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

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Nuclear thermal propulsion (NTP) has been recognized as an enabling technology for missions to Mars and beyond. However, one of the key challenges of developing a nuclear thermal rocket is conducting verification and development tests on the ground. A number of ground test options are presented, with the Sub-surface Active Filtration of Exhaust (SAFE) method identified as a preferred path forward for the NTP program. The SAFE concept utilizes the natural soil characteristics present at the Nevada National Security Site to provide a natural filter for nuclear rocket exhaust during ground testing. A validation method of the SAFE concept is presented, utilizing a non-nuclear sub-scale hydrogen/oxygen rocket seeded with detectible radioisotopes. Additionally, some alternative ground test concepts, based upon the SAFE concept, are presented. Finally, an overview of the ongoing discussions of developing a ground test campaign are presented.

Nomenclature

AEC	=	Atomic Energy Commission
CERMET	=	Ceramic metallic
CSNR	=	Center for Space Nuclear Research
DRA	=	Design Reference Architecture
HEU	=	Highly enriched uranium
IMLEO	=	Initial mass to low Earth orbit
INL	=	Idaho National Laboratory
LANL	=	Los Alamos National Laboratory
LANTR	=	Liquid oxygen Augmented Nuclear Thermal Rocket
LASL	=	Los Alamos Scientific Laboratories (now called Los Alamos National Laboratories)
LEO	=	Low Earth orbit
NCPS	=	Nuclear Cryogenic Propulsion Stage
NERVA	=	Nuclear Engine for Rocket Vehicle Applications
NF-1	=	Nuclear Furnance-1

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NNSS	=	Nevada National Security Site
NRC	=	National Research Council
NSTec	=	National Securities Technology Corporation
NTP	=	Nuclear Thermal Propulsion
NTR	=	Nuclear Thermal Rocket
NTS	=	Nevada Test Site (now called Nevada National Security Site)
SAFE	=	Sub-surface Active Filtration of Exhaust
SNPO	=	Space Nuclear Propulsion Office
SNRE	=	Small Nuclear Rocket Engine

I. Introduction

NUCLEAR thermal propulsion (NTP) is the only recognized propulsion technology for rapid transit, low risk crewed missions to Mars and beyond. NASA Design Reference Architecture (DRA) 5.0 identified NTP as the preferred approach for a Mars mission, owing to its high thrust (10's klbf) and high I_{sp} (875-950 s).[1] The high specific impulse (I_{sp}) and high thrust capabilities of a nuclear thermal rocket (NTR) provide for a propulsion system that can reduce transit times, reduce initial mass to low Earth orbit (IMLEO) and permit greater shielding from cosmic rays for crew safety. In addition, the National Research Council (NRC) also identified rapid crew transit as a top technical challenge, and identified NTP as a high-priority technology for in-space propulsion technology development.[2] A number of mission architecture studies have been conducted to date, and Figure 1 shows one architecture concept for a NTP Mars transfer vehicle.

In 2012, NASA initiated the Nuclear Cryogenic Propulsion Stage (NCPS) project, now called the Nuclear Thermal Propulsion (NTP) project, to re-start development on a NTR and to address some of the developmental concerns. The NTP project is tasked with investigating the following: (1.) fuel materials, either zirconium-carbide (ZrC) composite or tungsten uranium oxide ($W\text{-}UO_2$) Ceramic metallic (CERMET); (2.) engine design; (3.) laboratory testing of fuel elements in a non-radiation environment; and (4.) ground testing of a small NTR at full power and full duration.

One of the key challenges of developing a nuclear thermal rocket is conducting verification and development tests on the ground, as identified in objective (4.) above. Ground testing is not uncommon to engine development programs, as the developer would like to have a controlled environment to verify the performance and characteristics of an engine before putting it into the space environment, putting payloads at risk, and having the engine beyond reach to mitigate design risks. However, NTR have much greater hurdles to face when planning ground test operations. While the former nuclear rocket programs, Project Rover and the Nuclear Engine for Rocket Vehicle Applications (NERVA) program, could test in open atmosphere, today's development efforts do not have that ability due to increased environmental and government regulations. Thus, methods need to be identified for ground testing nuclear thermal rockets which are sensitive to the environmental regulations of our day. This is compounded even more in today's political and national security sensitive environment, where concerns of handling large quantities of highly enriched fuel create even greater testing sensitivities. Since ground testing of an NTR is one of the more costly aspects of the program, numerous studies have investigated methods for affordable development testing an NTR on the ground within a limited budget. Various methods, including full-containment, above-ground exhaust filtration, and subsurface active filtration of exhaust (SAFE), also referred to as "borehole" testing, have been identified and studied. One of the leading concepts is the SAFE method, but it requires non-nuclear validation before it is applied to a small-scale nuclear rocket test.

Figure 1: Nuclear Thermal Propulsion (NTP) Mars transfer vehicle concept

II. History of NTP

Testing of nuclear rockets began in the late 1950's as part of Project Rover. The project, initiated by the Los Alamos Scientific Laboratory (now known as Los Alamos National Labs), tested a series of nuclear reactor engines of varying size at the Nevada Test Site, now referred to as the Nevada National Security Site (NNSS). The Kiwi, Phoebus, and Pewee engines, ranged in thrust scale from 111 kN (25 klbf) to 1.1 MN (250 klbf). Additionally, Project Rover included the Nuclear Furnace-1 (NF-1) tests. Project Rover was seminal in demonstrating the viability and capability of a nuclear rocket engine and test program with the goal to assess the feasibility of a hydrogen cooled reactor engines. As an interesting historical note, President Kennedy's special address to Congress (25 May 1961), which included his famous call to land a man on the Moon, also included the statement: "Secondly…accelerate development of the Rover nuclear rocket. This gives promise of someday 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." Figure 2 shows drawings of the various engine configurations tested during the Rover program.

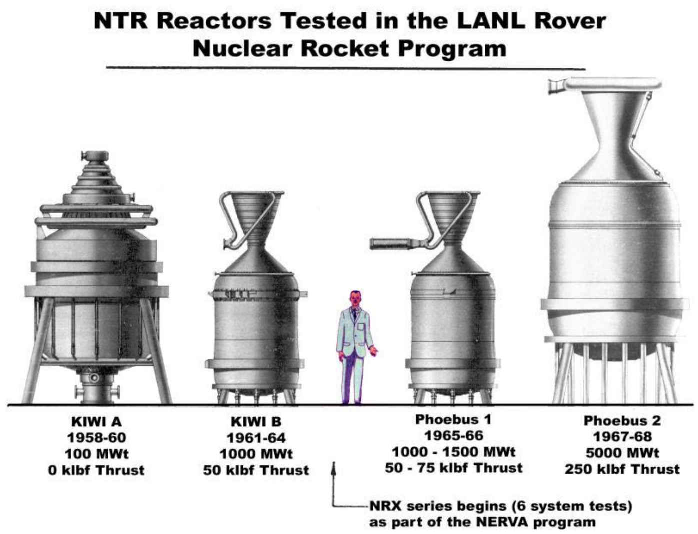

Figure 2: Drawings of various Project Rover NTR Reactors

The second major test effort was the Nuclear Engines for Rocket Vehicle Applications (NERVA) project. The Atomic Energy Commission (AEC) and NASA partnered to establish the Space Nuclear Propulsion Office (SNPO) and began project NERVA. NERVA was a parallel effort which overlapped some of the work on Project Rover, and began in early 1964. While Project Rover was focused on more fundamental research, NERVA was focused on technology demonstration. Like Project Rover, tests occurred at the Nevada Test Site. The NERVA program tested the NRX series of engines, as well as the XE′ engine. The XE′ engine was a 245-kN (55-klbf) engine that demonstrated optimum startup and shutdown sequence. Figure 3 shows a drawing of a potential NERVA flight engine concept.

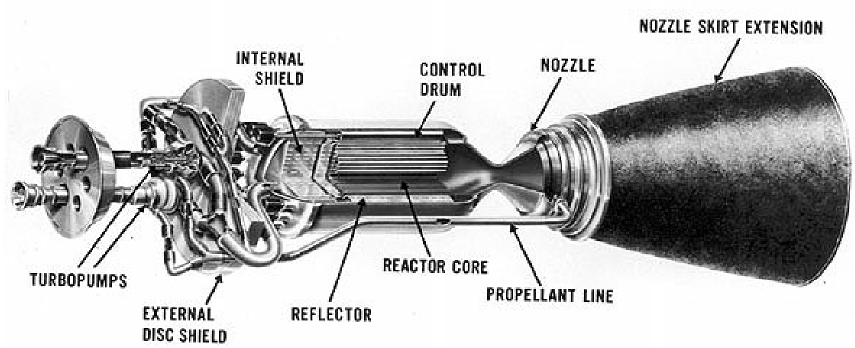

Figure 3: Drawing of potential NERVA flight engine

While testing of the Rover/NERVA engines were largely successful, one issue did continue to plague the development program, which was the issue of mid-band corrosion of the fuel elements. Rover/NERVA elements were largely a graphite composite matrix, in hexagonal form, as shown in Figure 4. Due to the high temperature, high pressure hydrogen propellant, the fuel elements were susceptible to a corrosion and cracking phenomena, leading to mass loss of nuclear fuel. This loss of nuclear fuel ultimately alters neutronics within the engine, degrades performance of the engines, and impacts the overall life of the system. While fuel element coatings were used to minimize this corrosion effect, those employed during Rover/NERVA were insufficient to completely mitigate the issue.[3]

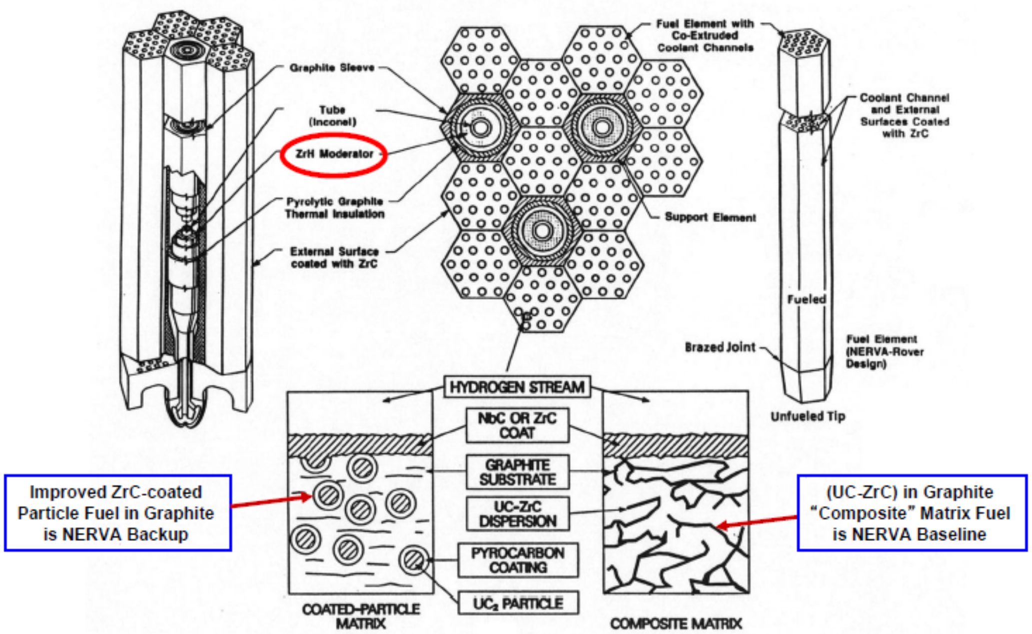

Figure 4: Heritage Rover/NERVA fuel element configuration

Ultimately Rover/NERVA was cancelled in 1973, but not before achieving a TRL 6 level of development. It also demonstrated the capability of a NTR system to achieve greater than 800 s of specific impulse. Much of the present design and understandings in the current NTP program are heritage from the Rover/NERVA programs.

III. Ground Test Options

With the exception of the NF-1 tests, ground testing of the Rover/NERVA engines were conducted in open air. NF-1 utilized a filtered exhaust approach to testing. Today, open air testing would not be permissible due to the risk and experience with fuel corrosion seen during Rover/NERVA. Yet due to the high-cost and risk of a mission to launch a nuclear rocket into space and utilize an NTR, it is still desirable to conduct some level of ground tests of the engine prior to flight to verify operation and performance. There are several methods for conducting ground tests, which are outlined here.

A. Open-Air Testing

The earliest and perhaps least expensive method for testing a NTP rocket would be to conduct open-air testing, preferably at a remote site. Here, the rocket would be placed on a test stand, and fired into the open atmosphere much like any typical sea-level testing of a traditional chemical propulsion rocket. As noted, this is how much of the testing during Project Rover/NERVA was conducted. Figure 5 shows a picture of a NERVA rocket firing in open atmosphere.[4] The risk with this method is the possibility of radionuclide expulsion from the engine should the fuel rods begin to degrade, as was noticed with Rover/NERVA. Since the 1970's, environmental considerations and government regulations have ruled this test option out from future possibility.

B. Above-Ground Scrubbers

The next possible consideration is to connect the rocket nozzle to a scrubber system to filter the exhaust and capture any radionuclides expelled by the engine. In this test option, the rocket exhaust is still expelled to atmosphere, but after having been passed through a number of filters and heat exchangers. The filtered exhaust (hydrogen-rich) is ultimately burned off in a flare stack. This was the method utilized during the Nuclear Furnace (NF-1) test series during the Rover project. A sample scrubber schematic is shown in Figure 6.[5]

Figure 5: NERVA tests in open atmosphere (from: AIAA 2011-5849)

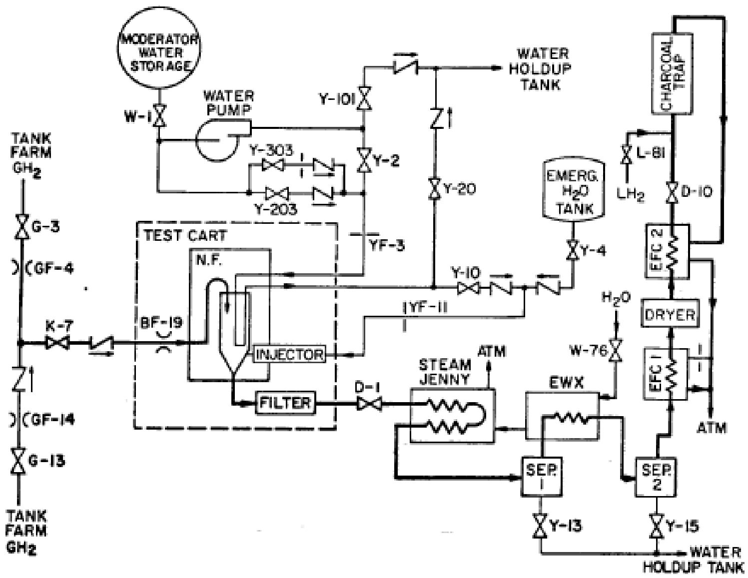

Figure 6: Nuclear Furance-1 (NF-1) Scrubber System (from AIAA 1989-2386)

C. Full-Containment

Another possible test option, would be to just capture all the exhaust of the engine for later processing to remove any potential nuclides. It is similar to the above-ground scrubber option, but the exhaust is not expelled to atmosphere directly. Instead, it is burned with additional oxygen to create oxygen-rich steam, cooled by heat exchangers and converted to liquid water, and the water collected into large storage tanks. Filters and particle traps along the way capture any condensable nuclides. The stored water is then slowly filtered into retention ponds for evaporation. Any excess non-condensable gases (e.g. remaining oxygen) are then collected and vented off to be burned. Figure 7 shows a schematic of a full-containment concept.[6]

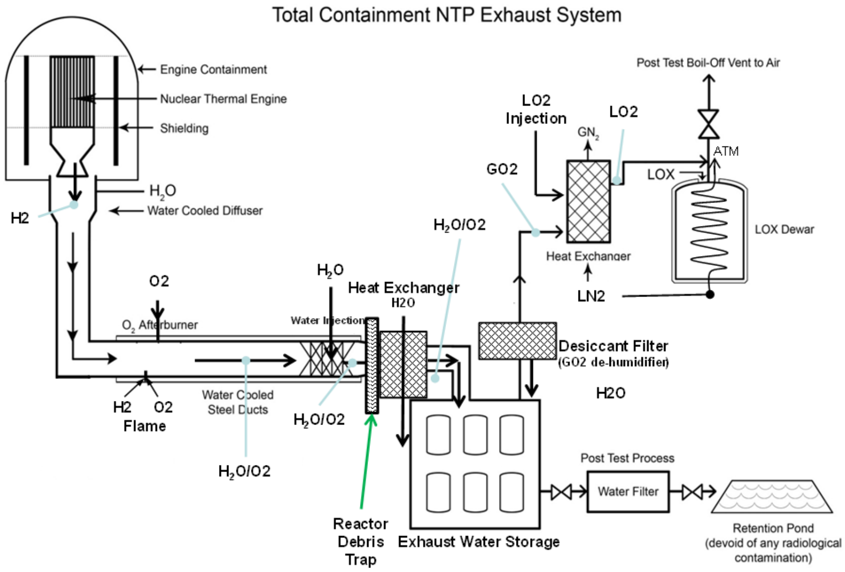

Figure 7: Conceptual schematic of a full containment NTP ground test system (from: NETS2015-5146)

D. Sub-surface Active Filtration of Exhaust (SAFE)

First envisioned in 1998, the Sub-surface Active Filtration of Exhaust (SAFE) concept utilizes the natural geology of the soil (alluvium) at the Nevada National Security Site (NNSS).[7-9] It was envisioned that this test method would be more cost effective due to the reduced build-up costs compared to a full-exhaust, scrubber type facility. The concept would take an existing borehole (left over from below-ground nuclear weapons testing) at the NNSS, place the rocket over the hole, and fire into the ground. Water spray would help cool and condense the exhaust. The exhaust would then vent through the porous alluvium soil, which would allow the soil to behave as a filter to capture nuclides. A conceptual drawing of a SAFE test set-up is shown in Figure 8. Due to the availability of boreholes at the NNSS and the relative lower-cost compared to other ground test options, particularly in building up scrubber systems, the SAFE concept is being viewed as the preferred ground test option plan going forward under the NTP project.

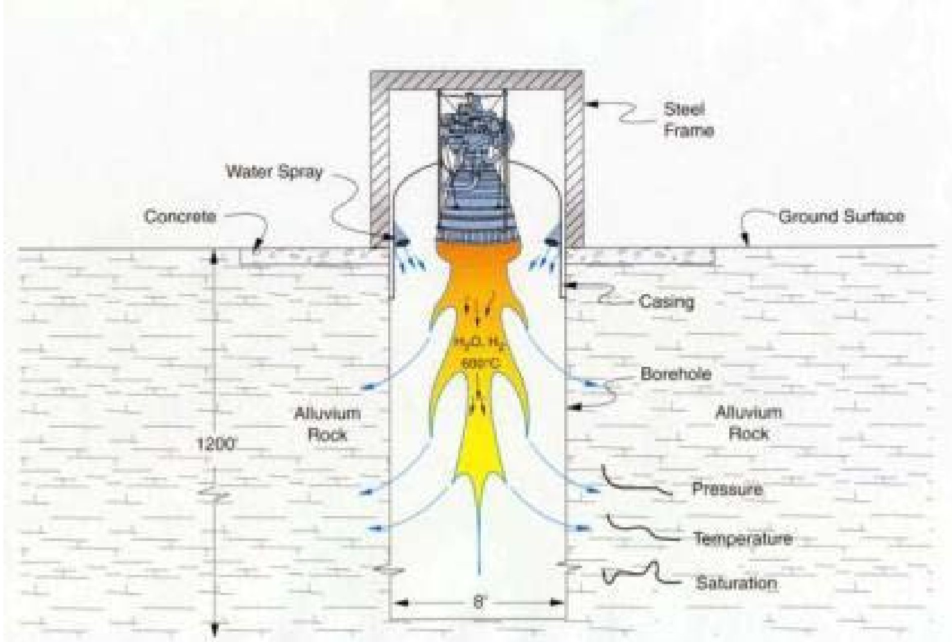

Figure 8: Conceptual drawing of SAFE test set-up (Source: Steve Howe, CSNR)

IV. Validation Plans for SAFE Concept

Before ground testing of a full-scale NTR can be accomplished using the SAFE concept, however, the concept needs to be validated. A number of studies have been conducted looking at the various soil characteristics and concept of testing at the NNSS.[9-11] While these studies have been useful in providing insight, it is still desirable to validate by conducting a series of sub-scale, non-nuclear rocket engine firings in a manner similar to a full-scale test. These sub-scale firings would seed the exhaust of the rocket with a detectible nuclide (such as Kr or Xe) and place sensors in satellite boreholes around the main borehole to detect if the nuclides are carried out by the buoyant forces of the hydrogen-rich exhaust gas.

The sub-scale, non-nuclear tests would utilize a hydrogen-oxygen (H_2-O_2) rocket as the test article. Aerojet Rocketdyne has proposed utilizing their Liquid oxygen Augmented Nuclear Thermal Rocket Simulator (LANTR), a non-nuclear hydrogen-oxygen rocket with oxygen afterburner, which simulates the exhaust products expected from a full-scale NTR test. Figure 9 shows a schematic of the LANTR mounted to a borehole cap. The use of a pre-existing, smaller borehole at NNSS will enable validation at reduced cost, while providing data that can be readily scaled for a full-size NTR or small nuclear rocket engine (SNRE). A mobile test platform will be installed over the borehole, with a mobile control center nearby, and a series of ground instruments placed around the borehole in the sub-surface geology. Figure 10 shows a model of the proposed test platform, with the LANTR in the center. The rocket exhaust will be traced using xenon (Xe) or krypton (Kr) gas, and the sub-surface effluents monitored around the borehole. Some studies have already been conducted to investigate the potential diffusion of ^{85}Kr in the soil, as shown in Figure 11.[9] However, these models used air exhaust, and didn't take into account hydrogen buoyancy effects. Some preliminary efforts have sought to understand the impact of hydrogen buoyancy within the alluvium soil around the test site. Figure 12 illustrates some of the buoyancy concerns. Non-nuclear sub-scale tests, with the proper exhaust constituents, will further lend confidence that the alluvium soil will trap any fission products, should they be released during an NTR test.

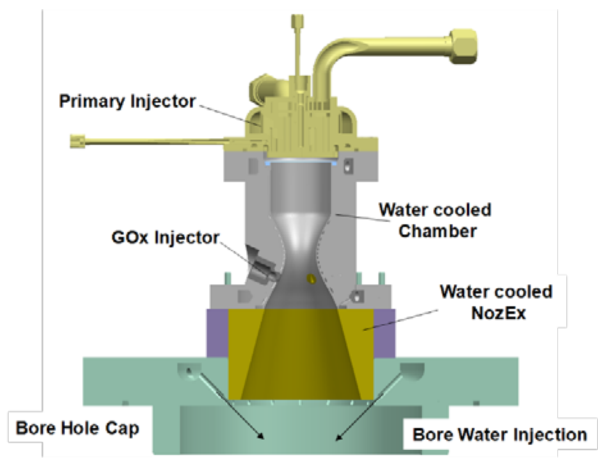

Figure 9: Schematic of LANTR mounted to borehole cap (from AIAA-2012-3743)

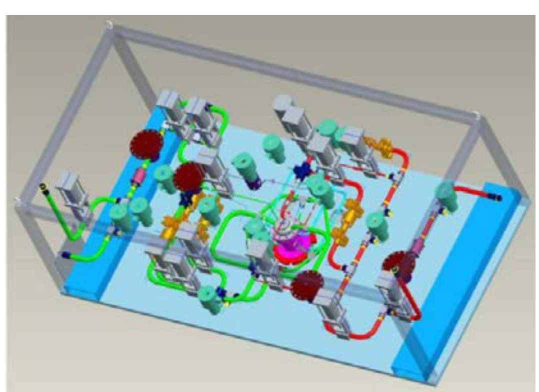

Figure 10: LANTR test article platform for SAFE testing (from AIAA-2012-3743)

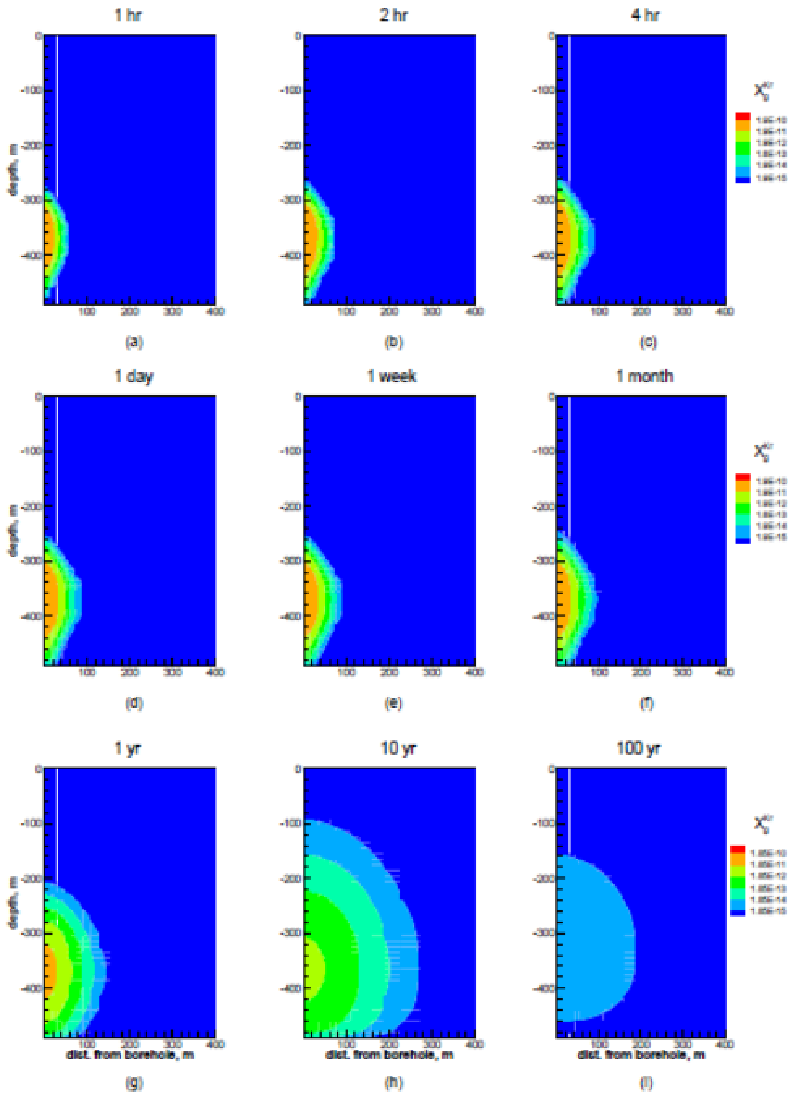

Figure 11: Mass fraction of ^{85}Kr between 1hr and 100 yr through a 100 m interval from sub-scale SAFE testing (from AIAA-2012-3743)

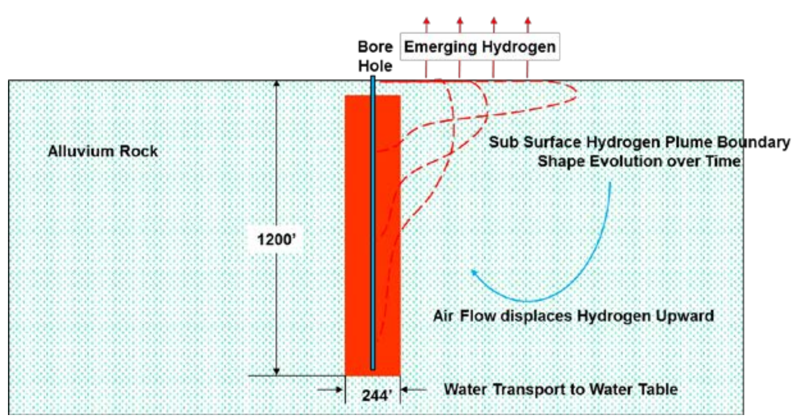

Figure 12: Figure illustrating potential hydrogen diffusion over time to surface following NTR SAFE test.

V. Alternative SAFE Concepts

Because of security regulations and the amount of highly enriched uranium (HEU) present in a SNRE-scale engine, above ground testing may pose additional costs which could be reduced if the test set-up was located below ground. This is due to the fact that even at the NNSS, a security perimeter, per Federal regulations, must be maintained due to the presence of the quantities of HEU and the accessibility of the site. Fortunately, NNSS has facilities which provide the capability for below-ground testing, which could also lower the security requirements due to more limited accessibility. As an alternative test method to a borehole, a previously excavated horizontal tunnel test at the NNSS could be utilized. Two options are being investigated as alternative SAFE concepts. They still rely on the use of soil or geologic features to capture or filter exhaust, but are variations on the previously defined SAFE method.

The first alternate concept is locating the test in the U-1a complex at the NNSS. The U-1a site is a below ground test complex, a series of inter-connected tunnels, where sub-critical nuclear tests can be conducted. For the NTP ground tests, a dedicated tunnel could be dug to accommodate the NTR, with a parallel drift serving as a temporary diagnostic (hot-cell) and preparation chamber. Should an incident occur causing a release of fissile material, or otherwise preventing safe conditions for personnel to approach the engine, the engine would already be located in such a manner that entombment could easily occur, providing an added measure of safety. Having a parallel drift serving as a temporary hot-cell would also reduce the need to transport the reactor off-site for hot-cell disassembly. The soil in the U-1a complex is also alluvium, similar to that of the planned borehole tests. As in borehole testing, site selection would be determined in a location free of faults, voids and other penetrations. Similar data collection to the borehole tests would be conducted.

A second alternative test method would be to locate the test article within the P-tunnel mountain complex at the NNSS. The P-tunnel set-up would be similar to that of the U-1a set-up discussed above. However, P-tunnel has solid rock walls as opposed to a more porous alluvium. The rock walls could help to provide heat dissipation reducing the need for water spray cooling. Heat exchangers could be used to condense the exhaust to help reduce pressure build-up. Since the NTR should ideally not produce fissile material during normal operation, a flare stack at the end of the run could be utilized to burn off excess exhaust. This would also help to regulate the pressure build-up in the tunnel during a test run. Nuclide detectors capable of measuring radionuclides would detect if any fissile material was released and would quickly close special valves to seal off the flare stack before the nuclides reach atmosphere. Figure 13 shows a concept of the P-tunnel test set-up.[6]

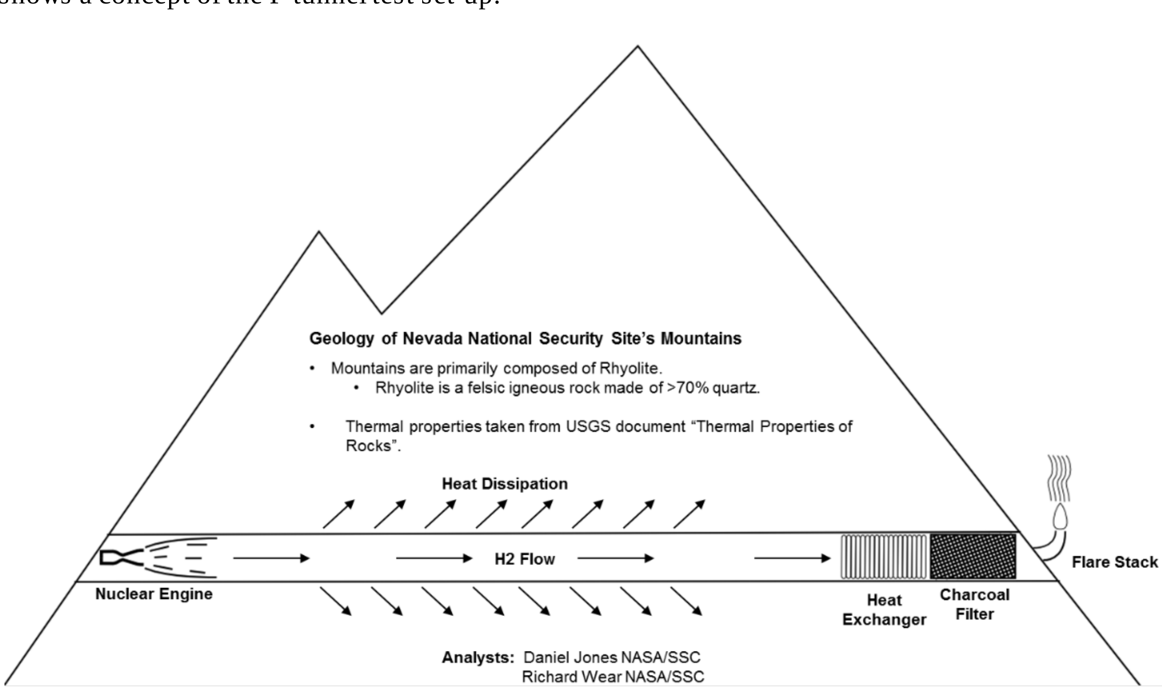

Figure 13: Concept of P-tunnel test set-up (From NETS 2015-5146)

VI. Recent Assessments

One of the challenges to assessing the costs and schedule of a ground test campaign is the history of NTP efforts conducted previously. Various engine sizes, ranging from 7 klbf to 75 klbf have been proposed at various times in the nuclear rocket program history. Past efforts to study the costs and feasibility of ground test options have not necessarily conducted apples-to-apples comparisons in scale, due to the shifting program requirements on engine size. While some cost drivers are independent of engine size, the order of magnitude difference between engine sizes can still lead to large cost differences in ground test options. For instance, a 2006 effort by the ARES Coporation reviewed ground test costs for a 222-kN (50-klbf) engine, while the current NTP program is looking towards a 34-kN (7-klbf) to 73-kN (16-klbf) engine class. The review also assumed a 25-year facility operation cycle, which may not be expected in the current program. An effort is underway to review historical cost proposals, and confirm scales to get a better understanding of how engine size and operation life-cycle impacts costs. Additionally, since assessments have been periodically conducted over the years since the late 1980's/1990's, cost inflation effects have also presented confusion between assessment efforts for comparative purposes.

The most recent assessments on SAFE testing costs have been conducted by the National Securities Technology (NSTec) Corporation, which completed two assessments in 2011. The first estimated cost of SAFE testing a NTR at full power and duration and the second estimated cost of performing the sub-scale non-nuclear validation SAFE testing using the LANTR rig from Aerojet Rocketdyne. The estimates from NSTec were based upon a 1999 estimate and test configuration conducted by Bechtel Nevada, and took into account inflation and changes in the regulatory environment, as well as a few other assumptions regarding the nature of the test. The sub-scale validation test estimates were made independently, and included the costs of preparation of the test site, drilling test boreholes and satellite holes, construction of protective berms, installation of trailers, feed systems (water, purge gases, propellants, etc.) and instrumentation, and needed security features. Costs were also provided by Aerojet Rocketdyne for support of the test series and reactivation of the LANTR rig.

Even with these recent estimating activities, there is still an ongoing discussion on what cost drivers impact ground test cost and schedule. Furthermore, due to government regulation, the Department of Energy is considered the owner and regulator of a proposed test site. Efforts are currently underway to engage NASA and Department of Energy (DOE) stakeholders to fully understand the regulatory and programmatic requirements to any ground test campaign, those impacts to cost and schedule, and how appropriate exemptions and interpretations may be applied. Regardless of what site may be used, or what test method is used, sub-scale validation tests will still be required for the SAFE method.

VII. Conclusion

Nuclear thermal propulsion is an enabling technology for Mars missions and beyond. However, before a nuclear rocket can be put into space and operated, ground testing must occur. A number of possible ground test options are presented. The Sub-surface Active Filtration of Exhaust (SAFE) concept is presently seen as a preferred method for ground testing. However, the SAFE concept must be validated. While some initial studies have looked at viability of the concept, a validation approach would include a sub-scale, non-nuclear test using a hydrogen/oxygen rocket in a borehole, seeding the exhaust with detectible radionuclides. Alternative methods, such as below-ground or mountain drift testing could build on the SAFE concept and provide reduced security infrastructure requirements. Discussions between the Department of Energy and NASA are ongoing to discuss regulatory and programmatic requirements of a ground test campaign, and how to best move forward on developing a ground test article.

Acknowledgments

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