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Steven D. Howe
David Bedsun
Deborah Lee
Margaret Townsend
Clay A. Cooper
Jennifer Chapman
Mel Bulman
Ronald Samborski
Daniel Brasuell
Stanley Borowski

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Ground Testing a Nuclear Thermal Rocket: Design of a sub-scale demonstration experiment

Steven D. Howe[1], David Bedsun[2], Deborah Lee[2], Margaret Townsend[2], Clay A. Cooper[3], Jennifer Chapman[3], Mel Bulman[4], Ronald Samborski[4], Daniel Brasuell[4], Stanley Borowski[5]

[1] Center for Space Nuclear Research, 995 University Blvd., Idaho Falls, ID 83415
[2] Nuclear Security Technologies, LLC, Las Vegas, NV
[3] Desert Research Institute, Reno, NV
[4] Aerojet Corp, Sacramento, CA
[5] NASA Glenn Research Center, Cleveland, OH

In 2008, the NASA Mars Architecture Team found that the Nuclear Thermal Rocket (NTR) was the preferred propulsion system out of all the combinations of chemical propulsion, solar electric, nuclear electric, aerobrake, and NTR studied. Recently, the National Research Council committee reviewing the NASA Technology Roadmaps recommended the NTR as one of the top 16 technologies that should be pursued by NASA. One of the main issues with developing a NTR for future missions is the ability to economically test the full system on the ground. In the late 1990s, the Sub-surface Active Filtering of Exhaust (SAFE) concept was first proposed by Howe as a method to test NTRs at full power and full duration. The concept relied on firing the NTR into one of the test holes at the Nevada Test Site which had been constructed to test nuclear weapons. In 2011, the cost of testing a NTR and the cost of performing a proof of concept experiment were evaluated.

Nomenclature

GCR - Galactic Cosmic Rays

LANTR - Lox Augmented Nuclear Thermal Rocket

MAT – NASA Mars Architecture Team

NSTec - National Security Technologies

NTS - Nevada Test Site (now Nevada National Security Site)

NERVA - Nuclear Engine for Rocket Vehicle Applications

NCSP - Nuclear Cryogenic Stage Program

NTR - nuclear thermal rocket

Isp - specific impulse

SAFE - Subsurface Active Filtering of Exhaust

I. Introduction

Several studies [1,2,3] have shown the potential benefit of using a nuclear thermal rocket (NTR) for in-space propulsion instead of chemical systems. Because of the high specific impulse (Isp) and high thrust capabilities of the NTR, the mission profiles can be 1) reduced in transit time, 2) have substantially lower initial mass in low Earth orbit, or 3) contain significantly more shielding against Galactic Cosmic Rays (GCR).

In 2008, after comparing several combinations of solar electric, nuclear electric, aerobraking, chemical, and nuclear thermal propulsion systems, the NASA Mars Architecture Team (MAT) released a report identifying the NTR as the preferred technology for a human mission to Mars [4]. In 2012, the National Research Council committee reviewing the NASA Technology Roadmaps [5], recommended 16 technologies out of the 330 reviewed for NASA to pursue as high priority—the NTR was third.

Consequently, in 2012, NASA initiated the Nuclear Cryogenic Stage Program (NCSP) to start the development of a NTR. The NCSP is examining 1) fuel materials, 2) engine design, and 3) laboratory testing of fuel elements in a non-radiation environment, and 4) ground testing of the NTR at full power for full duration.

The full power ground testing issue is considered one of the long poles in the program due to potentially high costs. Previous studies [6,7] had examined the cost of building a containment test facility and of using the Subsurface Active Filtering of Exhaust (SAFE) method. As part of the NCSP, a study was performed to evaluate the costs of testing a NTR using the SAFE technique. In addition, the study evaluated the cost of performing a sub-scale, proof of concept test to verify that the SAFE technique was valid. This paper summarizes the results of the cost evaluation of the sub-scale experiment.

II. History of nuclear thermal propulsion

In 1955, the Los Alamos Scientific Laboratory (LANL) began the Rover program [8] to develop a solid core nuclear rocket engine. The basic concept was to allow a graphite-fuel based nuclear reactor to reach high temperatures, to cool the reactor with clean hydrogen, and to exhaust the high-speed hydrogen for thrust. The advantages were seen to be shorter trip times, lower mass in orbit, and no possibility of accidental explosion.

In 1963, the Nuclear Engine for Rocket Vehicle Applications (NERVA) [9] began with Aerojet as the prime contractor and Los Alamos as a supporting contributor. The goal of the NERVA program was to transform the nuclear reactor technology developed by Los Alamos and produce a space qualified nuclear engine. Both the Rover and NERVA programs were terminated in 1972.

Before termination, however, the Rover/NERVA programs built and tested 23 reactors/engines, achieved fuel temperatures in excess of 2550 K, ran a reactor with a peak power of greater than 4000 megawatts, operated a system for over an hour, demonstrated start-up and shut-down operations, and proved that the graphite based reactor core could withstand the extreme conditions of operation [10]. The exhaust of the engine in the final days of the program was calculated to have a specific impulse of near 850 seconds, almost three times the performance of the kerosene engines of the Saturn V and twice that of the soon-to-be-developed LOX/hydrogen engines of the Space Shuttle. The impact of this performance would have been to reduce the trip time of a manned Mars mission from the 2.5 years, possible with chemical engines, to about 14 months.

In addition to the engine performance milestones, the Rover/NERVA efforts also demonstrated that the exhaust from a nuclear engine could be "scrubbed" clean of all fission products [11]. As the result of increased restrictions on emission of radioactivity into the atmosphere, the Nuclear Furnace was built in order to continue testing new fuel-element materials. The Furnace consisted of a 45 MW reactor in which many of the fuel elements could be replaced with experimental elements to assess behavior such as corrosion.

The Nuclear Furnace reactor was followed by a sequence of filters to clean the effluent. After passing through the reactor, the hydrogen exhaust was sprayed with steam to cool the gas and remove any particulates. The 1 kg/s flow then passed through a tube-and-kettle heat exchanger to further reduce the temperature. Next, the gas flowed through a silica gel bed to remove the water and any dissolved fission products. At this point, the only remaining products were the noble gases that were removed by passing the gases through a cryogenically cooled, activated charcoal bed. The result was a hydrogen jet that contained no detectable fission products.

Although the ability to clean the exhaust of fission products was demonstrated in the Rover/Nerva programs, any new program to develop a NTR may find the cost of such a method to be preclusive. Scaling up the flow rates from the 1 kg/s in the Nuclear Furnace to the 10 kg/s for a 20,000 lbf NTR could cost between $200-500 M [12]. Such a facility would required a significant human operations workforce and generate tons of waste that would need to be stored for long periods. In addition, if a new, improved fuel form can be manufactured that does not allow fission products to enter the exhaust stream, the need for a scrubbing facility is reduced to being an off-nominal, accident control facility.

In the late 1990s, one of us (Howe) developed the SAFE concept. This concept would utilize the methodology employed for nuclear weapons tests by injecting the exhaust from the NTR directly into the sub-strata at the Nevada Test Site. The SAFE concept would be simpler, less expensive from a capital cost standpoint, less expensive to operate, and allow any power level of NTR to be tested for full duration.

In 1999, the NASA Marshall Space Flight Center (MSFC) funded the first design and cost assessments of the SAFE concept [7]. The study was carried out by the Los Alamos National Laboratory and the prime contractor at NTS, the Bechtel Nevada Corp. The calculations of gas pressure and temperature exiting the reactor, and the diffusion of the gases into the alluvium strata were executed by LANL. The cost estimates for the test of a NTR and for a feasibility demonstration using a RL-10A engine were made by Bechtel Nevada.

The results of the study indicated that the feasibility test could be executed for $5M and that a NTR could be tested for $16M (all in 1998 dollars). Thus, the SAFE concept could allow a NTR to be safely ground tested for far less investment that a surface scrubber facility.

A. NEVADA TEST SITE

Until 1992, the primary use of the Nevada Test Site (NTS) had been to host the underground nuclear testing program performed by the Department of Energy laboratories. The site is situated 65 miles northwest of Las Vegas, Nevada, and encompasses over 1350 square miles. The area is geologically stable, experiences around 3 inches of rainfall per year, and has felt over 300 nuclear tests. Consequently, after so many years of such testing, the geology of the test site is believed to be extremely well characterized.

A large fraction of the NTS is composed of a thick layer of alluvium laid down by prehistoric inland seas. The alluvium is, essentially, packed sand that has a permeability of around 40 Darcys. The thickness of the alluvium varies greatly but can reach depths over 500 m. Because of the nuclear weapons testing in the past, a substantial infrastructure exists at NTS to support the safe handling of radioactive materials. In addition, significant experience is present to perform complex experiments. These capabilities make the NTS an excellent location to site the SAFE tests.

III. SAFE concept

The US nuclear weapons testing program detonated many nuclear devices at the NTS. Consequently, the sub-surface geology of the NTS is extremely well known. Over the years, several computational models were developed that accurately describe the diffusion of gases and fluids through the NTS geological strata.

The basis of the SAFE concept relies on the porosity of the alluvium layer to act as a filter. In essence, the concept proposes to put the nuclear rocket at the top of a standard, 8 foot diameter hole typically used for weapons tests as shown in Figure 1. The top of the hole will have a concrete slab coupled to a steel dome that seals around the nozzle throat of the engine and seals the hole. As the rocket fires the effluent into the hole, pressure will build. Eventually the pressure will reach a level where the amount of gas and water vapor driven into the porous rock equals the mass flow of the rocket. Consequently, the rocket can be operated for long periods over a relatively wide range of power levels. Thus, the requirements of the engine may be determined at a later stage in the program - no constraints are imposed by the capacity of a testing facility.

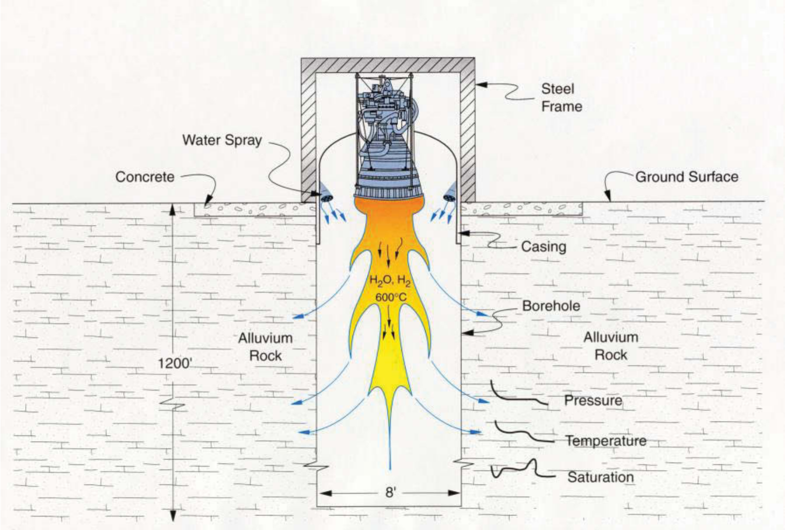

Figure 1. Schematic of the SAFE concept showing a NTR sealed over a standard hole at NTS.

The results of using calibrated diffusion codes to model the SAFE concept in 1999 were reported previously [7] 2003 paper. The concept was to incorporate a spray ring of water at the nozzle lip to cool the exhaust from 3000 K to 873 K. The combination of hydrogen and water vapor would then fill the hole and diffuse into the soil. The results showed that an engine of any size could operate over the hole for many hours. After about two hours, an equilibrium pressure of about 35 psi was reached. The codes showed that the water vapor would condense in the alluvium at around 1 m depth. The results indicate that if any radioactivity were present in the exhaust, the alluvium will capture the material and hold it—just as it has held the residuals from weapons tests for decades.

The study performed in 1999 estimated a total cost of $16M in infrastructure development at NTS to be able to test a NTR. The study also recommended that a proof of concept test using a RL-10a be executed for $5M. Both estimates are in 1999 dollars. These results showed that the SAFE method could be substantially more affordable for testing NTRs than a surface test facility. This is especially true if the exhaust does not contain any radioactive fission products which may be the case if the tungsten cermet fuel development program succeeds.

In 2011, the cost of testing a NTR at NTS was again evaluated. The dispersion of the exhaust into the soil was calculated using an independently developed diffusion code at the Desert Research Institute (DRI). The later study also recommended a proof of concept, sub-scale experiment to validate the code predictions.

IV. Dispersion Calculations

Numerical simulations were conducted to investigate the transport of gas, water vapor, and radionuclides from the borehole to the surrounding formation. Two active phases (gas and liquid) were simulated with five components: air, water, radiogenic tracer (^{85}Kr), tracer decay product (stable ^{85}Ru), and heat. Flow equations for the gas and aqueous phases were modeled with Darcy's law, solute transport in both phases with Fick's law, and conductive heat transport with Fourier's law. Mass (heat) transport occurs via fully coupled advection and diffusion (conduction) through both phases, with allowances for exchange between phases. A complete description of the governing equations is described in Pruess et al. [13]. The computational domain was arranged as radially symmetric flow, with an injection borehole in the center. The domain size extends from the face of the borehole (1 m radius) to 10,000 m, which is large considering the 100 yr timescale of the model. Vertically, the domain exists from the land surface to the 490 m deep water table. Hydraulic boundary conditions are prescribed flux along the injection interval and zero flux along the rest of the borehole, prescribed pressure along the upper (atmospheric) and lower (water table) horizontal boundaries, and prescribed gas static pressure along the outer vertical boundary of the cylinder. Porous media property data were obtained from characterization studies of Frenchman Flat [14].

Proper design of the injection facility requires that two criteria be met: (1) total (absolute) pressure in the borehole may not exceed 0.24 MPa (absolute), and (2) volume of subsurface contaminated with radioactive gas be minimized. Through a series of simulations, we determined that the optimum injection interval is 100 m.

A simulation where 600 ºC radioactive gas is injected through a 100 m interval for two hours is shown in Figure 2. Appreciable pressure differences extended outward for 40 m from the edge of the borehole for the first two hours of the test, while formation temperature and liquid saturation were affected to a distance of less than 2 m. The injectate immediately cooled and condensed upon entering the formation (the maximum temperature was 65 ºC), but never fully saturated the formation (the highest liquid saturation reached was 0.9). The pressure field decayed after four hours (two hours after the injection stopped); the saturation and temperature fields seen at four hours persisted for several months before dissipating to pre-injection conditions. The low grid resolution did not capture centimeter-scale behavior in the vertical direction such as downward drainage of water (as grid block heights were 10 m). The Bond number, $Bo = \rho g L^2 / \sigma$, where ρ is the density of water (M L^{-3}), g is acceleration due to gravity (L t^{-2}), L is a characteristic length (defined here as a "typical" pore diameter), and σ is the interfacial tension between air and water (F L^{-1}) is ~0.1; this suggests that capillary forces slightly outweigh gravitational forces, limiting downward drainage of liquid.

The mass fraction field of a gas tracer (as tracer density to gas density, X_g^{Kr} with the properties of ^{85}Kr) for the same simulation is shown in Figure 3. We estimated the initial inventory for a two-hour test as 283 mg radioactive Kr and Xe and assumed all radionuclides have the properties of krypton. For a two-hour test, the injection rate of tracer was 3.93×10^{-8} kg s^{-1}. Radionuclides came within 100 m of the land surface during the 100-year simulation. Within the first year of transport, the horizontal extent of radionuclide transport was forecast to be less than 150 m from the borehole. At approximately 10 years, radionuclides extended between 250 m and 300 m from the borehole, and by 100 years radioactive decay and low diffusion rate resulted in a radionuclide extent ~200 m from the borehole but with a mass fraction reduced to approximately four orders of magnitude below the initial mass fraction of the injectate.

The simulations did not consider the rise of a buoyant plume of hydrogen gas (i.e., buoyancy due to compositional differences between the injected gas and the surrounding unsaturated zone gas). A scale analysis suggests that this may be important [14], depending upon intrinsic permeability. We are currently preparing to investigate the role of compositional density differences using an updated version of the simulator used here. The model will also use updated permeability and porosity data that have been recently collected at Frenchman Flat. In addition, the thermophysical correlations (primarily density and viscosity) used in the model will be checked against existing data for the extreme temperatures used in the model.

V. Sub-scale experiment design

The studies by Bechtel-Nevada in 1999 and by National Security Technologies (NSTec) in 2011 indicate that the SAFE concept could be the most affordable method for testing a NTR if the gas diffusion rates are as predicted. Although several gas injection tests have been performed to calibrate the diffusion codes, none of the tests used hydrogen. Consequently, the codes need to be validated for a blend of hydrogen and water vapor.

During 2011, the authors met several times to define the goals of a sub-scale validation experiment and to define the experiment. The main goal was to produce an affordable experiment that could verify the computational model predictions. In addition, the mass flow, temperatures, and gas components had to reflect those that will be present in a NTR test. Furthermore, the diffusion and possible trapping of noble gases had to be experimentally addressed. Previous work indicates that almost all of any fission products, if present in the exhaust, will be trapped in the alluvium except the noble gases such a Xenon and Krypton. The test should determine if noble gases can also be trapped or, at least, diffuse to the surface over a long period.

A summary of the characteristics of a sub-scale test designed to answer the main goals is shown in Table I. The test will consist of injecting hot hydrogen produced by chemical combustion into a hole with a 0.61 m diameter. Temperature and pressure in the main hole will be measured. Three satellite holes of 0.305 m diameter will be placed around the main hole. The time of flight of the hydrogen to these holes will enable the diffusion rate to be

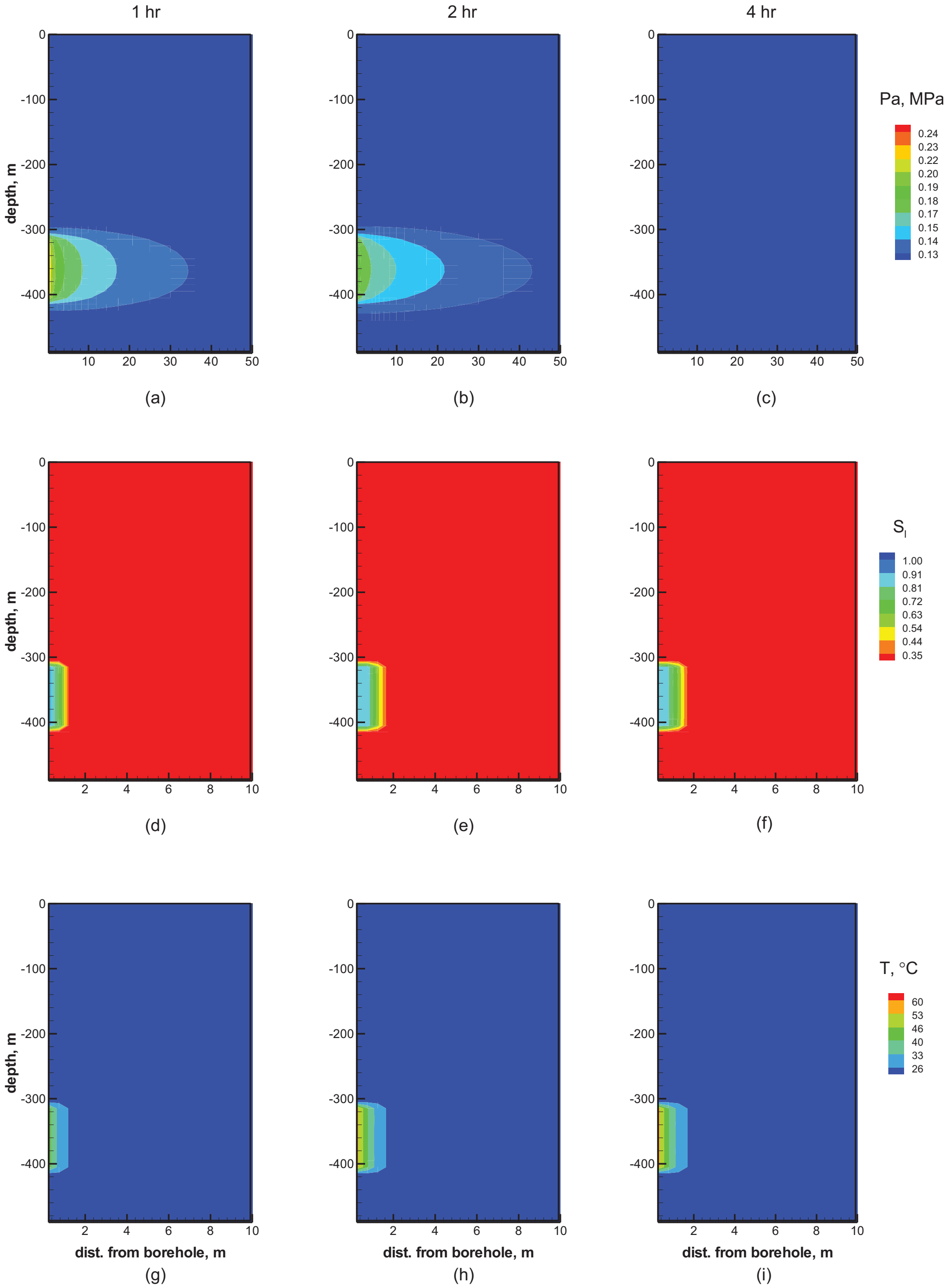

Figure 2. Pressure (upper row), liquid saturation (middle row), and temperature (lowest row) fields over a period of four hours after the start of injection. Injection stopped after two hours.

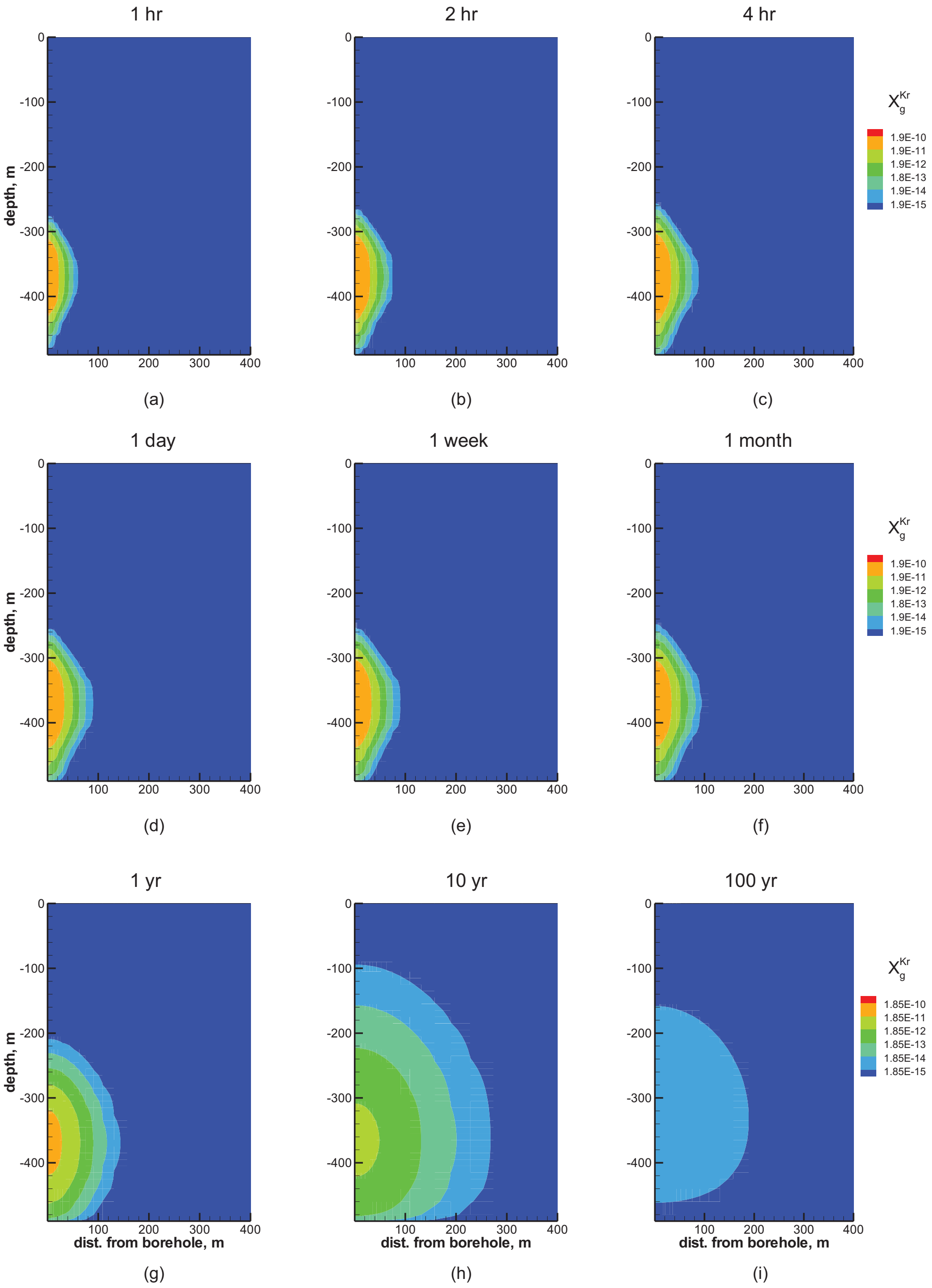

Figure 3. Mass fraction of ^{85}Kr between 1hr and 100 yr through a 100 m interval. The period of injection was between zero and two hours.

determined. Batch samples of gas will also be extracted from the satellite holes to look for xenon added to the hydrogen.

Table I. Summary of the sub-scale test characteristics

- Roughly 2 ft diameter hole is to be drilled- 300 ft depth
- Steel cased to 30 ft
- Concrete slab surrounds casing
- 3 separate 12” holes are drilled parallel to 300’ depth
    - 120 degree separation
    - 2m, 10m, and 30 m radial standoff
- Aerojet LANTR test rig can provide a hot hydrogen/steam mixture that properly simulates that produced by a dynamically scaled NTR
- Water spray at “nozzle” edge
- Nitrogen back fill before and after hydrogen test
- Valve shut after N2 fill
- Diagnostics
    - Pressure versus time in main hole
    - Temperature at top and bottom of main hole
    - Measure time to detection of H2 in three satellite holes
    - Measure moisture in satellite holes
    - Satellite holes have 1 segment vertically except hole #1 has 3 segments
    - Monitor Xe diffusion up through alluvium as a function of distance from hole using batch sampling and mass spec

The hot hydrogen/steam will be injected using an apparatus developed at the Aerojet Corporation as seen in Figure 4. The apparatus was originally used to demonstrate the Lox Augmented NTR (LANTR) concept [15] at the NASA Glenn Research Center. The injection apparatus is mounted in a test rig shown in Figure 5 which will be fitted to a collar attached to the top of the test hole.

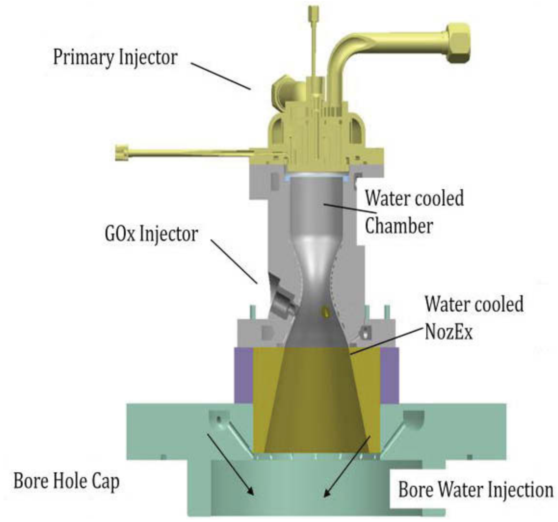

Figure 4. Hot hydrogen injection chamber built by the Aerojet Corporation. The unit was originally used to demonstrate the LANTR concept for NASA.

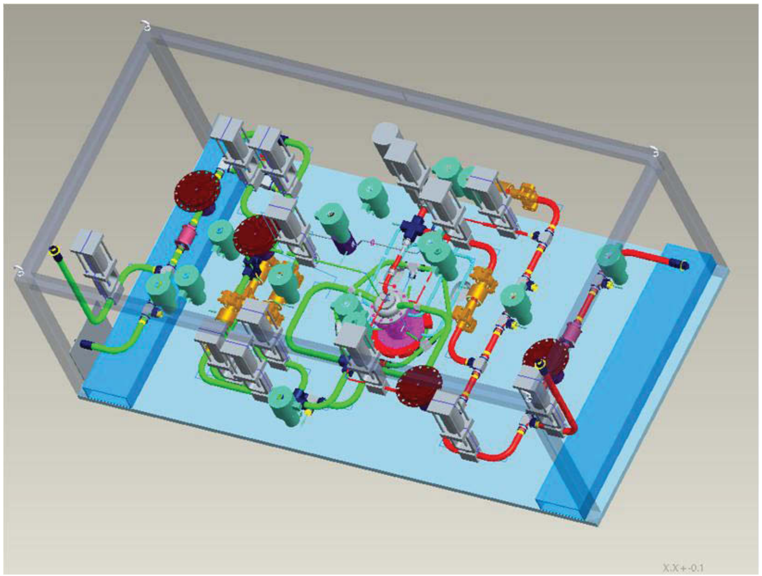

Figure 5. Test rig for the sub-scale SAFE test utilizing the Aerojet hot gas chamber.

VI. Cost Estimates

The NSTec Corporation is the prime contractor for operations on the NTS. During 2011, NSTec performed two assessments pertaining to SAFE testing – 1) estimated cost of testing s NTR at full power and full duration and 2) estimated cost of performing the sub-scale test suing the LANTR test rig from Aerojet.

The evaluation of the NTR test 1) keyed off of the Bechtel Nevada report from 1999, 2) accounted for inflation from 1999 to present, 3) accounted for changes in regulatory environment, 4) assumed that the NTR test utilized existing 8 foot diameter hole, and 5) assumed that the assembled NTR is delivered at the NTS gate and then taken away after testing and a cool down period. The total estimated cost of testing a NTR was $46,503,000 with 30% management reserve included.

The cost estimate for the sub-scale experiment was made independently from any previous estimates. The estimate included 1) preparation of the test site, i.e. roads, power, etc., 2) drilling and casing the four holes, 3) construction of an earthen berm around the test site, 4) installation of the instrument trailers, 5) installation of the instrumentation in the diagnostic holes, 6) installation of the various gas tankers, 7) installation of the water cooling system, and 8) construction of a safety fence. Costs were provide by the Aerojet Corporation with regard to 1) re-commissioning the LANTR test rig, 2) design and fabrication of an adaptor flange to couple the rig to the hole, 3) connecting the gas tankers to the rig, and 4) instrumentation for control of the LANTR rig.

The total estimated cost of performing the sub-scale test at NTS was estimated to be $3,870,000 including a 30% management reserve.

VII. Conclusions

Recent findings by NRC committees and NASA studies indicate the need for a NTR to support human and robotic exploration of the solar system. Development of a NTR will require ground testing at full power and full duration. Although the ability to scrub the NTR exhaust clean of any radioactivity was demonstrated in the Nuclear Furnace tests in the late 1960s, the power levels and mass flows of the NTR currently being considered would imply a test facility that would cost several hundred million dollars. In addition, if the new tungsten fuel form for the NTR is shown to inhibit the release of any fission products from the NTR core, i.e. the exhaust is clean, then the need to scrub the exhaust with a complex, costly surface facility is removed.

The SAFE concept was conceived to use existing infrastructure at the Nevada Test Site to affordably allow testing of a NTR. The estimated cost of testing the NTR is around $45 M using the SAFE method. If computational models are correct, the concept allows for engines of any size to be tested at full power and full duration, unlike the surface facility that will be designed for one power level. However, the computational models must be validated before proceeding with a major test program.

A sub-scale test using hot hydrogen injection into a suitably sized hole has been designed. The test will allow validation of the computational models by measuring time of flight of the hydrogen from the source hole to surrounding diagnostic holes. The test will also verify that noble gases in the hydrogen will be trapped or diffuse slowly through the geologic strata. The estimated cost for the sub-scale test is around $3.8 M.

Successful completion of the sub-scale test will support the use of the SAFE concept. The SAFE method enables a NTR to be tested affordably and in the short term. Thus, the SAFE method could enable the NTR to be developed in a shorter time frame allowing a new, high performance propulsion system to take humans to Mars and probes to the far reaches of the solar system.

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