JOURNAL OF PROPULSION AND POWER
Vol. 17, No. 3, May–June 2001

Safe Testing of Nuclear Rockets

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In the early 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 support the concept of using a nuclear rocket to decrease mission time. These same needs have been recognized in later studies and, 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/Nuclear Engine for Rocket Vehicle Applications 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 concept would allow variable-sized engines to be tested for long times at a modest expense. A system overview, results of preliminary calculations, and current status of a proof-of-concept demonstration are presented.

Introduction

SEVERAL studies[1–3] over the past decade have identified the difficulties of sending crewed missions beyond the moon. Most prominent of these are the radiation levels between 1 and 2 centi-severt (cSV), where 1 cSV is equivalent to 1 Roentgen Equivalent Man, 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 solid-core nuclear thermal rocket (NTR) is the most likely candidate to achieve this performance in the near future.

During the past few years, the NASA Johnson Space Center has reexamined potential Mars mission scenarios.[4] The baseline assumptions in their design reference mission have been 1) a solid-core nuclear rocket for trans-Mars injection, 2) aerobrake capture at Mars, 3) previously positioned cargo mission to put the return ship, which uses chemical propulsion, into Mars orbit, and 4) aerocapture at Earth. Total mission time is 900 days away from Earth. The mission profile includes a 6-month transit to Mars, a 536-day stay on the surface, and a 6-month return flight. The difficulties inherent in this scenario are long exposures to GCR, long stay times on the Mars surface, and the need to develop at least seven major new technological systems to complete the mission.

Because of the high specific impulse afforded by the NTR, 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 such as 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 may be incorporated into the transfer module. Development of a NTR would have tremendous benefits to future exploration of space, both crewed and uninhabited. The primary question, though, is can the United States develop and test such a system economically under current national guidelines. Previous estimates indicate that a nuclear rocket test facility could cost up to $500 million. The subsurface active filtering of exhaust (SAFE), concept may allow nuclear rockets to be tested for a few million dollars per test. If verified, the SAFE testing concept could enable the development of a high-performance propulsion system to take humans to Mars and beyond.

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) program began with Aerojet as the prime contractor and Los Alamos Laboratory as a supporting contributor. The goal of the NERVA program was to transform the nuclear reactor technology developed by Los Alamos Laboratory 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 MW, operated a system for over an hour, demonstrated multiple start-up and shutdown 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 lbf-s/lbm, almost three times the performance of the kerosene engines of the Saturn V and twice that of the soon-to-be-developed liquid oxygen/hydrogen engines of the space shuttle. The impact of this performance would have been to reduce the trip time of a crewed 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 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

Received 13 January 2000; revision received 5 April 2000; accepted for publication 13 July 2000.

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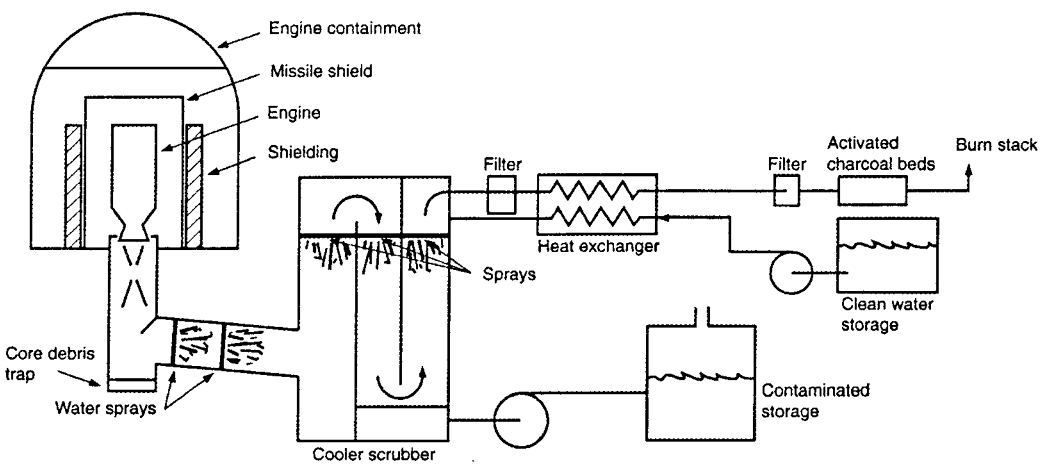

Fig. 1 Schematic scrubber facility limited to testing 15,000-lb thrust engine.

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, which 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.

In 1985, Los Alamos Laboratory participated with NASA centers in a six-month study[5] to examine all aspects of a crewed Mars mission. During the course of the study, the idea of using the nuclear rocket was reintroduced. Trade studies showed that use of nuclear propulsion could reduce the IMLEO by at least a factor of two. Alternatively, the study showed that a round trip mission of 434 days was possible. In addition, the equipment necessary to fabricate the fuel of the nuclear rocket still existed at Los Alamos Laboratory along with the ability and expertise to test such a system at the Nevada test site.

In 1989, President Bush announced the start of the Space Exploration Initiative (SEI). The ultimate goal was to send a crewed mission to Mars by 2018. This time, the nuclear rocket was considered as one of the baselines for the mission by NASA. As part of a joint Department of Energy (DOE)/NASA team, Los Alamos Laboratory worked to show the cost and feasibility of recovering the solid-core technology. In addition, the cost and requirements of refurbishing the old testing facilities at Nevada were examined.

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 DOE 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 in. 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 ft. 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 $= 0.987 \times 10^{-8}$ cm^2).

In a typical test of a nuclear device, a hole varying from 6 to 10 ft in diameter is drilled to depths greater than 1200 ft. 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, which must be contained below the surface. 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.[6]

In addition to testing nuclear weapons, the Rover/NERVA tests were all executed at NTS. Overseen by the DOE, 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 as shown in Fig. 1. Previous studies[7,8] 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 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 have developed 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 tens 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 (see Fig. 2). 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 two-dimensional 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 the exhaust of a RL10-5A engine into a vertical borehole with a diameter of 2.4 m (8 ft), extending to a depth of 360 m (1200 ft), typical of emplacement holes at the NTS. The upper 30 m of the hole is lined with a steel casing. The earth

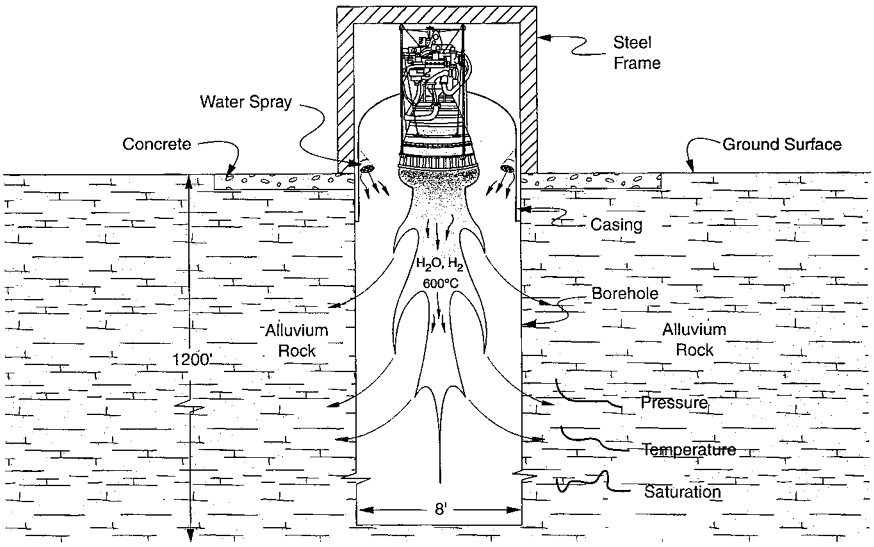

Fig. 2 Schematic of the SAFE testing concept.

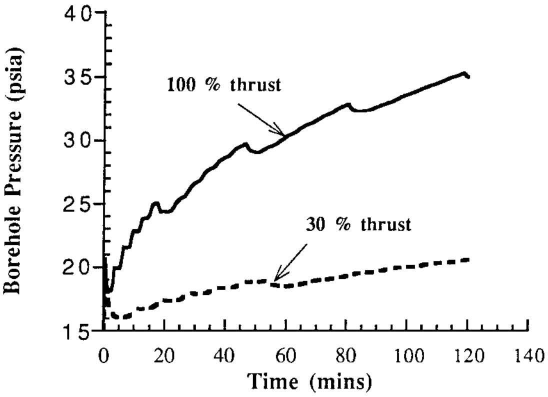

Fig. 3 Average borehole pressure vs time for 100 and 30% thrust cases.

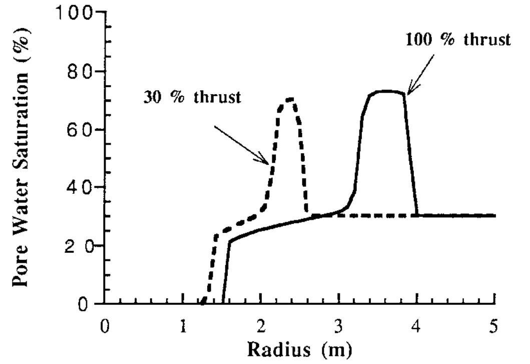

Fig. 4 Pore water saturation vs radius from borehole center, at 2 h, for the two cases.

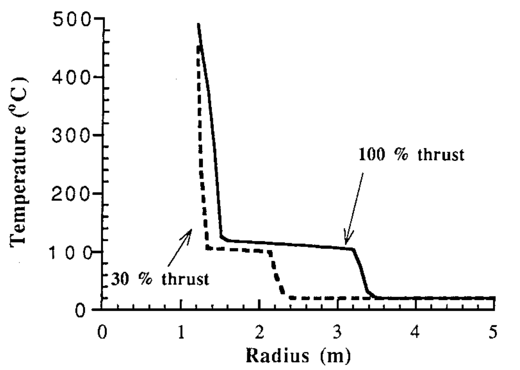

Fig. 5 Temperature vs radius from borehole center, at 2 h, for the two cases; wall is at 1.2 m radius.

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. Furthermore, 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.

Results of the simulations are summarized in Figs. 3–6. Figure 3 indicates the pressure rise in the borehole at the middepth level. In both cases, the pressure rise exhibits an initial spike of a few pounds per square inch, which subsides, followed by a more gradual rise. In the 100% thrust case, after 2 h, the pressure has risen to about 36 psia and in the 30% thrust case to about 21 psia. 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 middepth level (not shown) is much faster and smoother, reaching near-steady levels, in 10 min or less, of about 450°C for the 30% case and 480°C in the 100% case.

Figures 4–6 compare profiles of pressure, temperature, and pore water saturation radially out from the borehole in the surrounding alluvium 2 h 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. Figure 4 compares the pore water saturation profile at 2 h 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. 5) 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°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. 6) 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.

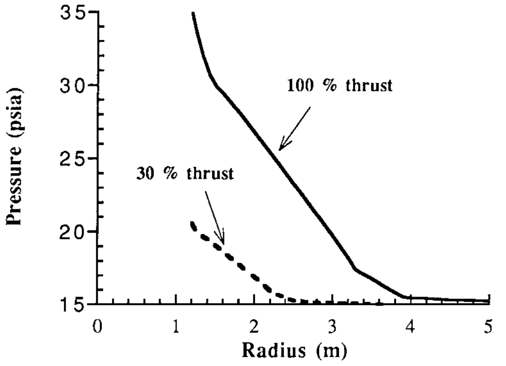

Fig. 6 Fluid pressure vs radius from borehole center, at 2 h, for the two cases.

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, that is, 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 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 NTS. The NTS has a long history of nuclear weapons testing and has recently developed a new sitewide Environmental Impact Statement that has been publicly accepted and allows for the deposition of fission products underground. In addition, subcritical 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 National Environmental Policy Act 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 have designed an experiment to verify the permeability of the alluvium rock

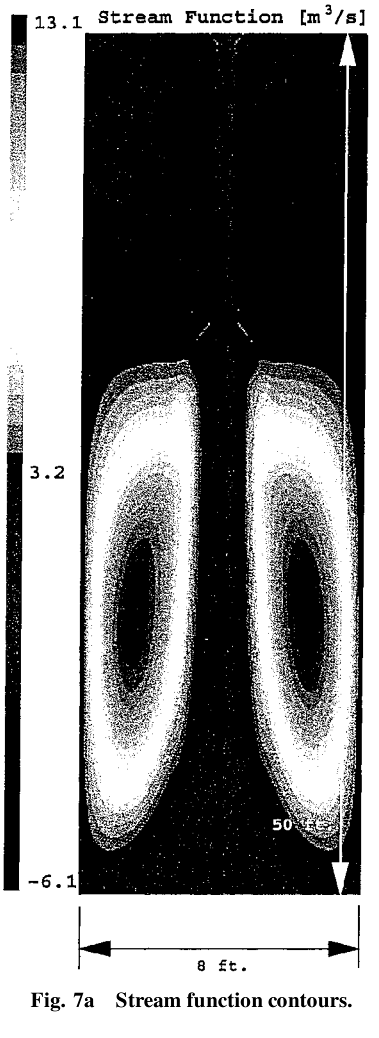

Fig. 7a Stream function contours.

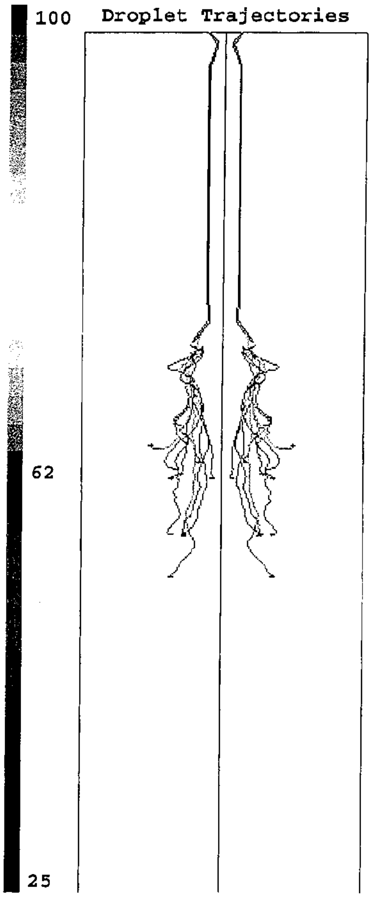

Fig. 7b Droplet trajectories colored by temperature, °C.

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,[9] a commercially available CFD tool for these analyses.

A transient CFD analysis was first performed to assess the timescale 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 to cool the gas before its impingement on either the wall of the hole, the exterior of the rocket nozzle, or the rocket support elements.

Figure 7a contains a contour plot of the stream function in this axisymmetric flowfield. A clear recirculation zone is evident, followed by relatively uniform flow into the lower portion of the hole. The axial extent of the hole shown is 50 ft, with a hole diameter of 8 ft. The radial scale has been expanded by a factor of two to highlight details of the flowfield. The upper throat is that of the rocket nozzle itself, which is then connected to a diffuser section that extends approximately 15 ft. The aim of the diffuser is to prevent a shock wave from forming in the rocket nozzle in the event of excessive pressure buildup in the hole.

We have chosen to cool the gas rather than to cool the critical components to take advantage of the phase change energetics of liquid water. If we chose to water cool the critical elements internally, including the upper portion of the hole down to 150 ft, 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 1-h test of an RL-10 rocket at 30% thrust, we will need 15,000 gal of water, which would fill the bottom 40 ft of the hole if it all recondenses within the hole, that is, 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 submodel available in FLUENT to pursue this more detailed analysis. This model includes heat, mass, and momentum exchange between particles and the bulk

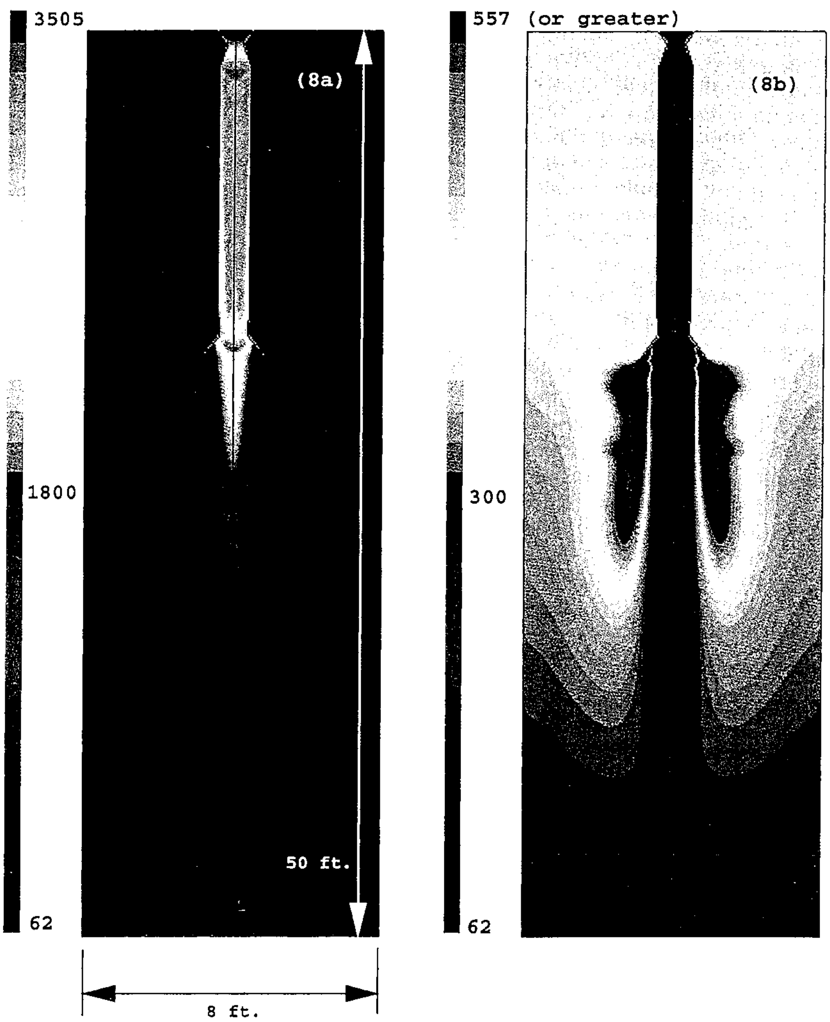

Fig. 8 Static temperature contours, °C.

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 earlier estimate 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 shown in Fig. 7. We also assume that the water is sprayed inward at a 45-deg angle at 115 ft/s, impinges on the high-velocity rocket exhaust (~10,000 ft/s), and results in droplets that average 50 μm in diameter.

For this analysis we calculate the steady-state flowfield indicative of the situation at long test times. Figure 7b contains a plot of 10 typical droplet trajectories given the stated assumptions. Note that they do not follow the same pathlines due to the randomizing influence of flow turbulence. Also note that they have all evaporated before impinging on the wall or leaving the recirculation zone (compare to Fig. 7a). From this we expect that significant cooling has taken place, as is demonstrated in Fig. 8a. Figure 8 contains contours of static temperature and indicates 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. This is highlighted in Fig. 8b, which has the temperature contours scaled between 62 and 557°C. Regions where the temperature is 557°C and above are shown as red. 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 before becoming fully mixed keep the region near the top of the hole cooler than the average. Perhaps a design that has the spray directed more toward 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 that the average downstream temperature not be permitted to climb above other critical limits, such as the melting point of alluvium.

During the past 18 months, the NASA Marshall Space Flight Center supported the Bechtel–Nevada Corporation (BN) to determine the costs associated with testing the SAFE concept. The results of the BN studies were that four 1-h tests of the RL10-5A engine could be conducted at NTS for a total of $10.5 million. Each of the tests would be used to prove the WAFE calculations, calibrate diagnostics, and validate the diffusion rates in the rock. The tests could be completed within 2 years of the starting date. In addition, BN has completed a study to determine the costs of testing a nuclear rocket at NTS. The results are that an initial investment in infrastructure would cost around $15 million. Each test of a nuclear system would cost around $1.7 million for a 1-h test. This study assumed a 15,000-lb thrust engine. Testing a larger engine or testing for a longer time is not considered to be a major impact on these estimates.

Conclusions

Sending a human crew to Mars will be risky and substantially more demanding than the Apollo missions. However, the primary risk factors of radiation exposure (between 1 and 2 cSV per week) and physiological degradation can be alleviated by performing fast round trip missions of months instead of years. An NTR offers the potential for making rapid transits to Mars. In the current environment, testing and verification of a nuclear system will prove expensive and time consuming. By utilizing the favorable geological features at the NTS along with 40 years of experience characterizing that geology, we have developed an alternative concept for engine testing. By the use of 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 might be accomplished for a few tens of millions of dollars 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 to answer the question.

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 before 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 the development of 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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