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Recent Activities at the Center for Space Nuclear Research for Developing Nuclear Thermal Rockets

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RECENT ACTIVITIES AT THE CENTER FOR SPACE NUCLEAR RESEARCH FOR DEVELOPING NUCLEAR THERMAL ROCKETS

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Nuclear power has been considered for space applications since the 1960s. Between 1955 and 1972 the US built and tested over twenty nuclear reactors/ rocket-engines in the Rover/NERVA programs. However, changes in environmental laws may make the redevelopment of the nuclear rocket more difficult. Recent advances in fuel fabrication and testing options indicate that a nuclear rocket with a fuel form significantly different from NERVA may be needed to ensure public support. The Center for Space Nuclear Research (CSNR) is pursuing development of tungsten based fuels for use in a NTR, for a surface power reactor, and to encapsulate radioisotope power sources. The CSNR Summer Fellows program has investigated the feasibility of several missions enabled by the NTR. The potential mission benefits of a nuclear rocket, historical achievements of the previous programs, and recent investigations into alternatives in design and materials for future systems will be discussed.

I. INTRODUCTION

According to the Independent Review Panel [1] convened in 1999 to review the propulsion technologies examined in the NASA Advanced Space Transportation Program:

> "The Review Team categorized fission as the only technology of those presented [45 concepts were presented] which is applicable to human exploration of the near planets in the near to mid-term time frame…"

Nuclear power has been considered for space applications since the 1960s [2,3]. Both the US and the Soviet Union orbited nuclear reactors as sources of electricity for satellites. The only US reactor flown is space, the SNAP-10A, flew in 1965 [4]. The Soviet Union flew 33 reactors to power their Radar Ocean Reconnaissance SATellites (RORSAT) but the last flew is 1988 [5].

Between 1955 and 1972 the US built and tested over twenty nuclear reactors/ rocket-engines in the Rover/NERVA programs. The tests of the nuclear thermal rocket (NTR) demonstrated a specific impulse (Isp) of 850 s, a range in thrust from 25 Klbs to 250 klbs, operational duration of over two hours, and the ability to restart multiple times [6,7]. In short, the program demonstrated the ability to have a core running at 2500 K inside a cooled pressure vessel operating at near ambient temperature. Unfortunately, National priorities shifted away from space exploration and those programs terminated – yet the knowledge that such systems work and what they can accomplish has been invaluable.

Nuclear thermal rockets offer the potential for high-thrust and high specific-impulse. Many studies during the past few decades have identified missions where the NTR is either enabling or significantly enhances the mission performance. The Center for Space Nuclear Research (CSNR) has begun to reexamine 1) the technology involved in an NTR, 2) the benefits to various missions both manned and unmanned, and 3) the issues in redeveloping a NTR in the current socio-political environment.

II. HISTORY OF NUCLEAR THERMAL ROCKETS

In 1955, the Los Alamos Scientific Laboratory began the Rover program to develop a solid core nuclear rocket engine [6]. 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. 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 over 20 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. 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.

In 1968, the programs executed the Pewee test [8] which was the culmination of much of the data gained from the two test programs. The Pewee test demonstrated an engine design that had 25,000 lbsf of thrust, over 500 MWth, an Isp of 850 s and a thrust-to-weight of just under three. The engine used "once-through" tie-tubes for axial compression. Subsequent studies showed that around 25 kwe could be produced by closing the tie-tubes and circulating heavy gas through a turbine.

In 1999, the Los Alamos National laboratory executed a project to identify all remaining documentation and any hardware specific to the Pewee test [9]. The LANL effort sought to determine the database that still existed in Laboratory archives with regard to the Pewee engine test.

The results of the LANL archive search effort are that 1) over 1100 detailed component-subsystem-system documents and papers for the Peewee reactor/engine have been located, almost 150 detailed component/subsystem/system drawings and blueprints have been identified, some components and/or hardware developed during the Rover program for the KIWI-B, Peewee and Phoebus projects are still resident at LANL; and an "updated" CAD model for the Peewee reactor pressure vessel around which "current day" SOTA engine subsystem elements can be added has been generated. The fact that so much detailed information of the Pewee engine still exists adds support to the claim that a NTR can be recovered for a modest investment.

III. MISSION BENEFITS

Outer Planet Missions

As missions to the outer planets evolve from fly-by to rendezvous, the Delta-V requirements increase significantly. In addition, interest has now increased in the Kuiper Belt Objects. Using chemical propulsion and gravitational assists, these missions, if they can be achieved at all, will require decades before the probe would start to send back information. If the "time to first science" is desired to be no longer than ten years so that a major portion of a professional career is not spent waiting for the data, the mission needs to utilize a higher performance propulsion system.

From 2002-2006, NASA pursued development of a Nuclear Electric Propulsion (NEP) system to support the Jupiter Icy Moons Orbiter (JIMO) mission [10]. The envisioned NEP system used a nuclear reactor to make electricity which then powered a series of ion thrusters to provide thrust. Proponents of the NEP system claimed faster missions to the outer planets. However, the NEP method is inherently inefficient. Only around 15-20 % of the thermal power generated in the reactor manifests itself in jet power, i.e. thrust. The rest had to be sent into the vacuum of space via a large array of radiators. The radiator array made the ship very heavy. Estimates of the JIMO ship showed a specific mass of around 200-300 kg/kw. In order for the ship to achieve first science in 10 years, specific mass of below 30 would be needed. For longer missions, a lower specific mass would be required.

In 2004, the National Research Council convened a Committee on Priorities for Space Science Enabled by Nuclear Power and Propulsion [11] at the request of NASA HQ. One of the major issues found by the Committee was the long times to "first science" offered by the NEP vehicle being examined. The statement to the committee by NASA was that the NEP vehicle being considered for the JIMO mission could not provide a "time to first science" for any other mission under fifteen years. Alternatively, mission studies previously done at NASA [12] indicate that a NTR system would enable the "time to first science" to be less than ten years for many missions. Thus, the NTR community could provide the science community with new, unparalleled abilities.

The NTR has several benefits compared to either chemical stages or NEP stages. Potentially, some of these are:

- allows LEO departure with high-thrust and high-Isp;
- enables fast trips to either the Moon, Mars or the outer planets;
- NTR engines have negligible radioactivity at launch which simplifies handling and stage processing activities at KSC;
- The NTR uses many of the same technologies as chemical rockets;

- Short burn durations (~25-50 mins) and rapid LEO departure;
- Less propellant mass than all chemical propulsion implies fewer Earth to Orbit launches;
- NTR engines can be configured for both propulsive thrust and electric power generation -- **"bimodal" operation**
- Small engines can be used individually or in clusters to maximize mission versatility -- for robotic science, human Moon, and Mars missions
- NTR technology is evolvable to reusability

Over the past decades, many researchers have recognized the improved capabilities offered by NTRs. Robotic missions to the outer planets benefit from shorter mission flight times and higher payload masses—thus, greater scientific return. Similarly, human missions benefit from shorter exposure to galactic cosmic radiation and higher payloads for life support. Recent studies made at the CSNR have also identified the benefits of using an NTR to support a Lunar Outpost or to intercept an inbound "planet-killing" comet.

In 2007, a National Research Council committee was convened to assess the NASA Exploration Technology Development Program (ETDP) [14]. The ETDP contained 22 different projects developing technologies to support the human return to the moon, i.e. the Constellation program. One of the ETDP projects included a fission reactor design effort for the Lunar surface, i.e. the Fission Surface Power (FSP) project. However, one of the findings of the committee was that the one technological "gap" in the EDTP program was the lack of funding for the NTR.

Comet Intercept by an NTR

The study of planetary defense has drawn wide interest in various research communities. Although the probability of a large-scale impact event is small, the consequences of such an event would be disastrous. Study of the strategies available for protection against such an occurrence provides insight into what scale of comet could be deflected using near term propulsion technologies. In 2009, the CSNR Summer Fellows ascertained the benefit of using a NTR to carry maximum payload rapidly to an inbound, "Earth-killing" comet [13].

The CSNR study determined the worst plausible scenario for the available warning time (approximately ten months) of the comet approach and used empirical data available to make an estimate of the payload necessary to deflect such a comet as a function of the comet's mass. Optimization of the ship's initial mass in low Earth orbit (IMLEO) entailed a trade off between early interception (high delta-V trajectory but lower yield required for deflection) and late interception (low delta-V and less propellant mass but higher payload mass). The optimization also considered mission launch date and establishment of the ideal trajectory for an intercept mission. The study examined the potential for multiple missions launched at different times to contribute to the deflection of the comet. Comparison of various propulsion technologies for execution of this mission showed that the NTR outperformed chemically propelled systems substantially, i.e. that nuclear thermal rockets could achieve comet interception missions that are not feasible for their chemical counterparts.

The results of the study showed an optimum interception trajectory which is independent from the size of the comet. Although the initial goal of the study was to determine the IMLEO needed to destroy a 10 km diameter comet, the results showed that the largest comet that could be deflected using near term NTR technology has a diameter of 5.1 km. In order to achieve the deflection, nuclear warheads with a yield totaling 189 megatons needed to be launched from LEO with NTR. The study assumed that commercially available, chemically propelled rockets placed the warheads as well as NTR components into LEO. Assuming the maximum launching capacity of 24.5 tons to LEO per launch vehicle, 21 total launches were needed. This conclusion was possible given current launching capacity around the world. In other words, the mission required international coordination in order to be successful.

Human Crewed Missions

Missions to Mars

In 2008, the NASA Mars Architecture Team reported [15] two findings related to nuclear systems: 1) that a fission reactor for the surface was ENABLING for the mission, i.e. the mission could not be accomplished without it, and 2) the NTR was the PREFERRED propulsion system to carry the human crew to Mars and back.

The benefits to the human crews on missions to Mars have been delineated by several previous studies [16,17,18]. The primary benefit is the possibility of reduced trip time and, thus, exposure to space radiation. Another benefit is a significantly reduced IMLEO for a given payload mass as compared to a chemically propelled ship. This is, perhaps, more important because, despite desires, payloads will get larger as more equipment and resources are added to reduce risk. Increases in structure or payload mass are multiplied by the propellant mass needed to push them along. The impact on a NTR driven ship is much less than on a chemically driven ship because of the higher specific impulse of the NTR.

The radiation environment in free space is around 0.01 Sv/week depending upon the solar cycle. On the Mars surface, this may be reduced slightly but is still high compared to Earth. Thus, a typical conjunction class mission with a 900 day round trip will result in a total dose to the crew of nearly 2 Sv – the lifetime dose allowed by current government regulations for a radiation worker. Add to this the effect of zero gee and the psychological difficulties of living in cramped quarters for long periods and the mission success probability of a 900 day mission may get unacceptably low.

Current conjunction class missions for humans to Mars require 500 days at Mars so the Earth can return in its orbit. This necessitates a heavy demand on the life support systems for the crew and on the psychological burden to be faced by the crew. Opposition class missions require much higher Delta-V and cannot be done with chemical systems. A NTR driven mission, however, can do fast missions- perhaps as short as 440 days [16]. Such a mission dramatically reduces the dose to the crew and also alleviates potential psychological difficulties incurred in very long missions.

Support of a Lunar Outpost

One of the issues involved in using a NTR for a Mars mission is system reliability, i.e. what is required to "man-rate" a NTR propelled ship. Historically, upwards of 20- 30 full power tests of an engine system are required. This is probably an impractical number for the NTR. Conversely, if the NTR could be flown for unmanned missions, then reliability and performance values could be generated that would allow the NTR to be used for a human crewed mission.

In 2006, the CSNR Summer Fellows program undertook a study [19] to examine the feasibility, performance requirements, and financial justification of using a NTR to support cargo missions to the Moon to build a Lunar Outpost. The study followed the Exploration Systems Architecture Study (ESAS) [20] made by NASA in 2005 for the Vision for Space Exploration (VSE) dictated by President Bush. The ESAS plan entailed returning humans to the moon in 2020 for a series of short sorties. Then a Lunar Outpost was to be established that would support six humans for six months. The CSNR study used parts of the mass of the International Space Station, also designed to house six humans for six months, to estimate the mass of the lunar outpost as 250 metric tons. The results of the summer study indicated that use of a NTR as an Earth Departure Stage (EDS) can save significant amounts of mass and cost to support a Lunar Outpost.

By using an NTR for orbit to orbit transfer, the payload mass delivered to the lunar surface can be increased by 36%. The increase in mass delivered to the lunar surface translates into fewer launches of the Ares V heavy lift launch vehicle. The results are shown on Figure 1. These savings in mass constitute a financial savings that is estimated to be over $4B – well beyond estimates of the cost of developing a NTR. This performance improvement did not carry with it a performance penalty elsewhere in the design. Nuclear thermal rocketry proved a strong choice for the support of lunar exploration.

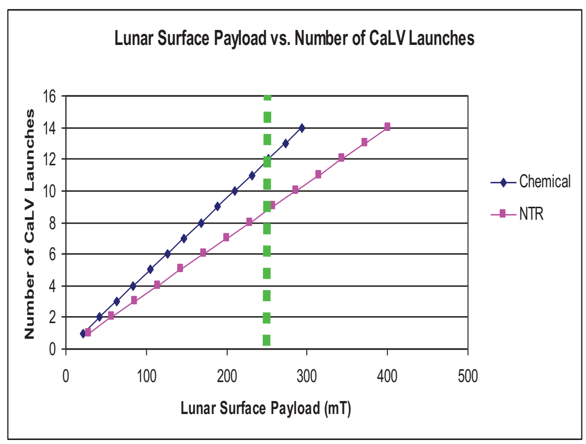

Figure 1. Comparison of the number of heavy lift launches needed to supply a Lunar Outpost using chemically powered or nuclear powered Earth Departure Stage.

IV. MAJOR ISSUES FOR RECOVERING THE NTR

Recovery of the NTR technology in the current socio-political environment is dependent on overcoming some major issues. Simply expressed they are:

- Performance sufficiently superior to justify "perceived" risk
- Cost of development
- Radioactivity emitted during operation
- Risk for "proliferation" on launch abort
- Sub-criticality on launch abort

The first one is a socio-political issue in that the US public has been told for decades by activists and the media that nuclear systems are dangerous. At launch, the NTR is simply a vessel that contains uranium locked in a matrix of graphite or tungsten. Technically, it is slightly radioactive but only to the extent that uranium is radioactive. No fission products are present. In the event of a worst case scenario, i.e. explosion of the rocket on the launch pad, parts will be distributed but no radiological threat will exist to the public.

The second issue has been studied by several review groups and by NASA for the past two decades. In 2008, a NASA supported team of government and industry participants spent several months designing a Fission Surface Power (FSP) system for the moon and estimating the cost of development [21]. The study estimated that the FSP would cost under $2B. This estimate encompassed three main categories: 1) reactor system development, 2) qualification of the system for space, and 3) alteration of facilities and security at the Kennedy Space Center to handle the system. The FSP estimate did not include any costs for ground based testing of a full power system nor any fuel development costs. The most recent estimate by NASA is that development of a NTR would cost around $3-3.5 B. This is consistent with the FSP estimate in that fuel development and ground testing of the NTR will increase the costs. In all, the costs are modest compared to the savings in launch costs, the improvement in mission performance, and the reduction in mission risk.

The third issue is probably the most important in the current socio-political environment. The primary benefit of the NTR is using it in LEO to escape Earth's gravity. However, the concept of having radioactive exhaust ejected into the upper atmosphere, regardless if it is technically not a threat to the biosphere, may not be publicly acceptable. The testing done during the Rover/NERVA programs showed that significant amounts of radioactivity were emitted in the exhaust in the form of fission products leaking out of the graphite fuel. Any new NTR fuel must demonstrate the ability to retain fission products at least during the initial "burn" duration.

Equally important is the fourth issue. The NTR will contain tens of kilograms of highly enriched uranium to fuel the reactor. This material is directly applicable to weapons if accumulated in pure form. In the event of a launch abort, the cold, easily handled, reactor core could reenter and land in a hostile nation. Preventing the nation from extracting the uranium from the reactor must be ensured.

Finally, in the event of a launch abort into the ocean, the reactor must remain in a subcritical state so that no heat is generated. In past systems, this is often accomplished by inserting neutron absorbing materials into the core. If the reactor enters the ocean, the neutrons will be moderated to lower energies where the fission cross section is larger. The neutron absorbing materials, however, prevent any multiplication in the core. This is true for thermal and epi-thermal reactor types such as the graphite fueled systems. However, the tungsten fueled reactors are "fast spectrum" reactors that rely on energetic, or fast, neutrons to maintain their reactivity. In the event of an ocean landing, the neutrons are moderated to low energies which are preferentially absorbed by the tungsten instead of the uranium. Thus, the tungsten reactors are inherently subcritical on ocean immersion.

Issues three through five may all be addressed by using a tungsten-based fuel form. During the GE-710 program in the 1960s, the retention of fission products by the tungsten matrix was demonstrated using static irradiations. In addition, removal of the uranium from the tungsten matrix will be very difficult and would require a significant infrastructure in chemical processing. Conversely, a graphite based core could be fractured and burned in a simple incinerator leaving the uranium in the ash. The other main advantage of the tungsten fuel form is on the full-power, ground test facility. If the fuel can be shown to not leak radioactivity into the exhaust, then a large, expensive containment facility to scrub out fission products is not required. Use of a smaller test facility could dramatically reduce the program costs.

V. CSNR RESEARCH ACTIVITIES

NTR Fuel Development

Because of the desire to reach extremely high temperatures in the reactor core, the Rover/NERVA programs relied on a graphite-based fuel. Consequently, graphite based fuels (beaded or composite) have the best data base and proven experience. The primary weakness of using graphite is that it must be coated with zirconium-carbide (ZrC) to prevent the graphite from chemically reacting with the hot hydrogen flowing tens of microns away in the flow channels. Cracking of the ZrC led to “mid-band corrosion” which was a major problem for much of the Rover program. Toward the end of the programs, tests of composite fuel elements in the Nuclear Furnace indicated that the mid-band corrosion problem was considered solved.

Fuel testing of the beaded fuels in the Rover/NERVA tests demonstrated various undesirable failings for reactor-fuel integrity and fission product retention [22,23]. The brittle nature of the core design resulted in cracks and thermal instability under the duress of engine vibration and propellant flow. Incompatibility of the coefficient of thermal expansion between the fuel and cladding resulted in significant fuel mass erosion from the corrosive hot hydrogen environment. With the loss of fuel mass, fission products were also released into the exhaust. Figure 2 shows an example of the midrange corrosion problem for PEWEE and Nuclear Furnace (NF-1) fuel elements for various fuel and coating compositions.

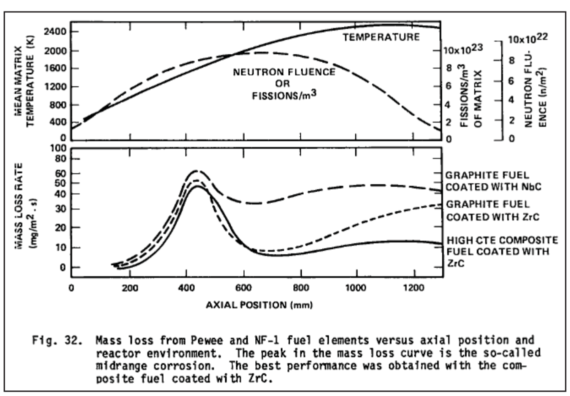

Figure 2. Midrange corrosion of PEWEE and NF-1 fuel elements. Figure extracted from reference 4.

At the time of the Rover/NERVA programs, an alternative fuel form using tungsten cermet composites was also investigated [24]. The GE-710 program in the 1960s and a program at the Argonne National Laboratory (ANL) later, both examined performance of tungsten based fuels for NTR operation. Fuel elements, see Figure 3, were irradiated and physical characteristics were measured but no reactor was ever tested with a tungsten core. Recently, interest in tungsten based fuel has increased because of the demonstrated capability to retain fission products in the metal matrix so that non-radioactive exhaust may be possible.

Tungsten-cermet fuel is potentially a high-endurance fuel and has excellent compatibility with high-temperature hydrogen gas. Tungsten has better thermal conductivity, a higher melting point, and is more resistant to creep deformation at elevated temperatures. Finally, tungsten is more resistant to radiation migration within its matrix and is more resistant to physical changes induced by radiation, such as neutron absorption [25]. It has been previously shown that fission product gases released within a tungsten-cermet matrix can be effectively contained for temperatures up to 1550ºC.[26]

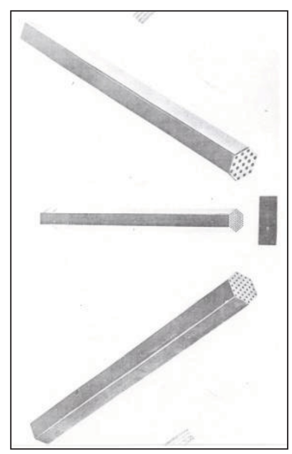

Figure 3. Tungsten cermet fuel elements fabricated in the GE-710 program in the 1960s.

Further enhancements of the tungsten-cermet fuel can be made using various tungsten-compatible additives. Rhenium and molybdenum can be added to the tungsten to reduce the brittleness and improve the toughness of the metal material. The ductile-to-brittle transition temperature is also adjusted through the addition of these materials. To reduce fission product migration and fuel inventory, the grain boundaries of the ceramics can be modified with various stabilizers such as thoria (ThO_2) or gadolinium oxide Gd_2O_3.

In 2007, the CSNR undertook a small project to investigate the ability to fabricate tungsten fuel elements. By using the Spark Plasma Sintering furnace at the Idaho National Laboratory, several samples of tungsten element were produced [27]. The samples were 3 cm in length, had a hexagonal cross section with 0.75 inches across the flats (same as the NERVA elements), used cerium oxide as a surrogate for uranium dioxide. The results are shown in Figure 4. The elements have 95% theoretical density with a 40% by volume blend of CeO_2.

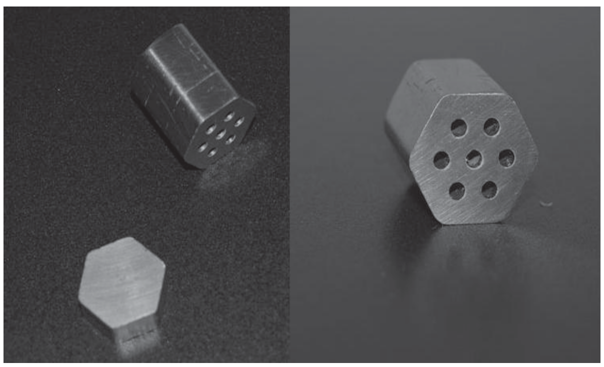

Figure 4. Tungsten nuclear thermal rocket fuel elements loaded with CeO_2 (40% vol.), which acts as the UO_2 simulant. The samples were fabricated using the Spark Plasma Sintering furnace.

Tungsten Cermet Pewee

Because so much information exists on the Pewee reactor test, many in the NTR community support the recovery of that engine using graphite based fuels. However, the advantages of the tungsten fuels in the current socio-political environment seem very clear. In 2009, the CSNR undertook a study to determine if a tungsten-based fuel loaded core with the exact dimensions of the Pewee engine would be critical [28]. MCNP was used to develop a model of the Pewee core including the beryllium reflector and the pressure vessel. Then the fuel region was replaced with a material consisting of uranium-nitride in a tungsten-rhenium matrix. The tungsten matrix had a 25% rhenium content indicated by the Ge-710 program. All other dimensions were consistent with the Pewee engine.

The results are shown in Figure 5. The criticality as indicated by K-effective is plotted versus the volume fraction of the UN compared to the total volume of the core. A direct substitution of the fuel is still readily critical. The results indicate that a lower fuel fraction could be used that would ensure containment of the fuel and the fission products.

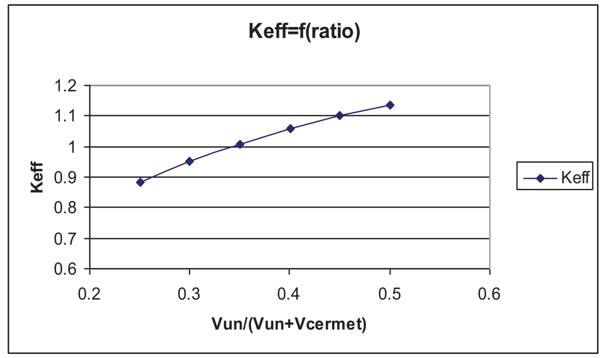

Figure 5. Results of MCNP calculations for tungsten loaded Pewee

Tungsten Based FSP

As previously stated, the long-term technological needs for the human exploration of space require an NTR propulsion system and fission surface power (FSP) system. Of these two systems, the fuel form for the NTR must meet more strenuous operational requirements. In the NTR, the fuel must survive longer than two hours at over 2500 K within a high mass flow of hydrogen. The FSP will operate for 3-8 years at a fuel temperature of 1000 K with a liquid metal coolant. Conceivably, fuel that is created, characterized, and qualified for the NTR could also be used in a FSP system, i.e. a Tungsten Based Fission Surface Power (TBFSP) design. However, the reverse is not true; the currently envisioned fuel for the FSP (UO_2 in a stainless steel cladding) cannot be used in the NTR. Because program development costs will be a significant factor in any future mission, the country will benefit from having a single fuel development program that can be applied to both systems.

In 2009, the CSNR executed a study designing the shield necessary to enclose the lunar FSP reactor. As part of this study, the UO2-stainless steel core of the FSP was replaced in the MCNP models with a tungsten based core with a 50% by volume uranium-nitride fuel. The Tungsten Based Fission Surface Power (TBFSP) core was adjusted in dimensions until the k-effective was the same as the FSP system. The results of the shielding study are shown in Table 1. Because of the self-shielding nature of the TBFSP, an external shield with significantly lower mass is needed. The tungsten based system had a system mass 20% less than the FSP.

Parameter	AFSP	TBFSP	Δ
outer diameter (cm)	48.8	41.7	7.1
height (cm)	79.7	52.9	26.8
reactor mass (kg)	~352	~225	127.0
BH2O Shield			
outer diameter (cm)	190.2	183.1	7.1
height (cm)	196.8	170.1	26.7
shield mass (kg)	6712.5	5510.3	1202.2
total mass (kg)	7064.5	5735.3	1329.2
Trilayer Shield			
outer diameter (cm)	185.2	179.3	5.9
height (cm)	197.8	175.5	22.3
shield mass (kg)	6880.0	5286.6	1593.4
total mass (kg)	7232.0	5511.6	1720.4

Table 1. Shield Parameters for AFSP and TBFSP.

<u>Economically Ground Testing the NTR</u>

The second "long-pole" in recovering the NTR is the ability to perform full power full duration ground tests. This was done during the Rover/NERVA programs over 20 times by exhausting the effluent into the air. This operational mode is no longer possible. While the combination of electrical heating and computational modeling may allow a reduced number of full integral tests to be made, full power and full duration are required to qualify an engine for operation is space. This requires a new way to test.

At the end of the Rover/NERVA programs, a small reactor called the Nuclear Furnace (NF) was used to test advanced fuel elements. The NF had a full power of 44 MWth and a hydrogen gas flow of 1 kg/s. In addition, the NF demonstrated that the exhaust could be "scrubbed" entirely clean of all fission products. Conceivably, the scrubber design can be scaled up to accommodate the higher gas flows, 7 to 15 kg/s, that will be present in a full power engine test. Past studies of this concept indicate that such a facility would cost between $150 M to $500 M [29,30]. This is a significant investment and may preclude interest in recovering the NTR.

Alternatively, a concept called the Subsurface Active Filtering of Exhaust (SAFE) was developed in the mid-1990s [31], see Figure 6. This concept utilized the extensive knowledge of the geology of the Nevada Test Site obtained over 50 years of nuclear weapon testing. Computational modeling of the concept shows that the exhaust from a NTR could be contained in one of the large holes (typically 8' by 1200' deep) present at NTS. The cost of using this concept has been estimated to be under $50M. In addition, if a fuel can be made that does not leak into the exhaust, then the ground test facility need only be a "off nominal backup" not a radioactive filter. This reduces the motivation to build a large facility and adds impetus to the SAFE concept.

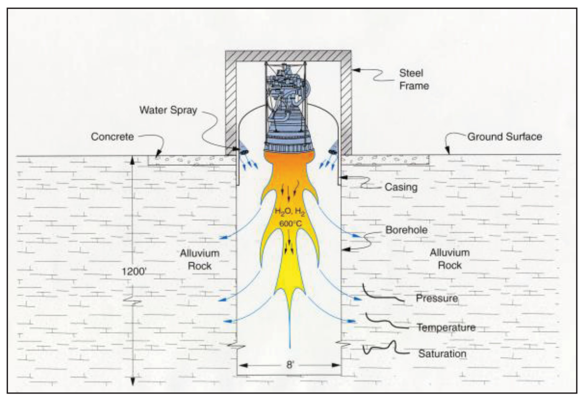

Figure 6. Schematic of the SAFE testing concept.

In any case, if SAFE can be proven feasible, it is less expensive and faster to build. If proven infeasible, then the design of a surface facility must be started soon in order to meet the timeline for a human mission to Mars. In 2007, NASA funded a study to reexamine the feasibility of the SAFE concept. A collaboration between the Idaho National Laboratory, the CSNR and the Desert Research Institute (DRI) in Las Vegas, NV evaluated the original configuration for testing NTRs first proposed by the Los Alamos National Laboratory (LANL) in 1998 and also designed a proof-of-concept experiment. Using a different code resident in DRI, the original LANL results were confirmed with regard to pressure built up in the hole during an NTR operation [32]. The study also showed that an experiment using an eight inch diameter hole pressurized with hot argon gas could validate the code estimates for under a million dollar cost.

VI. SUMMARY AND CONCLUSIONS

The NTR is a single system that could enhance or enable both manned and unmanned missions throughout the solar system. The technology achieved a NASA TRL-6 level during the 1960s in the Rover/NERVA programs. Because of the current socio-political environment, tungsten based fuels may offer several advantages over the graphite based fuels used in the previous engines. The CSNR has undertaken a variety of feasibility studies to show that tungsten based fuels 1) offer significant advantages for many missions, 2) can be fabricated using powder metallurgy techniques and the SPS furnace, 3) have reduced mass and shielding requirements compared to standard reactor designs, and 4) could be substituted into previous NTR designs such as the Pewee engine. The NTR is the best candidate for near term technology advance to support the exploration of space.

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