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Abstract. Several studies over the past few decades have recognized the need for advanced propulsion to explore the solar system. As early as the 1960s, Werner Von Braun and others recognized the need for a nuclear rocket for sending humans to Mars. The great distances, the intense radiation levels, and the physiological response to zero-gravity all supported the concept of using a nuclear rocket to decrease mission time. These same needs have been recognized in later studies, especially in the Space Exploration Initiative in 1989. One of the key questions that has arisen in later studies, however, is the ability to test a nuclear rocket engine in the current societal environment. Unlike the Rover/NERVA programs in the 1960s, the rocket exhaust can no longer be vented to the open atmosphere. As a consequence, previous studies have examined the feasibility of building a large-scale version of the Nuclear Furnace Scrubber that was demonstrated in 1971. We have investigated an alternative that would deposit the rocket exhaust along with any entrained fission products directly into the ground. The Subsurface Active Filtering of Exhaust, or SAFE, concept would allow variable sized engines to be tested for long times at a modest expense. A system overview, results of preliminary calculations, and cost estimates of proof of concept demonstrations are presented. The results indicate that a nuclear rocket could be tested at the Nevada Test Site for under $20 M.

INTRODUCTION

In 2002, the NASA Administrator announced the creation of the Nuclear Space Initiative. One of the aspects of the initiative is to develop a nuclear propulsion system for unmanned exploration of the solar system. At present, this effort is focused on examining nuclear reactors to provide electrical power to low-thrust, high-specific impulse thrusters such as an ion thruster. In the near term, however, such systems may not reduce trip times significantly because of the high specific mass, greater than 50 kg/kw, offered by current designs. In addition, nuclear electric propulsion systems are complex and will not provide the necessary capability for fast human missions to Mars in the long run. Sometime in the next few decades, humans will attempt to land on the next planet. Reducing the trip time is the best method to ensure a safe trip. Reasonably-sized nuclear electric systems will not provide rapid transits. An alternative approach is to consider the development of a bi-modal nuclear system in which the reactor can operate as both a rocket for high thrust and an electrical power source for either payload support or secondary propulsion. In the opinion of one of the authors (Howe), any nuclear system will require demonstration of full-power operation in a ground-based test facility. The test facility for a rocket will be significantly different than that for an electrical power system. As the result of a study by the Los Alamos National Laboratory and the Bechtel-Nevada Corporation, a simple and relatively cheap method for testing nuclear rockets has been developed.

Several studies (Mendel, 1986; Paine,1986; Cohen,1989; Stafford,1991; Cooke, 1997) over the past decade have identified the difficulties of sending manned missions beyond the moon. Most prominent of these are the radiation levels between 1 to 2 cSV per week from galactic cosmic rays (GCR) and the substantial decalcification of bone that occurs in a zero gravity environment. In addition, psychological problems may develop that are associated with living in confined quarters for long periods of time. The effects of all of these threats can be reduced substantially by reducing the total mission time. To accomplish this and maintain a reasonable mass fraction for the Initial Mass in Low Earth Orbit (IMLEO) of the ship, a high thrust system with a high specific impulse will be required. The bi-modal, solid-core Nuclear Thermal Rocket (BiNTR) is the most likely candidate to achieve this performance in the near future.

Because of the high specific impulse afforded by the BiNTR, all propulsive, opposition class missions can be considered. Propulsive deceleration will provide the crew an active means to adjust to unforeseen events whereas passive concepts like aerobraking may be more susceptible to unknown developments such as a fluctuating Mars atmosphere. Thus, all propulsive missions may reduce the risk of the mission. In addition, because of the engine s performance, the mass required for extra shielding against the space radiation environment can be incorporated into the transfer module. Finally, the ability of the BiNTR to produce high levels of electrical power will enable such enhancements as actively cooled refrigeration of the hydrogen tanks, deployment of secondary-satellites for communication powered by microwave transmission, high data rate transmissions, and more complex instrumentation. In general, a power rich environment is advantageous to the survival of the crew.

Development of a BiNTR would have tremendous benefits to future exploration of space - both manned and unmanned. The primary question, though, is can the US develop and test such a system economically under current national guidelines.

HISTORY OF NUCLEAR PROPULSION

In 1955, the Los Alamos Scientific Laboratory began the Rover program 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) 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 programs were terminated in 1972. Before termination, however, the Rover/NERVA programs built and tested 23 reactors/engines, achieved fuel temperatures in excess of 5500 F, 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. 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. 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 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.

Nevada Test Site

The primary use of the Nevada Test Site (NTS) over the past 40 years has 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 of land area, 1100 buildings, 400 miles of paved roads, two airstrips, and 10 helipads. 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.

Much of the Test Site lithology consists of broad expanses of sandy alluvium extending down past 1000 feet. Alluvium is a brown to gray composite of unconsolidated or caliche-cemented sand and gravel. Typically, alluvium layers may have a porosity up to 40%, low water content, and a permeability up to 40 darcys (1 darcy=$0.987X10^{-8}$ cm^2). In a typical test of a nuclear device, a hole varying from 6 feet to 10 feet in diameter is drilled to depths greater than 1200 feet. The nuclear device is placed at or near the bottom of the hole and the hole is then backfilled. Detonation of the device produces hot gases and steam that must be contained below the surface. In order to verify that containment will occur after a test, the geology in and around the hole is heavily studied. In addition, substantial testing has been performed over the years to characterize the movement of both gas and fluids through the alluvium layer. The results of these efforts have been used to benchmark a computational model called WAFE (Travis, 1986).

In addition to testing nuclear weapons, the Rover/NERVA tests were all executed at NTS. Overseen by the Department of Energy, the Nuclear Rocket Development Station at Jackass Flats at NTS was home to three test cells, the Engine Test Stand, and two large assembly/disassembly facilities.

The difficulty for any future recovery of the NERVA technology is the scaling up of the Nuclear Furnace process to the power levels that are needed for the nuclear engine. The process involved cooling the exhaust with a water spray, dehydrating the cooled gases, and then removing the noble gases from the hydrogen with activated charcoal filters. The final product was a clean stream of hydrogen gas. Previous studies (Bohl, 1986; Brengle, 1992) of a full scale facility utilized a 60 psia driving pressure out of the engine to force the effluent through the scrubbing system. Cost estimates made during the SEI program in 1991 ranged from $100 million to $500 million for such a scrubber facility. Such a facility would be an up front capital expense. In addition to the capital expense, the tons of filter material that trap the few grams of fission products would have to be handled and stored.

We propose to examine a concept that resembles the procedures used to test nuclear devices, relies on the inherent natural characteristics of the geology at the NTS, and could possibly reduce the cost of testing nuclear rockets into the 10s of millions of dollars.

SAFE CONCEPT

Because of the relatively rare geological characteristics at NTS and the four decades of experience using that geology, a unique method of testing nuclear rockets has been identified. 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 hole that has been sealed as depicted in Figure 1. 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.

We have performed a set of calculations using the WAFE code to model the SAFE concept. WAFE is a 2-D model of water, water vapor and noncondensible gas flow and energy transport in permeable soil and rock materials. It was developed initially for the underground testing program to estimate transient pressure, temperature, and water saturation changes in stemming columns and geologic units surrounding a hot pressurized cavity produced by a nuclear test.

Our simulations modeled a vertical borehole with a diameter of 2.4 m, extending to a depth of 360 m, typical of emplacement holes at the NTS. The upper 30 m of the hole is lined with a steel casing. The earth surrounding the hole is alluvium, uniform in properties. Typical values for relevant properties of alluvium at the NTS are a porosity of 35%, a permeability of 8 darcys, and initial pore water saturation of 30%, at a temperature of 20 C. Simulations start with injection of the exhaust gases (H_2O and H_2) into the borehole at the bottom of the steel liner. Two cases were considered: 100% thrust, and 30% thrust. For the 100% thrust case, a total of 73.4 kg/s of H_2O (17.4 kg/s from the engine exhaust plus 56 kg/s of cooling spray) and 0.64 kg/s of excess H_2 were injected. For the 30% thrust case, a total of 20.5 kg/s of H_2O (4.9 kg/s from the engine exhaust plus 15.6 kg/s of cooling spray) and 0.33 kg/s of excess H_2 were injected. In both cases, injection temperature was assumed to be 600 C. (The cooling spray added at the top of the borehole is a necessary feature; otherwise, borehole temperatures would be over 3000 C and would damage or melt the steel casing and cause major chemical changes in the alluvium. Further, other simulations indicated that borehole pressure rise would be considerably higher without the water spray. See a later section of this paper for a discussion of the cooling water spray.

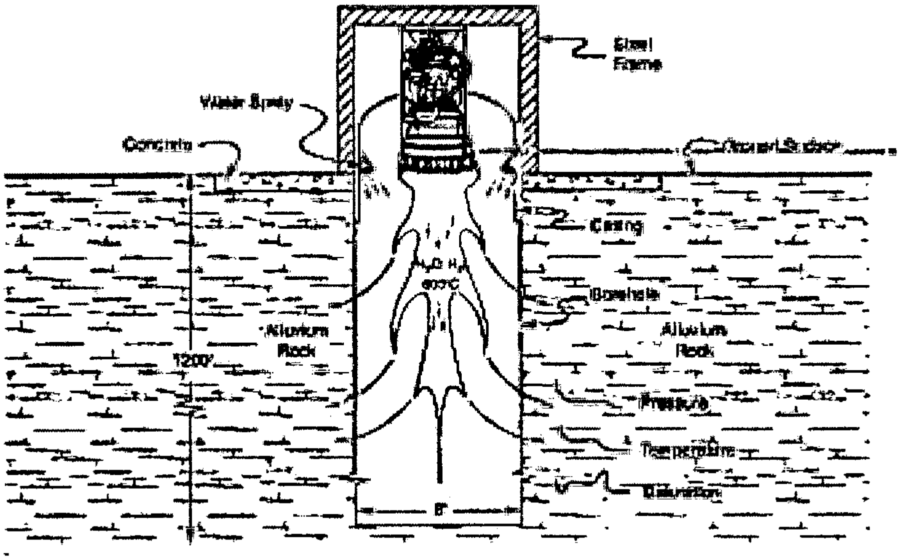

FIGURE 1 Artist s Concept of the SAFE Configuration.

Results of the simulations are summarized in Figure 2-5. Fig. 2 indicates the pressure rise in the borehole at the mid-depth level. In both cases, the pressure rise exhibits an initial spike of a few psi, which subsides, followed by a more gradual rise. In the 100% thrust case, after 2 hours, the pressure has risen to about 36 psia, and to about 21 psia in the 30% thrust case. The rate of pressure increase is diminishing in both cases with time, as the rate of flow into the surrounding soil increases. The pressure history displays an oscillatory pattern superimposed on a gradual, $t^{1/2}$ profile, reflecting nonlinear fluid flow and energy transport dynamics. The temperature rise at the mid-depth level (not shown) is much faster and smoother, reaching near-steady levels, in 10 minutes or less, of about 450 C for the 30% case, and 480 C in the 100% case.

Figures 3-5 compare profiles of pressure, temperature and pore water saturation radially out from the borehole in the surrounding alluvium at 2 hours after start-up. These show the characteristic profiles of two-phase flow in porous media. As the hot steam and hydrogen gas penetrate into the alluvium, condensation occurs in the cooler rock. An elevated water saturation shell develops. As more steam and hydrogen enter, the rock heats up and water begins to boil off, and the shell moves farther out into the rock, where the process is repeated. The pressure, temperature and saturation profiles develop a similarity solution form. Fig. 3 compares the pore water saturation profile at two hours for the 30% and the 100% thrust cases. The elevated saturation reaches about 75% in the full thrust case, and about 70% in the low thrust case. The saturation shell moves out faster and is thicker at full thrust. However, the rate of advance of the saturation shell is decreasing due to the cylindrically diverging geometry. In both cases, the temperature profile (Fig. 4) is similar — a rapid decrease from the hot borehole wall to the beginning of the boiling water region, then an almost-level plateau of about 100 ^{O}C through the boiling water region, and then a drop-off to ambient temperature at the outer edge of the elevated water saturation shell. The pressure profile in both cases (Fig. 5) is essentially linearly decreasing from the borehole wall to the front of the temperature wave. The simulation results indicate that the alluvium is quite capable of handling the inflow of steam and hydrogen from the borehole, even at full thrust conditions. The temperatures are also at a sufficiently low level that chemical changes in the alluvium may not occur, or will be limited to the borehole wall skin.

These simulations are idealized to some degree. They do not include any heterogeneity in the soil properties, and they do not consider any chemical changes that might occur in the borehole wall due to elevated temperatures, nor do they consider raining , i.e., condensation of steam in the lower, cooler portion of the borehole, with puddling of water at the bottom of the borehole. Based on previous experience, these are not expected to greatly change the

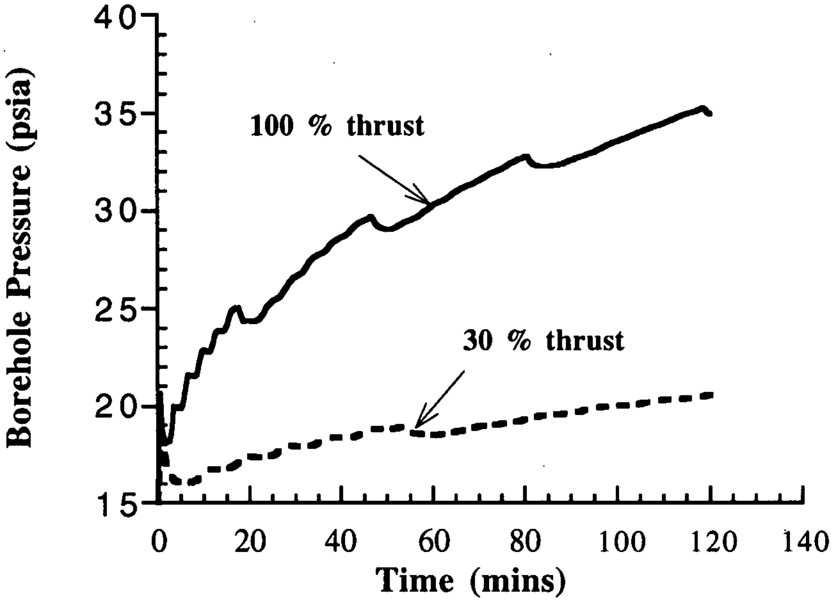

FIGURE 2 Average Borehole Pressure vs. Time for 100 % Thrust Case and 30 % Thrust Case.

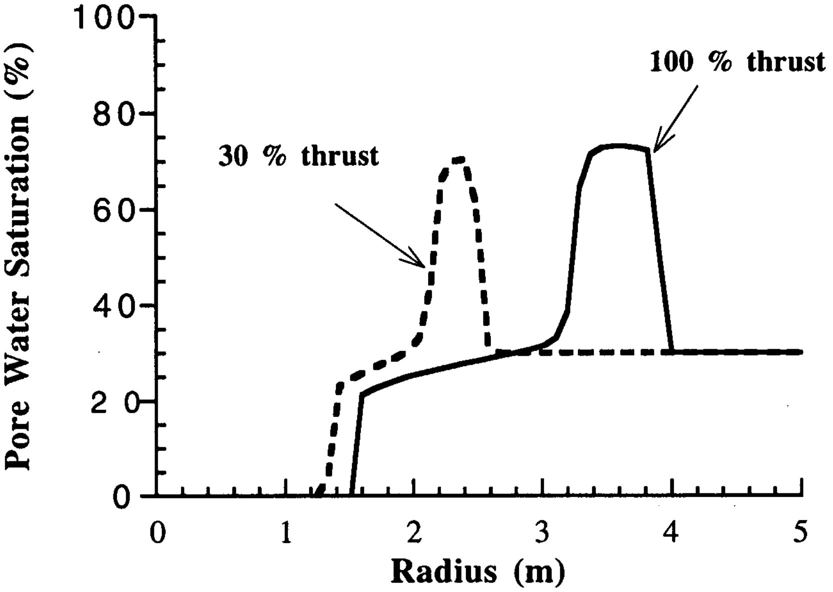

FIGURE 3 Pore Water Saturation vs Radius from Borehole Center at 2 hours.

results presented here. The WAFE model can also be used to estimate how long it will take for the surrounding alluvium to cool off and for the water saturation profile to return to ambient conditions. Transport of tracers in the borehole gases can also be computed. Other geometries, such as tunnels used at the NTS for some underground tests, can also be simulated, as well as more complicated geology.

With regards to the environmental compliance issue, we have made initial contacts at the Nevada Test Site. The NTS has a long history of nuclear weapons testing and has recently developed a new site-wide EIS that has been publicly accepted and allows for the deposition of fission products underground. In addition, sub-critical experiments of fissile systems continue to be performed at NTS even though nuclear weapons testing has been halted. Informal discussions with personnel at the DOE/Nevada Operations Office with regards to NEPA controls have revealed no obvious preclusive regulations. At this point, we feel that the SAFE concept can be executed within the guidelines. Clearly, though, further work is needed to accurately address this issue.

To prove the technical feasibility of this concept, we propose to design and execute an experiment to verify the permeability of the alluvium rock strata at the NTS by using a chemical-combustion rocket engine to pressurize a hole. A RL10 engine, at 30% throttle, will generate 5.25 kg/s of effluent with a 5:1 oxygen:hydrogen mass ratio. The engine would simulate the behavior of a nuclear engine reasonably well except for the presence of water vapor in the effluent. Potentially, the condensation of water vapor may clog the pores in the rock restricting the flow of the more diffusive hydrogen. Regardless, benchmarking the WAFE code will be extremely beneficial. By measuring the equilibrium pressure, the temperature profiles downhole, and, eventually, the flow rate of various gases and water through the rock, we will ascertain the potential of the concept for future consideration.

Another question concerning RL-10 effluent is the impact that the hot exhaust gas will have on the rocket support structure. Exhaust temperatures in excess of 3000 C are expected. Preliminary designs suggest that a limit of ~600 C will have to be imposed on gases that impinge on critical support elements. To this end we have undertaken detailed computational fluid dynamic (CFD) analyses of the preliminary rocket support design and its interaction with the rocket exhaust. We use FLUENT, a commercially available (Fluent Inc.) CFD tool for these analyses.

A transient CFD analysis was first performed in order to assess the time scale for heat up in the hole. This analysis showed that a strong recirculation zone forms just downstream of the rocket nozzle, and that temperatures at the wall approach the exhaust gas temperature within just a few seconds. This indicates that steps must be taken in order to cool the gas prior to its impingement on either the wall of the hole, the exterior of the rocket nozzle, or rocket support elements.

We have chosen to cool the gas rather than to cool the critical components in order to take advantage of the phase change energetics of liquid water. If we chose to internally water cool the critical elements, including the upper portion of the hole down to 45.75 m, the water requirements would be enormous and far exceeding the supply available at the desert test site. Assuming constant properties and equilibrium thermodynamics for water vaporization, we estimate that the water required to spray cool the exhaust gas to a resulting temperature of 600 C would be 15.6 kg/s. For a one-hour test of an RL-10 rocket at 30% thrust, we will need 60 m^3 of water, which would fill the bottom 12 m of the hole if it all recondenses within the hole (i.e. is not transported into the walls).

It remains to be demonstrated whether these bulk thermodynamic estimates remain valid in a more detailed analysis. Of primary concern is whether a droplet sprayed into the exhaust stream will evaporate fast enough to affect cooling of the gas that enters the recirculation zone. A droplet that remains intact downstream of the recirculation zone will still evaporate, but it will not be effective in cooling components near the top of the hole.

We have invoked the dispersed phase sub-model available in FLUENT in order to pursue this more detailed analysis. This model includes heat, mass and momentum exchange between particles and the bulk continuum phase. Particles can be treated as droplets that heat up, vaporize, and boil. The effect of turbulence in the flow can be included in the calculation of droplet trajectories.

In this detailed analysis, we have included transport properties as functions of temperature for both H_2 and H_2O (liquid and vapor). This and the finite rate of water droplet vaporization are the primary differences between the estimate above and the detailed analysis to be presented here. We have assumed that a high capacity water spray ring can be installed near the end of the diffuser. We also assume that the water is sprayed inward at a 45 degree angle at 35 m/s, impinges on the high velocity rocket exhaust (~3,000 m/s) and results in droplets that average 50 microns in diameter.

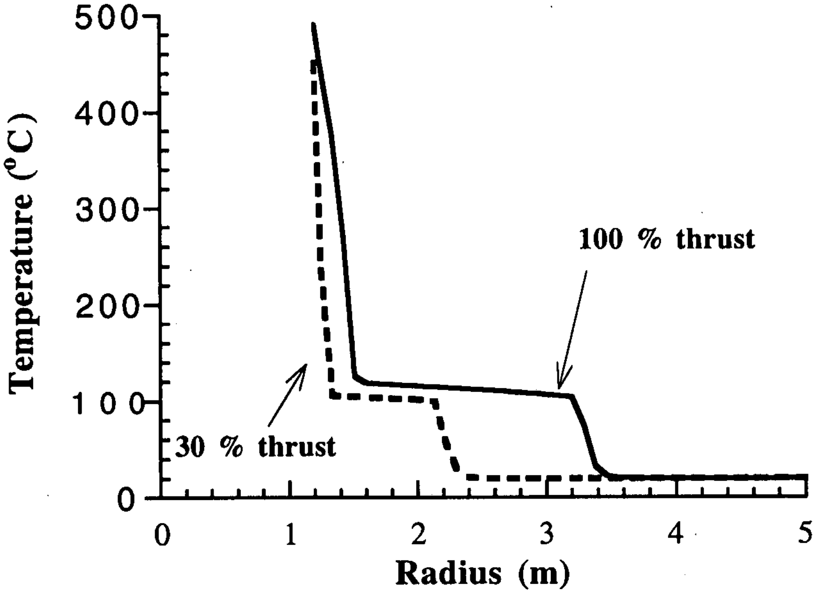

FIGURE 4 Temperature vs Radius from Borehole Center at 2 hours. (Wall is at 1.2 m radius)

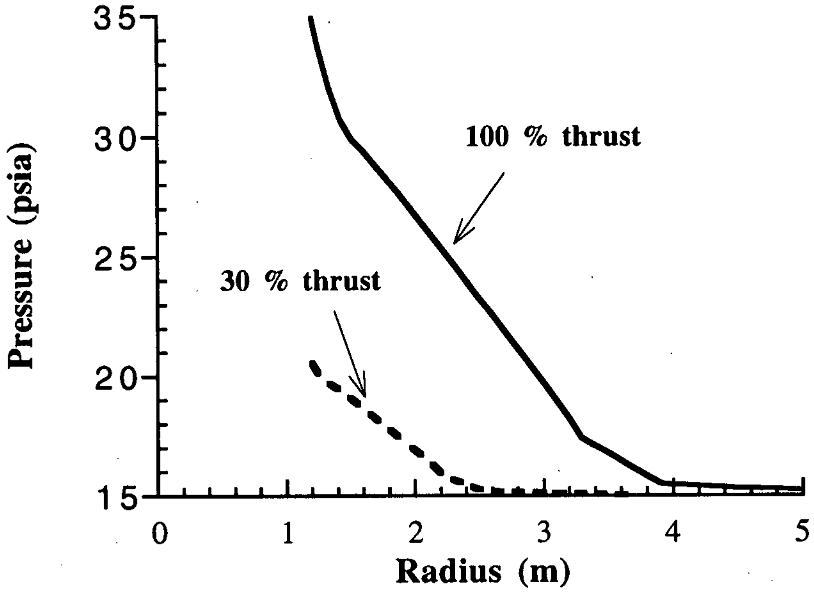

FIGURE 5 Fluid Pressure vs Radius from Borehole Center at 2 Hours.

For this analysis we calculate the steady state flowfield indicative of the situation at long test times. The calculations show that they have all evaporated prior to impinging on the wall, or leaving the recirculation zone.

From this we expect that significant cooling has taken place. Calculations further indicate that a uniform temperature of less than 600 °C has been established in the flow going down the hole. In fact the downstream temperature is close to 560 °C. Even lower temperatures persist in the region near the top of the hole. Near the top of the hole the temperature of the gas has been reduced to approximately 425 °C.

The reason that the uniform downstream temperature is 557 °C and not 600 °C is due to the more accurate heat capacities used in the CFD calculation compared to the constant properties assumed in the initial estimate. It is just as likely that the calculated temperatures could have been a little higher than 600 °C rather than a little lower. The temperature near the top of the hole is even lower because some fraction of the exhaust gas is cooled and recirculated to the top before mixing completely with the very hot exhaust gas near the rocket centerline.

This analysis demonstrates that cooling of exhaust gas with a cold water spray is a viable methodology. Other configurations for the spray may be of greater efficacy and require less overall cooling water usage. For example, we have shown that gases cooled by the water that enter the recirculation prior to becoming fully mixed keep the region near the top of the hole cooler than the average. Perhaps a design which has the spray directed more towards the top of the hole could be even more effective and require less water to cool these elements to 600 °C. We must then be careful to not permit the average downstream temperature to climb above other critical limits, such as the melting point of alluvium.

COST ESTIMATE

Development of the conceptual design was required in order to be as thorough as possible in identifying potential show stoppers for testing a nuclear rocket engine at NTS and to determine a rough order of magnitude (ROM) cost estimate that was as complete as possible. To avoid duplicating engineering effort, the conceptual design that was developed for chemical rocket engine testing presented to NASA on April 29,1999 at NASA/MSFC was used as a starting point in developing the nuclear rocket engine conceptual design. The significant differences with the nuclear rocket tests compared to the chemical rocket tests were identified as follows:

- Use of a highly enriched nuclear core as an energy source and the requisite security to handle the core
- Presence of neutron and gamma radiation during testing and gamma radiation after testing is completed
- Exhausting of fission products such as strontium/yttrium and cesium/barium into the bore hole
- Possibility of unknown credible failure modes of the rocket engine which may impact the ultimate detailed design of the testing facility such as redundancy for some systems
- Requirement for an Environmental Impact Study vs. an Environmental Assessment
- Use of unique structural materials such as high purity aluminum for the rocket stand
- Generation of radioactive waste specifically the cooling water

These differences required various assumptions and solutions to be identified. The significant assumptions impacting the conceptual design are as follows:

- Staging at the Device Assembly Facility (DAF) is required due to weapons grade material present
- Dewatering of bore hole is required after each test to reduce concern with introducing fission products into water table
- Lower portion of bore hole is required to be lined to eliminate concern with introducing fission products into water table
- Control rod/drum fails safe therefore a stuck control rod/drum is not considered credible due to design of rocket engine core
- Short term temporary storage of two nuclear rocket engines after testing is required until NASA takes custody and removes from site
- Radiation monitoring is required
- Post-test disassembly of rocket engines will not be required at the NTS since testing will be reliability testing

As a result of the above basic input, refractory is only needed to shield the surrounding concrete foundation from excessive temperatures to avoid damage and subsequent failure. Further, the concrete foundation and rocket support structure preliminary sizing requirements were determined by assuming a maximum pressure of 45 psi, thereby providing a scale drawing for the support stand and rocket engine. The rocket support structure does not use the rocket itself as a structural member in accommodating the bore hole pressures during testing. The cooling water system capacities were also determined based on the above 600C temperature. In addition, a hydrogen burn off system is required for various purging and relief activities anticipated during operation and was conceptually designed and sized. With regard to the safety pressure relief system, the type of relief devices were determined and the basic system requirements were quantified. This relief system is intended to provide protection from unanticipated excessive pressure in the bore hole if rocket exhaust gas actual dissipation through the surrounding soil is less than calculated. Specific fuel and fuel system costs were better characterized based on preliminary input from a possible fuel supplier, Air Products. It is anticipated that this available fuel system equipment will be leased and operated by the vendor having the requisite expertise and capacity.

Identification and Resolution of Show-Stoppers

Areas having potential significant issues or show-stoppers were initially identified. Show-stoppers were viewed as any technical or non-technical issues that could possibly result in the inability to perform the nuclear rocket testing at the NTS. These were areas that could involve either a technically insurmountable problem, a problem representing a cost prohibitive situation, or a highly sensitive political concern. Therefore the following areas that were investigated included 1) Permitting, 2) Creation of an Environmental Impact Statement, 3) Site Restoration, Safety, 4) Water table contamination by fission products, and 5) Containment Requirements.

Subsequently each of the above areas were investigated in detail in conjunction with developing the conceptual design and rough order of magnitude cost estimate. As a result it was shown that permitting including production of an Environmental Impact Statement, the restoration of the Site, and addressing safety requirements did not involve any technical, non-technical, or cost prohibitive show-stoppers. However, the concern with the possibility of water table contamination by fission products required a more involved evaluation to resolve this concern. Calculations were performed by LANL that indicate the quantity and migration of fission products result in fission product concentrations that are very small in the surrounding soil and are comparable to the present Nevada Drinking Water Standard concentration limits. In addition, it was decided to provide a de-watering system that would pump out the contaminated cooling water from the bore hole after each test thereby further reducing the fission product quantity released to the surrounding soil. Also the lower portion of the bore hole would be lined, which again would minimize any fission product migration to the water table. Therefore this design approach along with other current NTS experiences with such concerns would allow concluding that fission product contamination would not represent a show-stopper.

As far as any political concerns that may exist, it is generally felt that as long as the requisite approval processes are followed and adequate time is provided to obtain these approvals then there should be no non-technical or political show-stoppers given the current environment. In fact, it is felt that the NTS is the best and possibly the only logical place to conduct this type of testing.

ROM Cost Estimate

The BN rough order of magnitude cost estimate is based on the conceptual design described in this FSR and associated drawings.

The BN cost estimate makes the following significant assumptions:

- Use of an existing LANL bore hole at the NTS
- Period of performance is assumed to be approximately 24 months which includes 4 of those months for actual testing.
- A two week staging activity is required at the DAF
- Performance of four test firings of the rocket engine for 1 hour duration each
- BN will run the diagnostics during the testing and provide the test director
- De-watering of the bore hole after each test will be required

- Characteristics of the nuclear rocket engine such as thrust, exhaust temperature, etc. are the same as chemical rocket engine.
- Less than 2 grams of fission products are exhausted into bore hole from each one hour test
- No radiation contamination will occur except on the inner surface of the rocket exhaust bell and in the bore hole

The significant costs in the BN estimate were found to be 1) Production of the Environmental Impact Statement, 2) Rocket fuel system and fuel, 3) Construction of the satellite bore holes, 4) Project Team, 5) Cooling water system, 6) De-water system, and 7) DAF staging. The cost estimate provides two costs. One cost is for conducting the first test which includes all one time only costs, i.e. capital improvements to the NTS facilities and infrastructure. Then an additional cost is provided for a subsequent test. These costs are $15,082,000 and $1,631,000 respectively. These costs do not include any development costs of the engines nor transport and long term storage costs. Thus, after a $15M investment in the NTS infrastructure, a nuclear rocket could be tested at the same facilities for under $2M.

SUMMARY

Sending a human crew to Mars or sending unmanned missions to the far outer planets in a few years will require nuclear propulsion systems. A bi-modal nuclear system offers the potential for enabling both of these missions. In the current environment, testing and verification of a nuclear system in a surface-based scrubber facility will prove expensive and time consuming. By utilizing the favorable geological features at the Nevada Test Site along with 40 years of experience characterizing that geology, we have developed an alternative concept for BiNTR engine testing. By using the permeability of the rock strata at NTS, the effluent from a nuclear engine could be entrained into the rock. The few grams of fission products that might be present would be captured and distributed throughout the rock layer in a low density distribution. Such a test may be accomplished for under $20M instead of a few hundred million required by a scrubbing facility. Proof of the SAFE concept using an RL10 chemical engine could be performed within a year for $5M to answer the questions of effluent dispersion and temperature gradients. Testing a nuclear system will require a capital investment of around $15M into the NTS infrastructure. Each subsequent test of a nuclear engine would cost under $2M.

Eventually, the vast distances to be traveled, the frailty of the human form, and the desire to reduce risk will dictate the need to use nuclear rockets for the human exploration of space. At some point prior to that development, someone will have to make the decision to build such a rocket. If the SAFE testing concept can be proven to be environmentally conformable and technically feasible, then the requirement of building a large, complex, expensive scrubbing facility will not be a driving force in that decision. By developing a safe, cheap, clean, and reliable method of testing nuclear rockets, this country can open the way to exploring the solar system.

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