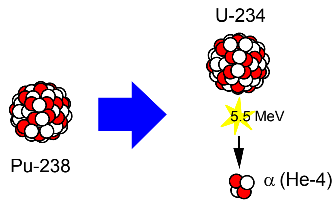
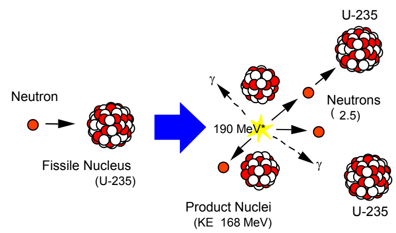
Basics of Nuclear Systems



Power = 0.558 W/g Pu-238
Natural decay rate (87.7-year half-life)

- Long history of use on Apollo and space science missions
  - **44 RTGs and hundreds of RHUs launched by U.S. during past 4 decades**
- Heat produced from natural alpha (α) particle decay of Plutonium (Pu-238)
- Used for both thermal management and electricity production



Power = Variable, 0 Watts to heat transfer limit

- Used terrestrially for over 65 years
  - Fissioning 1 kg of uranium yields as much energy as burning 2,700,000 kg of coal
- One US space reactor (SNAP-10A) flown (1965)
  - Former U.S.S.R. flew 33 space reactors
- Heat produced from neutron-induced splitting of a nucleus (e.g. U-235)
  - At steady-state, 1 of the 2 to 3 neutrons released in the reaction causes a subsequent fission in a "chain reaction" process
- Heat converted to electricity, or used directly to heat a propellant

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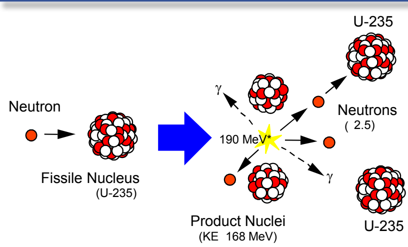
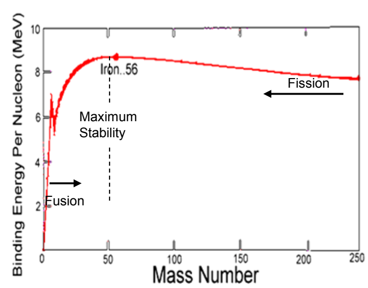
Nuclear Fission Process



180 MeV prompt useful energy (plus 10 MeV neutrinos) - additional energy released in form of fission product beta particles, gamma rays, neutron capture gammas (~200 MeV total useful)



- Neutron absorbed by heavy nucleus, which splits to form products with higher binding energy per nucleon. Difference between initial and final masses = prompt energy released (190 MeV).
  - —*Fissile* isotopes (U-233, U-235 and Pu-239) fission at any neutron energy
  - —Other actinides (U-238) fission at only high neutron energies
- Fission fragment kinetic energy (168 MeV), instantaneous gamma energy (7 MeV), fission neutron kinetic energy (5 MeV), Beta particles from fission products (7 MeV), Gamma rays from fission products (6 MeV), Gamma rays from neutron capture (~7 MeV).
- For steady power production, 1 of the 2 to 3 neutrons from each reaction must cause a subsequent fission in a *chain reaction* process

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Space Fission Fundamentals

Generating fission chain reactions is simple. Place the right materials in the right geometry – no extreme conditions required.

Fissile fuel has a very high energy density – 24,000,000 kWhr/kg.

Challenge is in designing fission systems to meet specific requirements, e.g. affordable terrestrial power plants, submarine and surface ship propulsion, compact power systems, space fission power and propulsion, etc.

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Space Fission Fundamentals

Historic (and near-term) space fission systems use uranium (enriched in U-235) for fuel. This fuel is plentiful. The uranium is typically in the form of a high melting point compound, such as UC_2, UO_2, UCZrC, UN, etc.

Space fission systems do not use Pu-238.

Space fission systems are essentially non-radioactive at launch.

Radioactivity associated with space fission systems is either prompt (from the fission process) or delayed (from accumulated fission products - function of time and power level).

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Space Fission Fundamentals

Nuclear thermal propulsion (NTP) systems typically use hydrogen for propellant (highest specific impulse for a given nuclear fuel temperature). The hydrogen is heated directly by the nuclear fuel. Other potential propellants include NH_3, CH_4, H_2O, etc.

Nuclear electric propulsion (NEP) systems convert heat from fission into electricity. The electricity is then used to power an electric thruster. Numerous power conversion options exist, including Stirling, Brayton, Rankine, Thermoelectric, Thermionic, and other.

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Space Fission Fundamentals

Space fission systems cannot explode like a nuclear bomb.

The primary risk from space fission systems is inadvertent start with personnel in close proximity to the system (criticality accident).

Criticality accidents are prevented through procedures and system design. Last significant criticality accident in the US occurred 23 July 1964 (concentrated uranium solution accidentally dropped into agitated tank containing sodium carbonate).

“10 foot” rule.

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Fission Introduction

- Creating a fission chain reaction is conceptually simple
  - **Requires right materials in right geometry**
- Good engineering needed to create safe, useful, long-life fission systems

- *1938 Fission Discovered*
- *1939 Einstein letter to Roosevelt*
- *1942 Manhattan project initiated*
- *1942 First sustained fission chain reaction (CP-1)*
- *1943 X-10 Reactor (ORNL), 3500 kWt*
- *1944 B-Reactor (Hanford), 250,000 kWt*
- *1944-now Thousands of reactors at various power levels*

Workers loading fuel at X-10 Reactor

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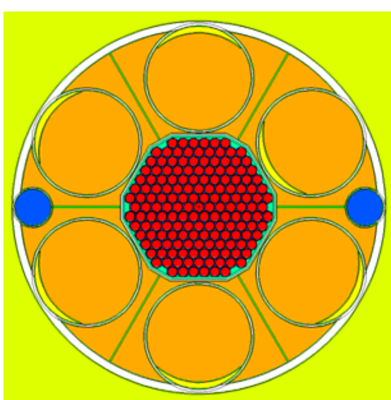
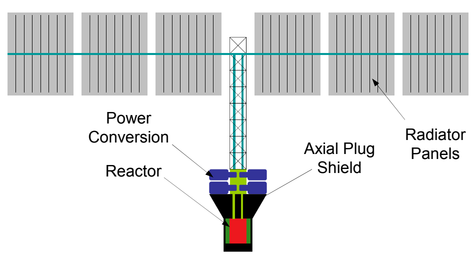
Fission Reactor Operation





- System power controlled by neutron balance
- Average 2.5 neutrons produced per fission
  - **Including delayed**
- Constant power if 1.0 of those neutrons goes on to cause another fission
- Decreasing power if < 1.0 neutron causes another fission, increasing if > 1.0
- System controlled by passively and actively controlling fraction of neutrons that escape or are captured
- Natural feedback enables straightforward control, constant temperature operation
- 200 kWt system burns 1 kg uranium every 13 yrs

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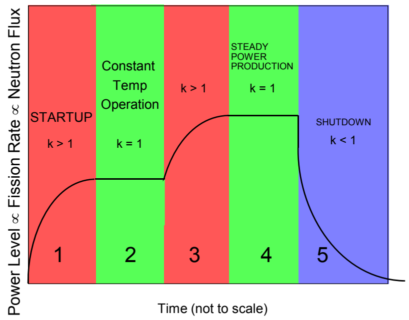
Reactor Operation (Notional)



Control drums rotate to provide positive reactivity (supercritical). Power increases, reactor heats up.

As reactor temperature increases, natural feedback reduces reactivity to zero. System maintains temperature.

Control drums rotate to provide additional reactivity, until desired operating temperature is achieved.

Reactor follows load, maintaining desired temperature.

Control drums rotate ~monthly to compensate for fuel that is consumed.

Control drums rotate to shut system down.

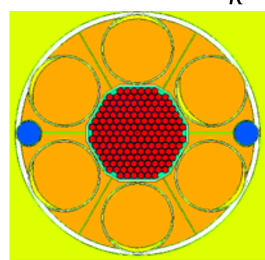
$k \equiv$ Multiplication Factor

$$= \frac{\text{Production Rate}}{\text{Loss Rate}} = \frac{N(t+l_n)}{N(t)}$$

< 1 (subcritical, $dN/dt < 0$)
$= 1$ (critical, $dN/dt = 0$)
> 1 (supercritical, $dN/dt > 0$)

$$\text{Thermal Power }(t) \propto N(t)$$

$$\text{Reactivity} \equiv \rho \equiv \frac{k-1}{k}$$



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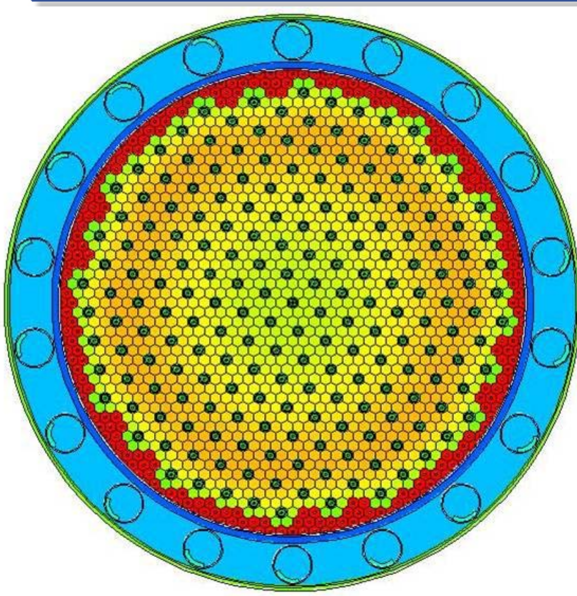
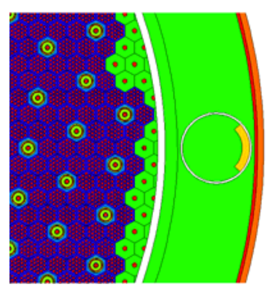
Space Fission Power and Propulsion Systems have similar "Nuclear" Design





500 MWt NTR burns 20 grams of uranium per hour

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Uranium Fuel

- Natural uranium consists of
  - U-234 0.0055%
  - U-235 0.720%
  - U-238 99.274%
- Most reactor designs use uranium fuel enriched in U-235
  - Space reactors typically use uranium fuel with >90% U-235
- Prior to operation at power, uranium fuel is essentially non-radioactive and non-heat producing
- Following long-term operation, fission product decay power is 6.2% at t=0 (plus fission power from delayed neutrons)
  - 1.3% at 1 hour
  - 0.1% at 2 months

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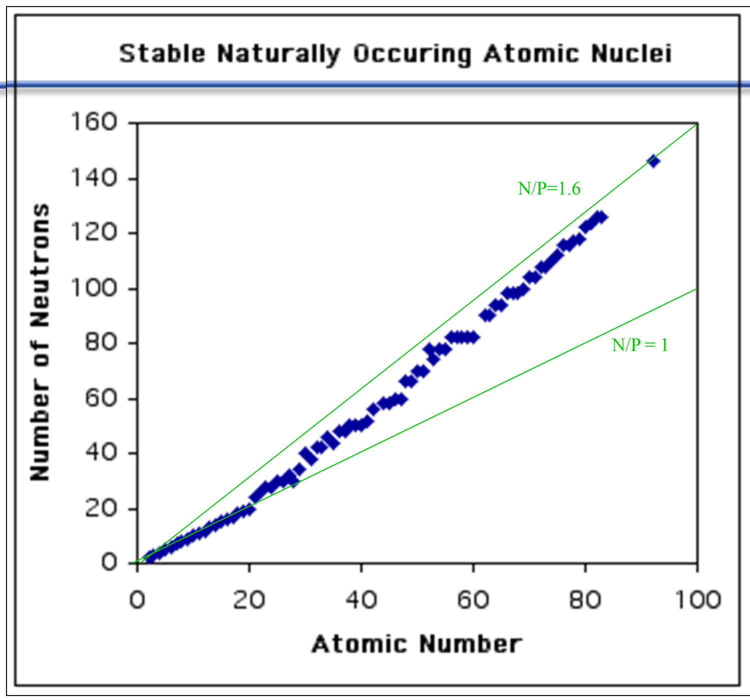

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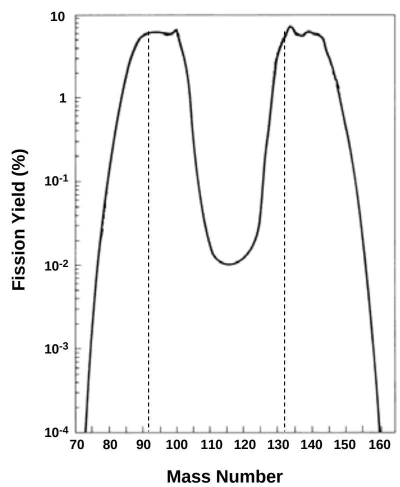
Fission Products

- Fission events yield bimodal distribution of product elements
- These products are generally neutron-rich isotopes and emit beta and gamma particles in radioactive decay chains
- Most products rapidly decay to stable forms – a few, however, decay at slow rates or decay to daughter products which have long decay times
- Example fission products of concern:
  - Strontium-90 (28.8-year half-life)
  - Cesium-137 (30.1-year half-life)
- Isotope amounts decrease by factor of 1,000 after 10 half-lives and 1,000,000 after 20 half-lives
- Decay power 6.2% at t=0 (plus fission from delayed neutrons), 1.3% at 1 hour, 0.1% at 2 months (following 5 years operation)

Product Yields for Thermal Neutron (0.025 eV) Fission of U-235



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Radiation Shielding

- Reactor needs to be shielded during operation and for a period of time following operation at significant power
- Hydrogen bearing compounds (e.g. LiH, H_2O) are most mass effective neutron shields
  - Neutron shielding only needed while operating
- High density, high atomic number materials (e.g. tungsten, uranium) are the most mass effective gamma shields
- For surface systems regolith is a good gamma shield, adequate neutron shield. Spacecraft and consumables good for in-space
- Reactor can be shielded to any level desired
  - Surface system "Trade" is against mass or burial depth
  - Reference configuration reduced operating dose to < 1/10 natural lunar background at 100 m
  - Dose rate drops rapidly following shutdown (power or propulsion)

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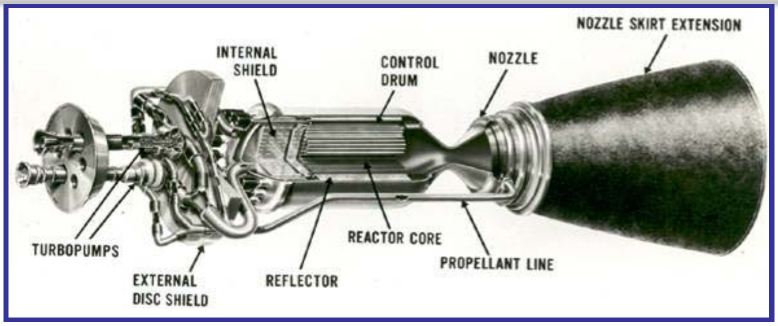
Nuclear Thermal Propulsion (NTP)



- Typical system: hydrogen from propellant tank (not shown) directly heated by reactor and expanded through nozzle to provide thrust
- ~850 second Isp demonstrated in ground tests at high thrust/weight
- Potential for > 900 s Isp with advanced fuel forms and cycles
- Potential Applications
  - Rapid robotic exploration missions throughout solar system
  - Piloted missions to Mars and other potential destinations
  - Potential to significantly reduce propellant needs and/or trip time

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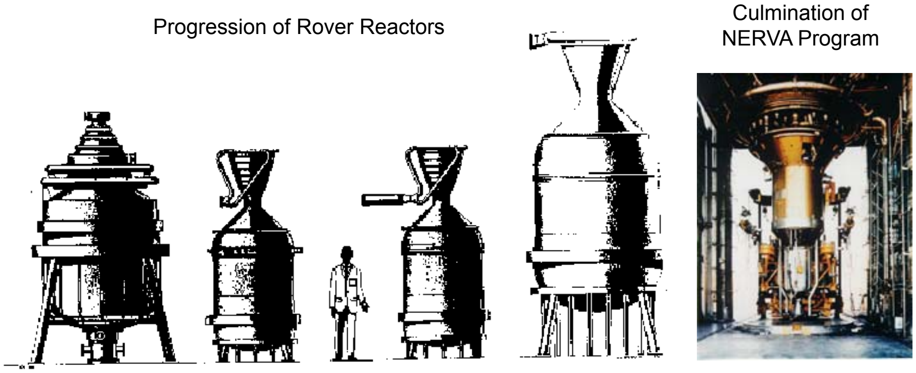
Rover/NERVA Engine Comparison

Progression of Rover Reactors

Culmination of NERVA Program



KIWI A	KIWI B	Phoebus 1	Phoebus 2	XE-Prime
1958-1960	1961-1964	1965-1966	1967	1969
100 MW	1,000 MW	1,000 & 1,500 MW	5,000 MW	1,140 MW
0 lbf Thrust	50,000 lbf Thrust	50,000 lbf Thrust	250,000 lbf Thrust	55,400 lbf Thrust

NERVA engines based largely on the KIWI B reactor design.

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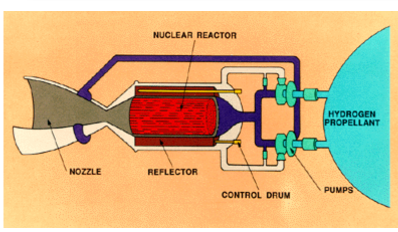
Phoebus-2A

♦

Proposed Types of Nuclear Thermal Propulsion



SOLID CORE NUCLEAR ROCKET