Subscale Validation of the Subsurface Active Filtration of Exhaust (SAFE) Approach to NTP Ground Testing

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Overview

- Introduction
- Brief History of NTP
- Ground Test Options
- Validation Plans for SAFE Concept
- Alternative SAFE Concepts
- Recent Assessments
- Summary

Introduction

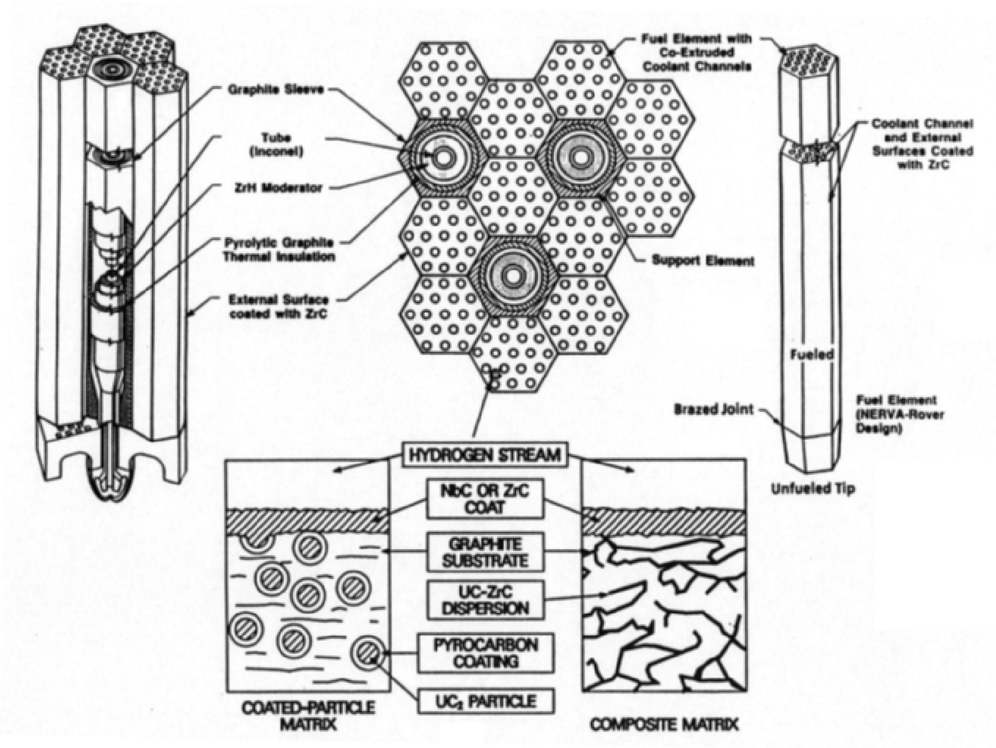
- Nuclear Thermal Propulsion (NTP) is an attractive propulsion method for crewed Mars Transit
- NASA DRA 5.0 identified NTP as the preferred approach for a Mars mission
  – High thrust (~10's klbf)
  – High I_{sp} (875-950 s)
- Benefits of NTP include
  – A propulsion system that can reduce transit times
  – Reduce initial mass to low Earth orbit (IMLEO)
  – Permit greater shielding from cosmic rays for crew safety
- Goals of NTP Program
  – Development of fuel materials (ZrC composite) or (UO_2 cermet)
  – Design of NTR engine (7.5 klbf, 16.4-klbf SNRE, 25 klbf, etc.)
  – Lab testing of fuel elements in non-radiation environment
  – *Ground testing of NTR engine at full power and duration (~ 1 hr.)*

Brief History of NTP

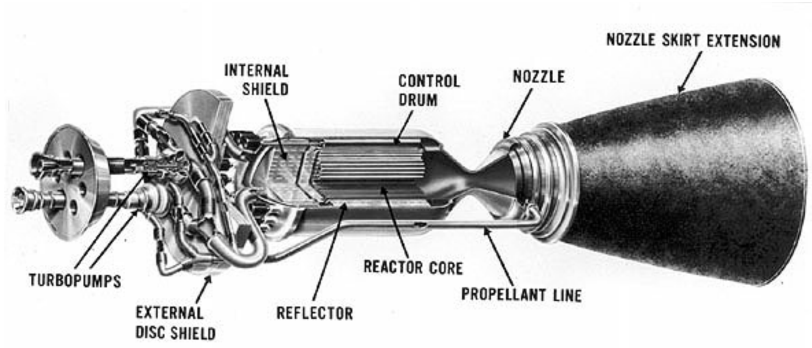
- Project Rover
  - Began in 1950's by Los Alamos Scientific Labs (now Los Alamos National Labs) and ran until 1970's
  - Tested a series of nuclear reactor engines of varying size at Nevada Test Site (now Nevada National Security Site)
  - Ranged in scale from 111 kN (25 klbf) to 1.1 MN (250 klbf)
  - Included Nuclear Furnace-1 tests for materials and fuel element testing
  - Demonstrated the viability and capability of a nuclear rocket engine test program
  - One of Kennedy's 4 goals during famous moon speech to Congress
- Nuclear Engines for Rocket Vehicle Applications (NERVA)
  - Atomic Energy Commission and NASA joint venture started in 1964
  - Parallel effort to Project Rover
  - Was focused on technology demonstration
  - Tested XE′ engine, a 245-kN (55-klbf) engine to demonstrate startup/shutdown sequencing

Results of Rover/NERVA

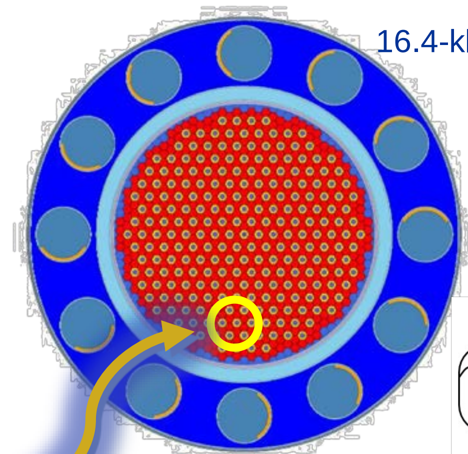
- Largely successful programs
  - Demonstrated 800+ seconds of specific impulse
  - Achieved TRL 6 level of development
  - Much of present design and understanding of NTP are heritage from Rover/NERVA
- Identified mid-band corrosion issue in fuel elements
  - Due to high temperature, high pressure hydrogen, fuel elements were susceptible to corrosion & cracking
  - Coatings were used to minimize corrosion effect, but insufficient to mitigate entirely
- Ultimately cancelled in 1973



Background on Nuclear Thermal Propulsion



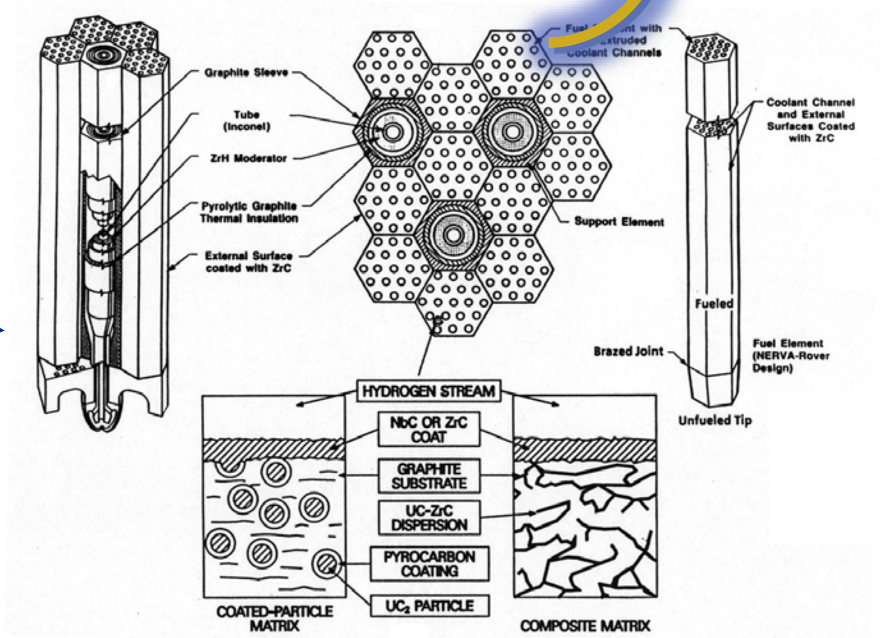
NERVA Concept Engine

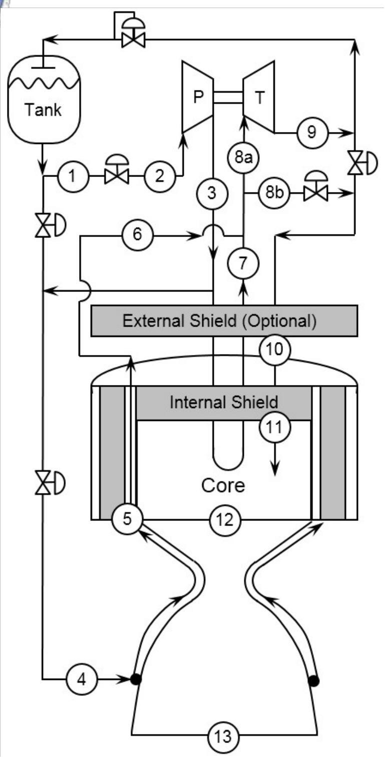


16.4-klbf SNRE Reactor Core

Fuel Elements

Tie-Tube Bundles





NTR Engine Cycle

Challenges to Ground Testing NTR

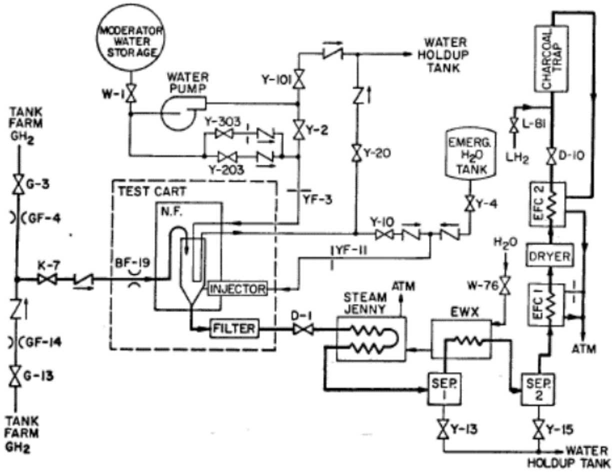
- Hot-hydrogen stream is passed directly through fuel elements
  - Potential for radioactive material to be eroded into gaseous fuel flow as identified in previous programs
  - NERVA and Project Rover (1950's-70's) were able to test in open atmosphere
    - Similar to conventional rocket engine test stands today
    - Nuclear Furnace-1 tests employed a full scrubber system
- Increased government and environmental regulations prohibit the modern testing in open atmosphere
  - Since the 1960's, there's been an increasing cessation on open air testing of nuclear material
  - Political and national security concerns further compound the regulatory environment

Ground Test Options

- Open Air Testing
  - Least expensive method and used during Rover/NERVA
  - Preferably at remote site (such as NNSS)
  - Environmental, political and regulatory concerns rule out as possibility for future test series

From: AIAA 2011-5849

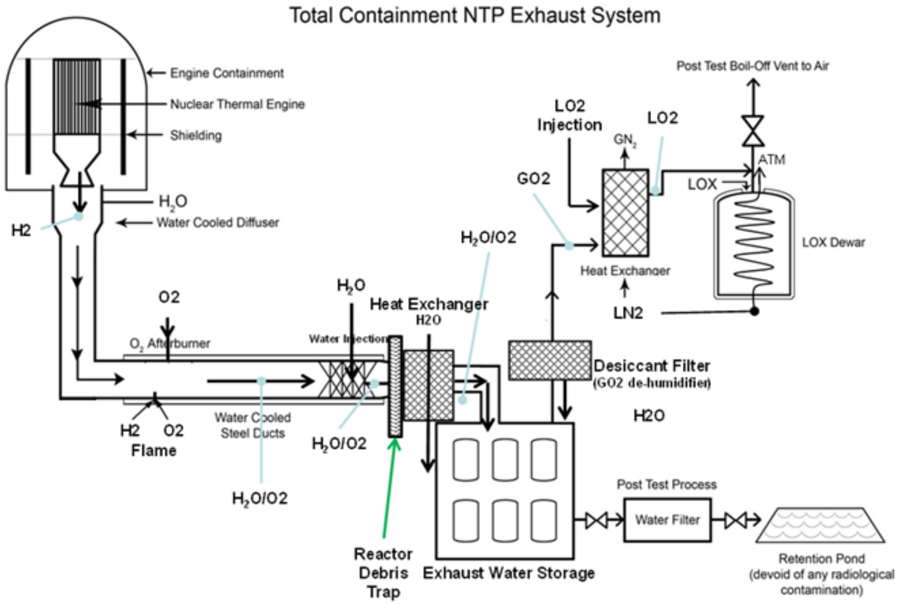
- Above Ground Scrubbers
  - Used during Nuclear Furnace-1 (NF-1) testing
  - Exhaust still expelled to atmosphere, but after series of filters & heat exchangers
  - Remaining hydrogen is flared off and burned



From: AIAA 1989-2386

Ground Test Options

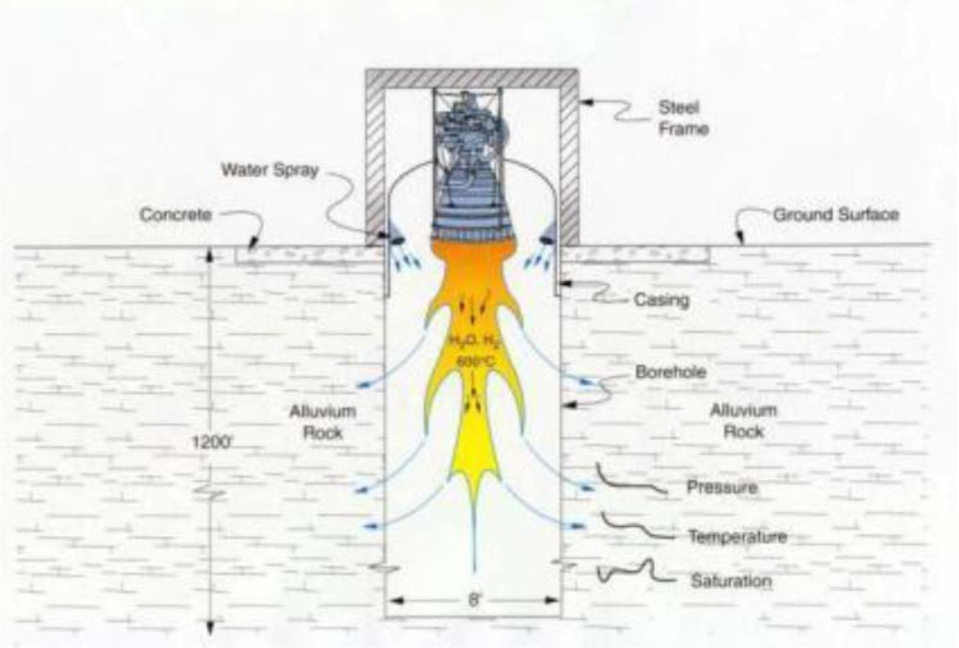
- Full-Containment
  - Similar to above-ground scrubber concept
  - Hydrogen exhaust is burned with oxygen to create steam, cooled, condensed and collected
  - Filters and particle traps capture any condensable nuclides
  - Exhaust water is then held in retention tanks and slowly filtered for evaporation
  - Non-condensable gases (e.g. oxygen) are collected, filtered and vented off



From: NETS2015-5146

Ground Test Options

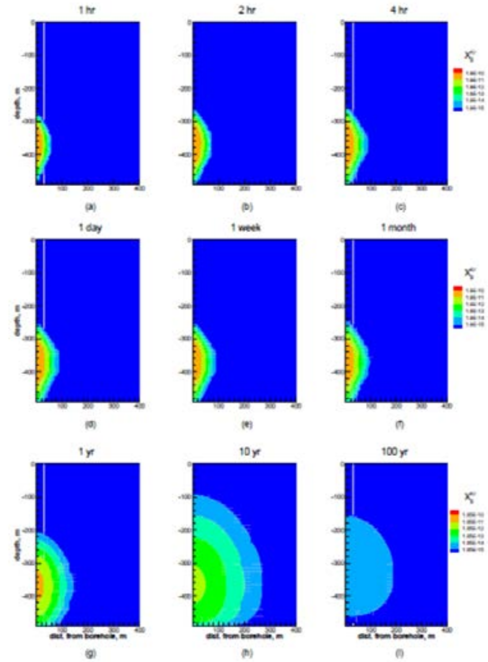
- Sub-surface Active Filtration of Exhaust (SAFE)
  - Conceptualized by Steve Howe, CSNR in 1998
  - Uses the alluvium soil of NNSS to act as natural filter
  - Uses existing “boreholes” at NNSS left over from below ground nuclear weapons testing
  - Envisioned as being a cost-effective option since costs for infrastructure (e.g. scrubbers and filters) are reduced, and existence of boreholes at NNSS
  - Water spray would help cool and condense the exhaust
  - One of leading ground test options for NTP project



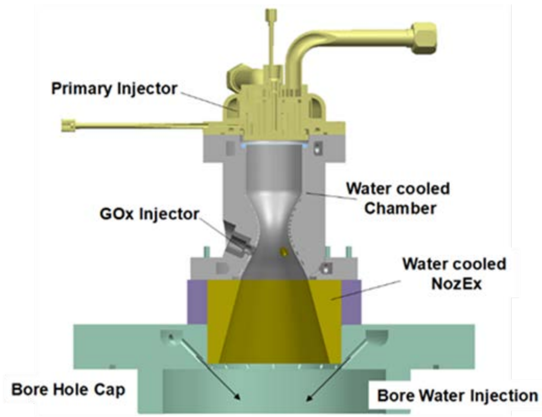
Source: Steve Howe, CSNR

Validation Plans for SAFE Concept

- Before SAFE concept can be utilized on a full-scale nuclear engine, must be validated
  - Several studies and models have investigated the soil characteristics and concept of tests at NNSS.
  - Physical tests need to be conducted to validate model predictions
- Plans are to utilize a non-nuclear rocket engine to produce high temperature exhaust at NNSS borehole
  - Tests will utilize Aerojet Rocketdyne Liquid oxygen Augmented Nuclear Thermal Rocket (LANTR) simulator
    - Hydrogen-Oxygen test article with oxygen afterburner
    - Simulates exhaust products expected from full-scale testing with water cooling
  - Will seed exhaust with Xenon or Krypton to measure nuclide migration through soil

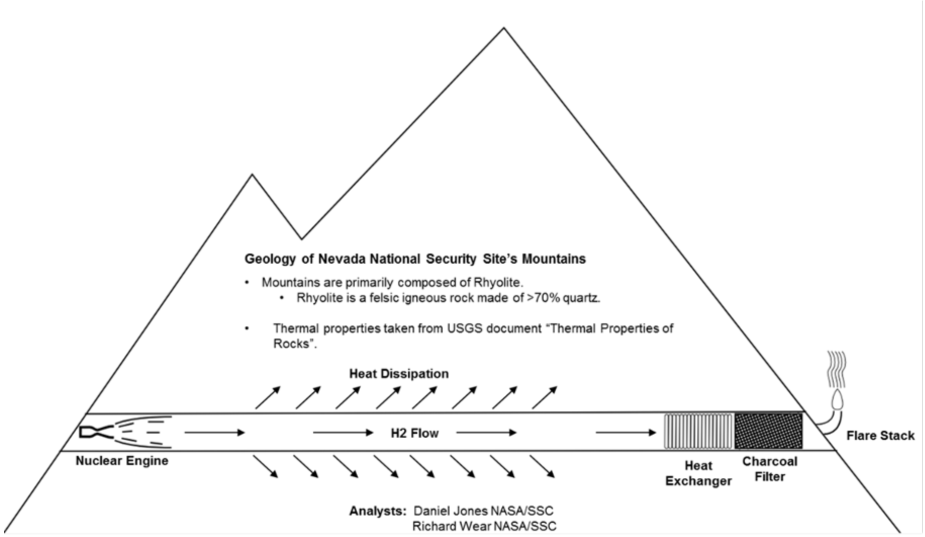


From: AIAA 2012-3743



Alternative SAFE Concepts

- Security regulations and HEU quantities for SNRE may pose increased costs for above ground SAFE tests
  - Alternative concepts being investigated based upon SAFE concept
- U1-A site at NNSS attractive due to below ground tunnels and soil characteristics
  - Would allow for quick entombment of engine should release incident occur
  - Temporary hot-cell could be located in parallel drift tunnel
- P-Tunnel site at NNSS attractive due to solid rock features in mountain tunnels
  - Could be attractive to reduce hydrogen diffusion through tunnel complexes and reduce water cooling requirements
  - Would use heat exchangers, filters & flare stack to vent to atmosphere and regulate pressure in tunnel



From: NETS2015-5146

Recent Assessments

- Numerous studies have reviewed ground test programs over history of NTP
  - Various engine sizes ranging from 7 kbf to 75 klbf were used as baseline from studies
    - Difficult to complete an “apples-to-apples” comparison due to varying scales and program direction
    - Ex: Recent review by ARES studied a 222-kN (50-klbf) engine vs. the 73-kN (16.4-klbf) scale engine under current investigation. Also considered a 25 year life-cycle
    - Difference in scales impact consumables, infrastructure requirements, security and regulatory requirements, etc.
    - Cost inflation since 1980’s/1990’s further compound comparisons
  - Most recent assessments conducted by NSTec in 2011
    - Full-power/duration tests at NNSS
      - Based upon 1999 Bechtel Nevada estimates and included inflation
    - Sub-scale SAFE validation tests
      - “Clean-sheet” cost assessment
      - Included costs of preparation of test site (holes, berms, trailers, etc.)
- Despite previous estimate activities, continual discussion of what cost drivers impact ground testing cost & schedule
- NASA and DOE stakeholders currently engaged to understand ground test requirements and impacts

Summary

- Nuclear Thermal Propulsion is an enabling technology for fast crewed Mars missions, but requires ground test facility
- A number of ground test options are possible
  - Sub-surface Active Filtration of Exhaust (SAFE) concept is one of the approaches for ground testing being examined
- SAFE concept requires a sub-scale, non-nuclear validation
  - Alternative methods based on SAFE concept would utilize below ground tunnels at NNSS for additional security/safety
- On-going discussions with NASA and DOE stakeholders reviewing regulatory and programmatic requirements for best path forward for ground testing