

Affordable Development and Qualification Strategy for Nuclear Thermal Propulsion

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A number of recent assessments have confirmed the results of several earlier studies that Nuclear Thermal Propulsion (NTP) is a leading technology for human exploration of Mars. It is generally acknowledged that NTP provides the best prospects for the transportation of humans to Mars in the 2030's. Its high Isp coupled with the high thrusts achievable, allow reasonable trip times, thereby alleviating concerns about space radiation and "claustrophobia" effects. NASA has embarked on the latest phase of the development of NTP systems, and is adopting an affordable approach in response to the pressure of the times. The affordable strategy is built on maximizing the use of the large NTP technology base developed in the 1950's and 60's. The fact that the NTP engines were actually demonstrated to work as planned, is a great risk reduction feature in its development. The strategy utilizes non-nuclear testing to the fullest extent possible, and uses focused nuclear tests for the essential qualification and certification tests. The perceived cost risk of conducting the ground tests is being addressed by considering novel testing approaches. This includes the use of boreholes to contain radioactive effluents, and use of fuel with very high retention capability for fission products. The use of prototype flight tests is being considered as final steps in the development prior to undertaking human flight missions. In addition to the technical issues, plans are being prepared to address the institutional and political issues that need to be considered in this major venture. While the development and deployment of NTP system is not expected to be cheap, the value of the system will be very high, and amortized over the many missions that it enables and enhances, the imputed costs will be very reasonable. Using the approach outlined, NASA and its partners, currently the DOE, and subsequently industry, have a good chance of creating a sustained development program leading to human missions to Mars within the next few decades.

Nomenclature

AEC	= Atomic Energy Commission
AIAA	= American Institute of Aeronautics and Astronautics
APEX	= Advanced Post Irradiation Examination
ALARA	= As Low As Reasonably Achievable
ATP	= Authority to Proceed
ATR	= Advanced Test Reactor
CFEET	= CERMET Fuel Element Environment Tester
CFM	= Cryogenic Fluid Management
Con-Ops	= Concept of Operations
CTE	= Coefficient of Thermal Expansion
DDT&E	= Design Development Test and Evaluation
DOD	= Department of Defense
DOE	= Department of Energy

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EIS	= Environmental Impact Statements
E-MAD	= Engine Maintenance and Disassembly Facility
EPA	= Environmental Protection Agency
ETF	= Engine Test Facility
ESF	= Engine Support Facility
ETS	= Engine Test Stand
IMLEO	= Initial Mass in Low Earth Orbit
INL	= Idaho National Laboratory
INSRP	= Interagency Nuclear Safety Review Panel
JANNAF	= Joint Army, Navy, NASA, and Air Force
JPC	= Joint Propulsion Conference
KDR	= Key Driving Requirements
MSFC	= Marshall Space Flight Center
NESHA	= National Emission Standards for Hazardous Air Pollutants
NEPA	= National Environment Policy Act
NERVA	= Nuclear Engine for Rocket Vehicle Application
NF	= Nuclear Furnace
NSP	= National Space Policy
NTP	= Nuclear Thermal Propulsion
N TREES	= Nuclear Thermal Rocket Element Environment Simulator
PD/NSC-25	= Presidential Directive/National Security Council Memorandum #25
ROM	= Rough Order Magnitude
RTG	= Radioisotope Thermoelectric Generator
SAFE	= Sub-surface Active Filtering of Exhaust
SAR	= Safety Analysis Report
SEI	= Space Exploration Initiative
SER	= Safety Evaluation Report
SNTP	= Space Nuclear Thermal Propulsion
SSC	= Stennis Space Center
TRL	= Technology Readiness Level
ZPPR	= Zero Power Physics Reactor

I. Introduction

Development of nuclear power for space use, and specifically of nuclear thermal propulsion (NTP) systems, will likely involve significant expenditures of funds and require major effort. The payoff of the development investments will occur with the greatly expanded mission capabilities that NTP systems will provide, and amortized over many future missions¹. That being said, it is clear that the development effort still needs to be economically viable for it to survive the budget-cutters axe. Thus, affordability is a major consideration in the planning of the program. In his 2011 AIAA/JPC paper², Bhattacharyya had laid out the conceptual basis of an affordable NTP development program. Briefly, the approach begins with the utilization of the considerable database from the past, recognizing the technical feasibility of the concept has clearly been established, and build on that base. Based on the currently conceived and projected missions, a matrix of data needs for NTP “qualification” should be constructed. Most of the non-nuclear subsystems of a base NTP system have been developed and tested in earlier chemical propulsion programs (albeit without the same radiation environment as NTP). The Rover/NERVA and Cernmet programs in the US and the extensive Soviet program developed a large volume of data on the nuclear subsystem. The elements of the matrix should be populated from evaluations of these earlier data, and the holes in the matrix identified. The development test program should be concentrated on filling these holes in the data matrix. Because of the schedule and cost issues with nuclear testing, use of non-nuclear tests should be maximized. Advances in fuel manufacturing techniques should be used to develop one of the two candidate fuels with maximum fission product retention capability, since release of fission products during operation has been at the root of many of the problems identified with NTP. Many of the individual design parameters can be verified by low-power nuclear critical experiments, and individual irradiations of fuels and materials. A limited set of issues can be identified that can be addressed by a well-designed integrated ground test program. Costs of ground tests (a major problem area identified in the past) can be minimized by developing a fuel with excellent fission product retention capability and selecting the smallest size engine for the mission. Prototype flights should be used as part of the development program. A bootstrapping

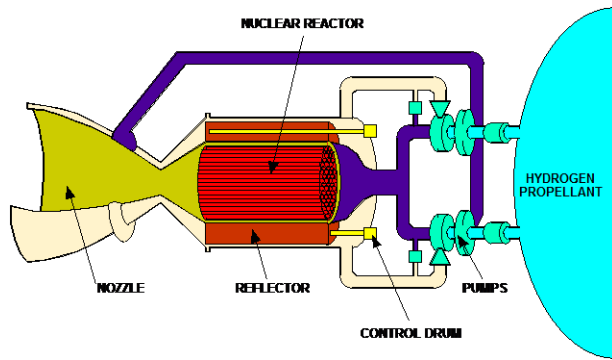


Figure 1. Major Parts of NTP System.

strategy of starting with a very conservative system, followed by progressive upgrades of capability should be adopted.

In a basic sense, NTP is a thermal expansion nozzle engine concept similar to liquid chemical propulsion except the energy to heat the propellant comes from a fission reactor instead of combustion. With hydrogen as propellant, the specific impulse is about twice that of chemical propulsion since the average molecular weight is very low without an oxidizer. The engine concept is shown in Fig. 1. A fission reactor is located in the thrust chamber and acts as a heat exchanger to heat the propellant to 2500K-3000K. The hot propellant expands through a

traditional de Laval nozzle. The feed system is very similar to the liquid engines and requires a turbopump. Surrounding the reactor are control drums containing neutron absorbers, used to control the reactor criticality and power level. Internal shielding inside the thrust chamber helps shield the outer components from radiation caused by the fission reactions. The major technical differences NTP has versus chemical propulsion include radiation released during operation, long start-up and shutdown, and lower thrust-to-weight due to the reactor and shielding mass. Figure 2 is an example of the radiation profiles for neutron flux and gamma rays during operation. The engine components and surrounding hardware (including instrumentation) must be able to survive the radiation environment. Figure 3 shows an example of the engine start-up and shut down phases. NTP start-up can take up to a few minutes, while shut-down depends on the length of burn and can take up to tens of hours before the energy released from the radioactive decay products gets down to tens of kilowatts. These added conditions of operation add complexity to the design and ground testing compared to traditional liquid rocket engines. In addition, the engine must operate for longer burn durations and restarts compared to liquid rocket engines.

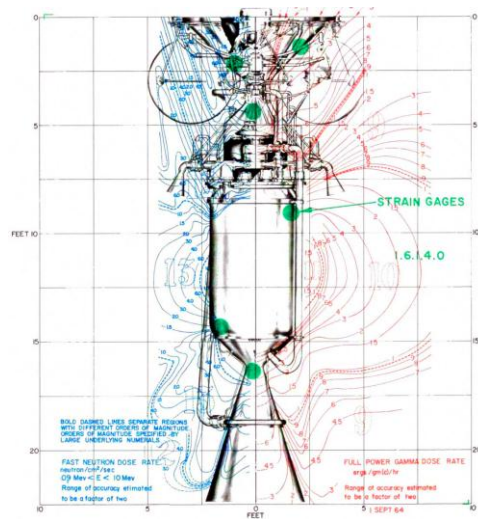


Figure 2. Predicted Radiation Profile for NERVA Flight Engine.

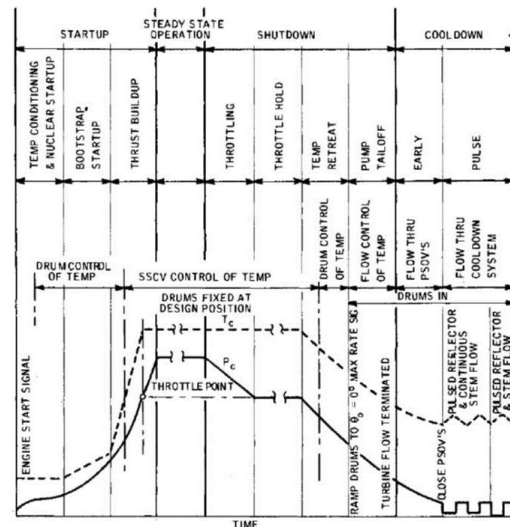


Figure 3. NERVA Engine Operational Phases³.

A. Lessons Learned from Past Programs

While there have been numerous paper studies that have made compelling arguments about the advantages of NTP, there have really been only four major programs around the world that involved development and testing of hardware. The first, most widely documented was the Rover/NERVA program in the US conducted during the period 1955–1973, see Fig. 4. A smaller complementary program, featuring cermet fuels and a fast spectrum reactor

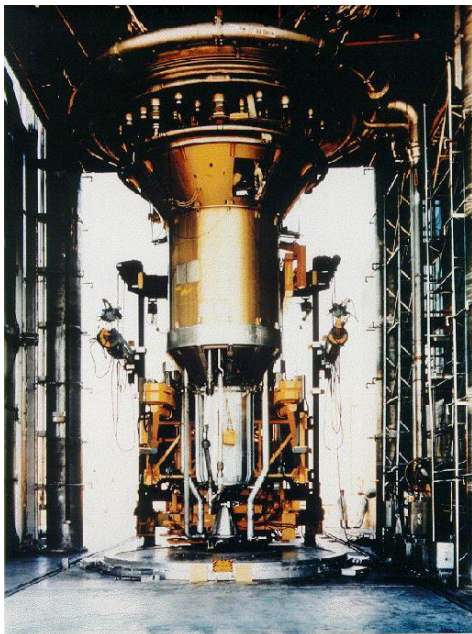


Figure 4. NERVA Test Engine XE' at Engine Test stand.

was conducted during the same period. In the USSR, a very significant nuclear rocket development program was undertaken, involving several Laboratories and the test site at Semipalatinsk. Finally, the Space Nuclear Thermal Propulsion (SNTTP) program was a more limited, but still significant undertaking funded by the DOD, carried out in the late 1980's to early 1990's. The total represents many billion dollars of development work (in current dollars) and is a very significant base on which to build the current NTP program.

The reports on the above programs have generally been exhaustive, and results of the test programs have been assessed extensively. The most significant lessons learned are summarized below.

1. The technical feasibility of the NTP concept was established via all of the separate effects and integral testing. This is a key point, since the NTP concept is complicated and involves advances in several technologies. All of the integral testing was done for the Rover/NERVA program, but the other programs added significantly to the database for the components, and in bolstering the confidence level in the determination of the viability of the concept. No show-stoppers to the deployment of NTP technology were identified.
2. The most challenging individual technology was the nuclear fuel, which had to operate at considerably higher temperatures than any other class of nuclear reactor, albeit for short periods of time. The extensive work performed in these programs established that there were several classes of fuels that had the potential to meet the demanding requirements.
3. The very high propellant (reactor coolant) gas temperatures needed to maximize the performance of NTP engines has encouraged the use of special measures to enhance heat transfer to the propellant from the high temperature fuel. High engine thrust-to-weight ratios require high fuel power densities, and measures must be taken to keep thermal stresses acceptable. Thus, the Russians used a twisted ribbon geometry of the fuel, and the SNTTP program went to small particulate fuel to maximize surface area for heat transfer. In the composite and cermet fuels, the heat transfer paths between the fuel and the coolant flow were kept as small as possible. Flow stability considerations argued against some of the special designs to enhance heat transfer surface area.
4. The test programs spanned the range of parameter levels (power, temperature, operational time) that are of interest for applications of NTP. The implication is that there will be no technology extrapolations needed from what has been shown to work for the practical NTP systems deployed for missions. This is not true for most advanced technologies, for which extrapolations of an order of magnitude or more are typical.
5. Not all of the problems identified during the programs were resolved by the time the programs ended. Principal among the remaining problems was the issue of integrity of the fuel forms during the test, and the release of fission products. The releases were not considered serious in the early days of nuclear testing, when most of the programs were operated, but would be unacceptable in terrestrial testing under current conditions. The releases could be an issue in human flights. The implications of this are that the containment of fission products during operation will be an important consideration in the choice of fuel type.
6. The non-nuclear, balance-of system components (pumps, nozzles etc) are generally common to those used for chemical propulsion systems, and generally available from other development work. There is an additional requirement of radiation tolerance, but the neutron and photon fluences are expected to be small, given the planned operating history, and straightforward exposure tests should be able to provide the necessary data to certify their use.

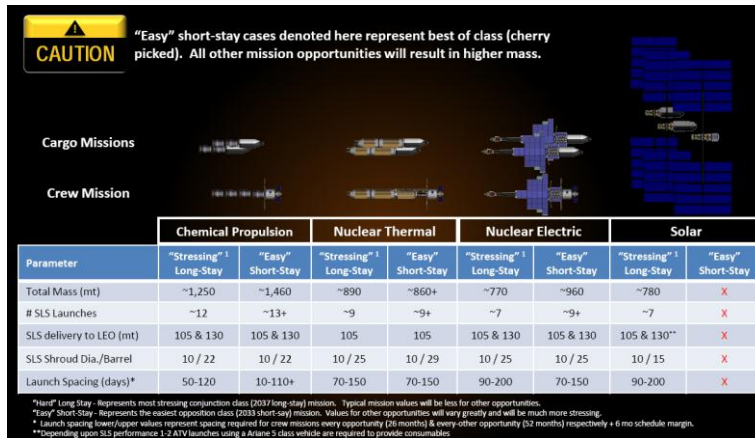


Figure 5. Launch Campaign and Transportation Options⁴.

7. In addition to the testing intensive programs discussed earlier, there were a large number of studies conducted by NASA to examine the potential utilization of NTP systems. In all of the studies it was concluded that there were significant advantages to NTP systems that made them better to all of the competing systems for human transit to Mars. Figure 5 shows the most recent comparison.

8. All of the past NTP programs were terminated prior to any flight tests primarily because of lack of missions. An accepted, compelling mission, with broad-based political support, is essential for the ultimate success of an

NTP development project. NASA is now developing the infrastructure with SLS and MPCV which are needed for the compelling missions which can utilize NTP.

9. A number of NTP development programs were terminated abruptly (which is atypical of many advanced technology programs). These abrupt stops followed by restarts after some elapsed time is a very wasteful method of technology development, because of the learning curves of the new participants, aging and unavailability of facilities, re-signing of contractors etc. One of the issues is that final reports on the work done in many of the programs were never prepared, adding to the overall wastage of effort, as much of the work had to be redone.

Additional lessons learned from the recent development of the J-2X rocket engine are also very helpful. Development engines in a program are not flight fidelity and can be tested to extremes to gauge margins to failure. Start with low safety factors and evolve them to human rated ones later in the program. Involve Safety and Mission Assurance upfront, along with a dedicated risk management effort. The J-2X element requirements document is a good starting point for good design and construction standards. J-2X has two certification engines and five/six development engines to test. The recent development of the A3 Steam-Ejector Test Stand, to be used to test the J-2X, will provide significant benefit in the areas of Civil Servant and Contractor experience base that will be directly applicable to the testing of a confined nuclear engine.

For reference, it is noted that the cost of chemical rocket engine development is not small. Extensive effort goes into engine development and qualification to guarantee the reliability and assurance to acceptable levels. Human rating a flight engine involves greater effort and cost than engines used for cargo and science only. Table 1 shows a rough cost for various rocket engines flown in the past. The most recent human rated engine development is with the J-2X engine. The ROM cost is over a few billion dollars. Thus, the added cost for dealing with a nuclear engine's operation and handling adds complexities and is unlikely to be cheaper than chemical engine development. However, what justifies the added cost is the huge savings for a human mission to Mars shown in Fig. 5. Saving 3-4 heavy launches for each mission adds up very quickly. If future launch cost for heavy lift launch vehicles is about \$500M⁵, then a 4 launch savings on a single mission pays for the majority of NTP development, not accounting for

Table 1. Cost of Past Chemical Rocket Engines.

Engine	Thrust (lbs)	Period	Development Cost FY12
F-1	1500K	'59-'66	~\$3.0B
SSME	470K	'72-'81	~\$4.1B
J-2	200K	'60-'66	~\$2.6B
RL10A-3	15K	'58-'63	~\$0.9B

the schedule savings with fewer launches. In addition, as the number of launches decreases, the probability of leaving earth orbit increases⁴.

The total cost for the Rover/NERVA program operating from 1955-1973 is \$7.6B in FY13 dollars⁶. The total cost included AEC and NASA funds allocated. The cost included the evolution of different test cells, test stands, engine maintenance and disassembly hot cells, and a variety of engine sizes along with the manpower for all the engineering and operations. To minimize NTP

development cost, the current strategy is to focus on a small engine size (utilize a cluster of engines for the mission), the minimum required test facility, utilize existing hot cells for component inspection, and incorporate many past lessons into the development to take advantage of all the early effort and resources expended.

II. Development Needs

A. Concept of Operations

A Concept of Operations must be developed that takes into account the resources used from Rover/NERVA Programs and collective resources of NASA and the Department of Energy and combines them in a cost effective manner.

The Concept of Operations (Con-Ops) to be developed should start at the component level and move through flight operations. It should take into account Technology Readiness Levels (TRL)⁷, contracts needed from the beginning to end of the program, construction of facility cost, manpower estimates and the flow of data, information and money at all external programmatic interfaces. While this sounds like a daunting undertaking, by using triage, adequate margins (both programmatic and technical), and by employing field experts who understand the relationship of the Key Driving Requirements (KDRs) to the choice of margin as it relates to the sensitivity and impact to the system performance, schedule and budget, a reasonably accurate and affordable set of plans can be prepared.

The Con-Ops should be developed by first determining the overall functional activities that have to take place to design, develop, test, and fly a nuclear rocket. This can then be translated into KDRs for that activity. The possible solutions in the list can then be traded, one against the other. How the different solution sets may be put together, and what level of risk is acceptable can then be compared through the lens of cost and schedule. The best Con-Ops would then be the one with the best balance between programmatic and technical risk, schedule and budget. Political aspects of the winning Con-Ops must also be considered. Sometimes the trade space is larger than what is defined in a study. Many final decisions in NASA's past have taken into account things like maintaining engineering skill and manpower for later planned activities, even when a cheaper or more technically pure solution was identified.

One key to a good Con-Ops and cost estimation is the early and accurate identification of low TRL technologies. At every level of the engine, stage and supporting infrastructure a survey of the TRLs as they relate to use in a nuclear engine and vehicle should be made by experts in the given area. Each technical specialty should identify areas where the current TRL is inadequate to proceed into the design phase. By definition, the TRL can be no higher than 4 or 5 for any of the component on a nuclear stage. TRL 5 is characterized by testing a prototype in a representative environment. Certainly this was done, for some technologies, in the Rover/NERVA programs. However, it was done by a different team, the designs were different, and different tools were used. This means that much of the technology will be at TRL 3 or 4. This does not mean that these are difficult to do, or that the program should not be undertaken. Rather, it simply indicates that there is an element of risk that translates into difficulty in accurately estimating the operational needs, schedule and budget associated with bringing up the TRL. Technical experts can provide input to systems engineers to determine the TRL. This can then be used in existing cost models to determine the projected cost to bring the technology up to the required level. TRLs are often overestimated because nested low TRLs are not considered, or impact at the contractual and manufacturing levels are not considered. Overestimated TRLs will most often be manifested in budget overruns and schedule slips later in the program and may cause a poor choice of Con-Ops.

Another key to developing a good Con-Ops is the accurate identification of requirements and what is required for validation of that set of requirements. Validation activities, especially at the engine and stage level will drive infrastructure costs. Validation at the component level can drive contract cost and often become critical items in the development schedules. Development of facilities and the number of tests performed will directly correlate with the TRL levels of the system and its components. The lower the TRL and the more challenging the design, the more Test-Fail-Fix Cycles will be required. Often the development portion of the testing is underestimated. Methodologies have been developed, based on TRL, design complexity and team experience that estimate the amount of development testing that will be needed to fix unforeseen problems and validate the resulting engine and stage design.

B. Engine Requirements from Mission Analysis

For Mars, mission level analysis has shown the need for engines that can produce from 25,000 lbf to 35,000 lbf thrust at 900 seconds of specific impulse. Total burn durations of around 100 minutes during the mission will be accumulated over four firings. The longest burn would be 45 minutes. Keeping the thrust to these lower levels and flying clusters of engines can proportionally reduce test facility requirements on the exhaust side of the engine test facility. This also can facilitate single engine out operations for some if not the entire mission, thereby enhancing system reliability.

Determining the requirements for human rating a nuclear propulsion system could possibly be a challenge. Past NASA human missions had abort or rescue options. This will not likely be the case for Mars missions, or any other long distance or long duration mission. It is possible that a larger numbers of tests will be needed to produce a design that engineers and managers have sufficient confidence in to proceed into Certification Testing and subsequently human flight. The generation of statistical confidence at the prototype and specimens level may also be a way to establish confidence that mission success is reasonably assured. Designing to minimize single point failures and include redundancy will be included in the engine and stage requirements set. (*See NASA NPR8705.2B Human Rating Requirements for Space Systems*)

The precise approach to NTP engine qualification has not been determined yet. However, parallels from chemical rocket development can be used to lay out options. Unlike chemical engines, a nuclear engine cannot be green run before flight for acceptance testing. A green run is usually a fully power level test of an engine prior to flight. Solid rocket motors are not green run, their viability for flight relies on design margin and careful quality control. It is likely that this type of an approach combined with zero or low-power critical testing may be used for a nuclear engine or combined engine and stage prior to flight.

JANNAF guidelines recommend six engines as a minimum be developed to human rate a chemical rocket engine. Four of those six engines would be development engines. The development engines design would be very comparable to the other two certification engines. Typically twice the operational life and numbers of starts would be demonstrated without failure or significant issue to qualify as human rated. This will likely be a minimum standard for a nuclear engine. Ultimately, for reasons outlined in the preceding paragraphs, more than two certification engines may be required to validate the design, manufacturing and quality control processes.

C. Status of Database from Past Work

Reports on the four major hardware-based programs listed earlier have been produced, and are available for review. As expected, there is an extensive set of reports from the Rover/NERVA program, with decreased amounts of information on the Cermet and SNTP programs, reflecting the smaller magnitude of effort expended in these programs. In the case of the Russian program, considerable volumes of data have been made available by the Russians in the post 1990 period of openness; however, the fidelity of the data has been questioned, and the lack of formality of the available reports has been an impediment to the use of the data. Data from each of these programs will be discussed below⁸:

a) Rover/NERVA Program: The program designed a large number of reactors and built and tested twenty of them. Of these 17 were test reactors, one safety reactor and two ground test engines. The power levels of these reactors ranged from 44 MWt, to 4100 MWt, and the times of operation ranged from a few seconds to 109 minutes (of accumulated operating time). The large number of reactors built and tested provides a sharp contrast to the current practice of limited funding programs, and reflects a major difference in the public attitudes towards nuclear programs. The peak temperature attained in the composite fuel was 2750K, corresponding to a specific impulse of 848s. While several of the graphite based fuels showed potential, the (UC,ZrC)C composite fuel was seen to be the most robust, and best suited to follow-on work. Considerable test data were presented for the fuel, including measured thermal/mechanical properties. At the end of the program, the one remaining unresolved issue was the leakage of fission products from the coated fuel. This has been attributed to the mid-band corrosion problem, caused by mismatch of CTE's between the fuel and the coating.

b) Cermet Program: The cermet fueled reactor program was run as a parallel alternative to the mainline NERVA program. It was designed to take advantage of the compatibility of tungsten and hydrogen and the possibility of attaining high temperatures with a tungsten matrix. In essence, the fuel consists of UO₂ particles embedded in a tungsten matrix. The presence of the large amount of natural tungsten required the use of a fast

spectrum reactor, as opposed to the epithermal reactors that were a feature of the NERVA program. No reactors were built for this program, but cermet fuels (using UO_2 and UN) were fabricated and tested in non-nuclear and nuclear environments. The fuel performed very well in non-nuclear tests with hot hydrogen at temperatures up to 3000K with cycling. It also successfully withstood multiple nuclear transient tests at temperatures up to 2900K, and ramp rates of 16000K/s. In addition, the fuel performed well under steady state nuclear irradiation at temperatures of 2000K, and burn up of 1.6 atom %. The fuel also promises significant safety advantages; first in its mechanical robustness, which reduces the risk of criticality on accidental compaction of the core, and second in its ability to provide inherent subcriticality under submersion accidents. The main shortcoming of the fuel is the lack of as extensive a database as the composite fuels.

c) SNTP Program: The SNTP program featured a modified version of the TRISO particle fuels, with a UC_2 kernel, and various carbide coatings. The temperatures attainable with this fuel were limited to the 2400K-2800K range, and advanced bi-carbide fuels were identified as a growth option. Several non-nuclear and a few irradiation tests were performed. Fuel fabrication efforts with the UC_2 kernels were successful, but the early tests showed flow instabilities that needed to be addressed. The program was terminated without major nuclear testing.

d) Russian Program: The Russian (actually the USSR program) included a large variety of fuels and what has been reported as an extensive set of nuclear and non-nuclear tests in hot hydrogen. No NTP reactors were constructed, but special purpose reactors were designed and operated to test fuels and fuel assemblies under prototypic flow conditions. In addition, nuclear critical experiments were performed to confirm the validity of the core designs.

For the (UC, ZrC, NbC) tri-carbide fuels, very impressive performance numbers were reported (3100K exhaust gas temperature, for a period of one hour). However, it was difficult to verify the results, and it seemed unlikely that stoichiometric stability could be maintained at those temperatures. The Russians claimed the use of a special binder, but the composition of the binder was not revealed. They also reported success with their version of cermet fuels, using carbonitride fuels. In view of the uncertainties, it was judged to be prudent to not use their experience directly, but add them to the large body of information that supported the viability of NTP systems.

D. Key Development Items

From the above discussions it is clear that while most of the components in the NTP system will have to be designed and sized for the application needed, there are two areas that will need long lead development effort. The first is the nuclear fuel, which is the central component of the nuclear reactor that drives the propulsion system. The second is the approach and facilities to be used for the integral ground testing of the propulsion system prior to flight.

The programs described earlier had developed and tested various kinds of nuclear fuel for the NTP application. While many of the fuels showed promise, most of them did not display the high temperature performance and or stability needed for NTP mission applications. In fact none of them emerged from the programs with an unblemished record, which leads to the need for a development program before final acceptance. The three which appeared to have the most potential were the (UC,ZrC)C composite fuel developed during the NERVA program, the W- UO_2 cermet fuel developed during the parallel cermet program, and the bi-carbide fuel used by the Russians (and examined during the SNTP program). The Russians also worked on tri-carbide fuels in their quest for very high temperatures. The Russian fuels were not considered to be candidates for the current program because of questions regarding their claims. That left the two fuels UC,C composite and cermets as the two candidate fuels. The former had the advantage of an extensive data base, under prototypic operating conditions, but did suffer from significant fission product release problems at elevated temperatures – attributed to the mid-band corrosion problem, caused by a mismatch of CTE's between the fuel and the necessary coatings. The latter had rather limited testing during the NERVA program, but showed great promise, and revealed no obvious show-stoppers. A number of reviews (e.g. Bhattacharyya, 2001) concluded that a prudent NTP development program would start with both the candidate fuels, and based on test results that address the performance criteria of the fuel, a down selection to a primary fuel could be made during the program. The luxury of having two potential fuel types that could be acceptable is a strong risk reduction feature of the program.

The issue with the integrated ground test is that the environmental constraints on ground testing currently in force are far stricter than those that were adopted during the Rover/NERVA program. Specifically, the fission product releases that were considered allowable in the early days will be unacceptable today. The implications of this are that if conventional test facilities are utilized, and if the fuel releases fission products as it did earlier, scrubbing and containment systems have to be added on to the facility design, potentially increasing cost. The alternatives are to use innovative integral testing methods, and/or develop robust fuels that can contain fission products.

III. Programmatic Considerations

A few major programmatic considerations must be acknowledged which can impact the NTP development schedule and cost. Some of these require a long lead time and must be considered early in the program.

The National Space Policy (NSP) was recently updated under the Obama Administration in 2010. The NSP states “The NASA Administrator shall...By the mid-2030’s send humans to orbit Mars and return them safely to Earth”. This goal helps set a milestone on the NTP development schedule on when to have the engine certified for human missions. The NSP also has a section for Space Nuclear Power, which states the following:

Approval by the President or his designee shall be required to launch and use United States Government spacecraft utilizing nuclear power systems either with a potential for criticality or above a minimum threshold of radioactivity, in accordance with the existing interagency review process. To inform this decision, the Secretary of Energy shall conduct a nuclear safety analysis for evaluation by an ad hoc Interagency Nuclear Safety Review Panel that will evaluate the risks associated with launch and in-space operations.⁹

The nuclear safety launch approval process is composed of four requirements; Nuclear Environmental Policy Act (NEPA), Presidential Directive/National Security Council Memorandum #25(PD/NSC-25), radiological contingency planning, and risk communication^{10,11,12}. Figure 6 summarizes the process for each requirement. The processes have been used in the past and most recently for launching radioisotope thermoelectric generator (RTG) power system for spacecraft. RTG’s use decay heat from plutonium 238 and are radioactive at launch. A NTP engine uses a fission reactor and its radioactivity is extremely low at launch. However, similar launch approval process will be conducted for NTP to investigate impacts from a variety of probabilities from planned operation to possible accident and launch abort scenarios.

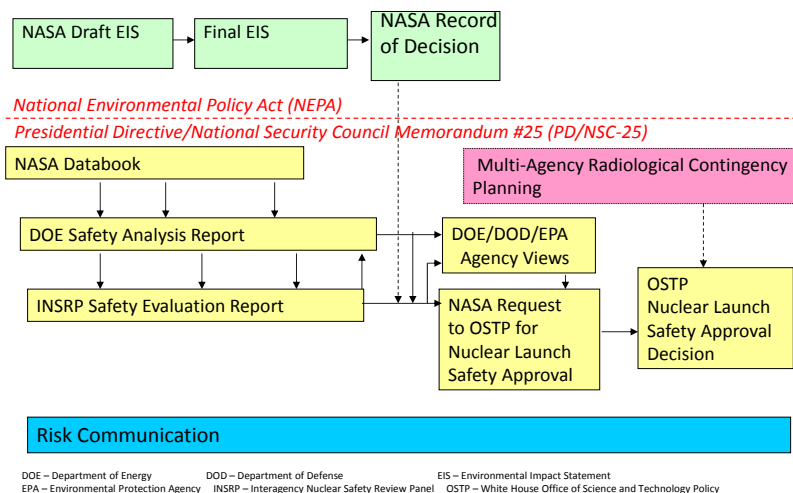


Figure 6. Nuclear Safety Launch Approval Processes¹⁰.

The NEPA became law in 1969 and is made of environmental impact statements (EIS) which assess potential environmental impacts and alternatives associated with mission development, integration, test, and launch. A decision to proceed with investments is needed before full development. The decision maker is the Associate Administrator for the mission. A public notice of intent is released to the public to prepare for a draft EIS for the launch site and ground test facilities. Early public meetings are recommended for education and to start collecting and responding to feedback as part of the draft and final EIS. It is important the public stay informed to avoid misconceptions. NEPA needs to start early before an authority to proceed (ATP) with NTP development. NEPA can be

done in stages. The duration can take 1-3 years and cost a few million dollars. Long term decommissioning and disposal issues are to be included.

The PD/NSC-25 process assures the agency has an independent safety assessment to baseline the safety recommendation. The process involves multiple agencies because of multiple safety responsibilities. The DOE will provide a safety analysis report (SAR) based on the NASA provided SAR databook. An ad hoc interagency nuclear safety review panel (INSRP) evaluates the SAR and prepares a safety evaluation report (SER), which is reviewed by DOE, DOD, and EPA. The NASA administrator requests nuclear safety launch approval through the Director of the President's Office of Science and Technology Policy and includes the SAR and SER. The process starts when the NTP development is beyond the critical design review. The process can take 3-5 years and depends on databook development. The cost can be in the tens of million dollars.

The radiological contingency planning involves the federal coordinating agency representative ensuring a prompt response to an emergency, up to and including implementation of the radiological annex to the national response plan. The planning provides recommendations and protective action guidance for the workers and general public safety for all situations (e.g., handling, transporting, storing, disposal, launch abort and other possible emergencies). Basic safety guidelines for a mission utilizing radioactive materials are to provide protection to the public, environment, and users such that radiation risk from exposures are as low as reasonably achievable (ALARA). Risk communication is considered throughout the project's evolution to ensure radiological risk is acceptable.

Safeguards and security are another programmatic consideration. Highly enriched uranium (20% and greater concentrations of U235 and 5kg quantities or greater¹³) requires protection against theft. NTP engine designs of the past used large quantities of highly enriched uranium. Special security is required whenever significant quantities are on-site, transported for launch, or retrieving a reactor from launch abort. Added cost and schedule is not just from added security manpower, but modifications to existing or new facilities to account for Category 1 security. The current program strategy is to minimize the amount of highly enriched uranium used in the new NTP reactor designs and investigate effects on engine performance. The added complexities of Category 1 security can dramatically decrease if the NTP engine design utilizes the minimum quantities of highly enriched uranium with low strategic significance. The change is being investigated to determine the effect on reactor design and safety posture.

These programmatic considerations are being accounted for in the NTP development plans since they greatly influence the engine design, ground testing, flight operations, program cost and schedule.

IV. Fuels Development

Based on earlier evaluations^{14,2} the decision was made to evaluate the two most promising fuels for NTP. The NASA/DOE team is working on cermet fuels (Fig. 7), and composite fuels (Fig. 8). Both the fuels have been shown to "work" in the earlier programs, and have the potential to meet requirements, so by carrying both fuels in the early phase of development, the development risk is minimized.

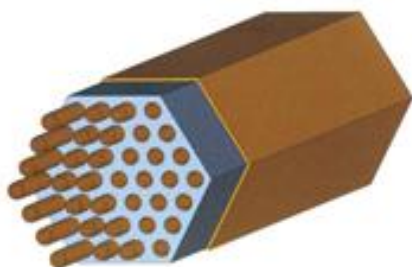


Figure 7. UO₂/W Cermet Fuel.

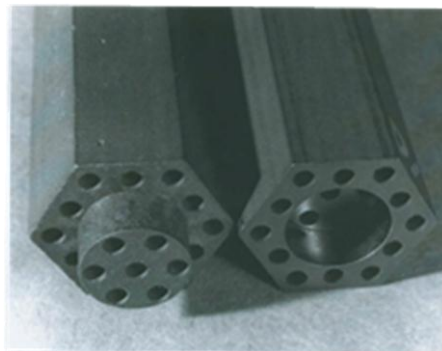


Figure 8. NERVA Composite Fuel.

The performance criteria that will be imposed on the fuels are listed below.

- a) Fabrications with acceptable quality assurance and control
- b) Temperature stability ($>2700\text{K}$ for $1000+ \text{ s}$)
- c) Mechanical/Structural strength
- d) Chemical compatibility (with contacted materials at high temperature in Hydrogen)
- e) Transient performance (multiple restarts)
- f) Comfortable margins to failure
- g) Fission product retention under operating conditions
- h) Easily adaptable to bimodal applications in the future
- i) Robustness for use in wider applications (e.g. high power steady state or nuclear electric propulsion systems).

Current work on both fuels is in the recapture of the fabrication methods. No significant showstoppers have been identified. Meanwhile work is in progress getting the non-nuclear test facilities (nuclear thermal rocket element environmental simulator-NTREES and cermet fuel element environment tester-CFEET) ready for testing both kinds of fuel samples as soon as they are ready. Thermal effects are significant for NTP, and in the interest of affordability, many of these effects can be tested in non-nuclear test facilities. The effects of a difference in power/temperature profiles in the test specimens can be accounted for analytically for initial evaluations. The tests planned include lifetime at peak temperature, compositional stability at temperature, chemical compatibility, transient stability, thermal cycling stability, etc.

The non-nuclear fuel element test rig at MSFC called NTREES is being investigated to test simulated reactor fuel elements to close conditions of operation without the radiation environment. The site is licensed to handle natural and depleted uranium. The fuel element is heated with an induction heater inside a pressure vessel with a nitrogen ambient environment. Hydrogen propellant flows through the element like in the engine with the same flow rates and pressures. The facility was designed to handle up to 5 MW input power to test the material compatibility, thermodynamics, material properties and endurance of various fuel element designs. Fuel element designs which show acceptable test results from NTREES can next be tested in radiation environments to examine the effects. Figure 9 shows the diagram and photo of the system.

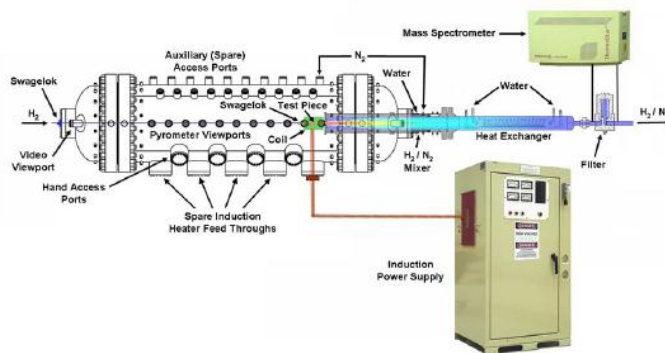


Figure 9. NTREES System Diagram and photo¹⁵.

Final testing of the fuel will need to be performed in a nuclear irradiation facility, which will incorporate all the effects (thermal and nuclear). The initial tests may feature small samples in contained hydrogen filled capsules to establish fission product retention capabilities, and thermal performance (to compare with NTREES results). The follow-on tests would involve the prime fuel selected, and use larger fuel cluster irradiations to establish interaction behavior. The tests would also determine fuel performance under operating conditions, as well as provide margins to failure. Facilities such as the ATR at INL (Fig. 10) may be used for initial nuclear testing, although they may not be able to achieve prototypic fuel power densities and operating environments. The availability of space in the limited test facilities in the US could be an issue in the overall schedule. Finally, nuclear critical tests would be conducted in critical facilities to confirm basic neutronic and nuclear safety parameters of the designed reactor core (Fig. 11).



Figure 10. ATR Reactor Core.

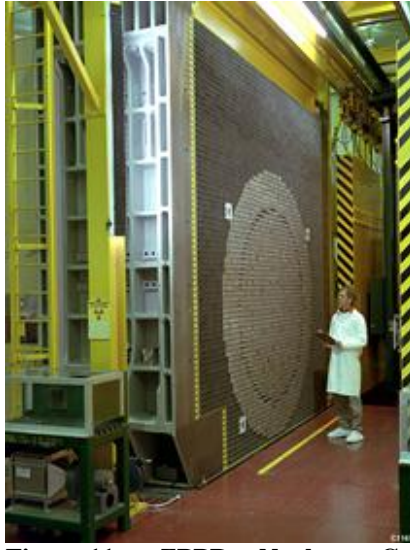


Figure 11. ZPPR Nuclear Critical Test Facility.

V. Ground Testing

Ground testing of space nuclear systems presents significant cost and schedule challenges in general because of safety reviews, licensing issues, and the fact that it is generally impossible to reproduce the 0g, vacuum conditions of space. The situation for NTP systems is further exacerbated by the possibility of fission product releases from fuel during testing. Because of changed regulations, the experiences of the Rover/NERVA days cannot be reproduced. In addition, the declining support for terrestrial nuclear development in the US has led to the loss of many of the testing capabilities that existed in the past. This has called for a re-thinking of the ground testing strategy, and examination of innovative options to support affordability. Figure 12 shows the current test topology.

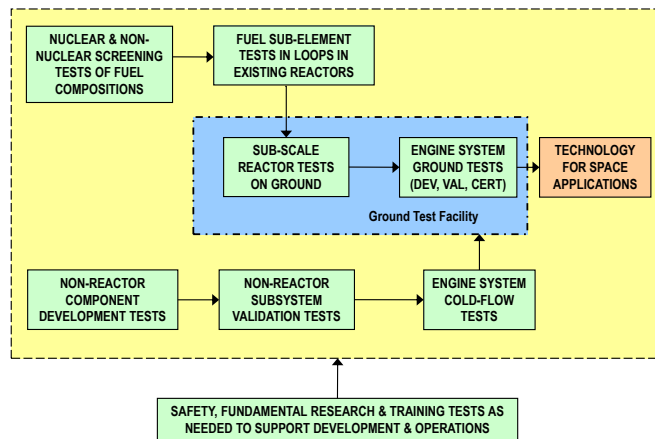


Figure 12. NTP Test Topology.

The National Emission Standards for Hazardous Air Pollutants (NESHAP 40 CFR61.90), which states “Emissions of radionuclides to the ambient air from Department of Energy facilities shall not exceed those amounts that would cause any member of the public to receive in any year an effective dose equivalent of 10 mrem/yr”. This means NTP exhaust filtering is required and is determined by the following:

- General public location from the test stand
- Wind speed and direction

- Possible releases of radioactive particulates and noble gases before filtering
- #engine tests per year and test durations

The last ground test of the Rover/NERVA program was the nuclear furnace test (NF-1) done in 1972. The NF-1, with a 44 MW reactor, used an effluent cleanup system which successfully demonstrated how the engine exhaust can be filtered. Figure 13 shows a schematic of the system. Basically, the exhaust was cooled down with water, filtered of particulates, and captured fission product noble gases with a charcoal bed at cryogenic temperatures.

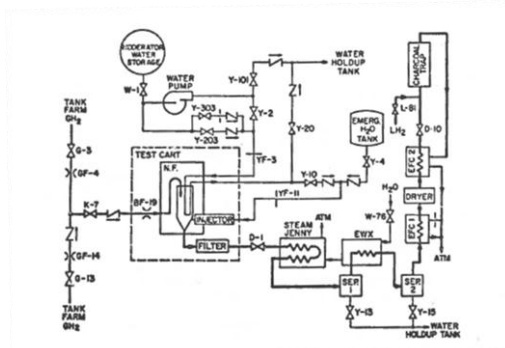


Figure 13. Nuclear Furnace-1 Schematic¹⁶.

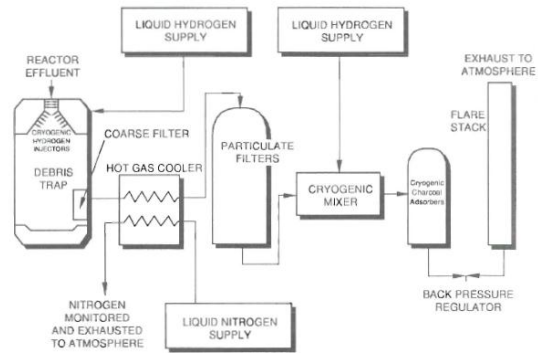


Figure 14. NTP Exhaust Filtering Concept¹⁷.

In 1993, the space nuclear thermal propulsion (SNTTP) program had an EIS made for the consideration of two DOE locations. The exhaust scrubber concept considered is shown in Fig. 14. With national policy to reduce radioactive discharges to a level that is as low as reasonably achievable (ALARA), 99.9% of particulates and condensed phase contaminants greater than .3 microns can be removed, and 99.5% of the noble gases (iodine, xenon, krypton) and vapor phase contaminants could be removed. The objectives of the scrubber are as follows:

- Ensure that radioactive material entering the ETS remains in the subcritical geometry
- Cool the test article effluent to temperatures acceptable for normal engineering materials used
- Remove particulates and debris from the effluent stream
- Remove halogens, noble gases, and vapor phase contaminants from the effluent stream
- Flare hydrogen gas to the atmosphere
- During test operations and accident conditions (including impacts of accumulated radiological material in the ETS) the releases are reduced to limits derived from the exposure regulation limits for workers and the public.

It is clear that a scrubber system can be designed to control effluent releases from test facilities. However, the cost can be significant, so it is prudent to seek ways to reduce effluents at the source. The two ways being examined are:

- Use of robust fuels with fission product retention capabilities
- Use of the smallest sized engine consistent with mission needs for testing

A. Functional Facility Capabilities and Operational Requirements

The functional facility capabilities and operational requirements are based on what it takes to qualify and flight certify the NTP propulsion system, subsystems, and engine components. Table 2 is a summarized list of major

nuclear facilities, test objectives, and major facility requirements for a comprehensive NTP development program. The operational requirements are based on qualification and certification requirements previously discussed. The actual facilities that will be used for this program will be determined from this set.

Table 2. Major Nuclear Facilities Functions¹⁸.

Major Facilities	Test Objectives	Major Facility Requirements
Engine Test Facility (ETF)	Ground demonstrates full scale NTP engine performance operating close to flight requirements and off-normal operations required to verify, qualify, and flight certify the engine system.	<ol style="list-style-type: none"> 1. Part of the nuclear engine system development station utilizing support infrastructure and transport system. 2. Utilize the facility hydrogen system and exhaust treatment system initially for PETR 3. Capabilities required to flight certify the engine. 4. Multiple test cells for redundancy.
Engine Support Facility (ESF)	Permit assembly, disassembly, maintenance and temporary storage of test articles and supporting subsystems.	<ol style="list-style-type: none"> 1. Part of the nuclear engine system development station utilizing support infrastructure and transport system. 2. Remote manipulator capability to handle a full scale engine. 3. Facility accommodates efficient decontamination and waste disposal.
Prototypic Element Test Reactor (PETR)	Conduct fuel element development, verification, and qualification in a multi-element, prototypic nuclear system environment.	<ol style="list-style-type: none"> 1. Part of the nuclear engine system development station utilizing support infrastructure and transport system. 2. Design hydrogen feed system and exhaust treatment system to expand to ETF. 3. Capabilities allowing clusters of fuel elements to go critical.
Hot Cell Facility	Permit post-irradiation examination of fuel specimens and post-test evaluation of engine components to evaluate performance	<ol style="list-style-type: none"> 1. Part of the nuclear engine system development station utilizing support infrastructure and transport system. 2. Proper instrumentation to characterize the full range of inspection measurements.
Control Point	Protected facility to remotely control and monitor the nuclear subsystem testing	<ol style="list-style-type: none"> 1. Part of the nuclear engine system development station utilizing support infrastructure. 2. Contains all control consoles, data acquisition, and instrumentation/control systems to operate the station and test articles. 3. Space for administrative support
Material Irradiation Effects Test Facility	Determine the effects of irradiation on materials considered for NTP	<ol style="list-style-type: none"> 1. Capable to simulate the wide range of radiation environments expected 2. Capable for flowing hydrogen exposure of materials during tests. 3. Adequate instrumentation to allow required material characterization. 4. Radioactive material handling capability.
Launch Processing Facility	Facility at the launch site to support processing and integration of the NTP flight engine with the launch vehicle	<ol style="list-style-type: none"> 1. Category 1 security.

Other functional facilities needed include non-nuclear test stands for NTP fuels, components, subsystems, and full scale engine cold flow. Most of these types of facilities already exist and need modifications to meet the test requirements. The non-nuclear tests can help find the “non-radiation” problems in the engine design without having the added complexities and cost of dealing with radiation until it becomes necessary to perform focused nuclear tests. Simulated reactor heat can be provided by electric heaters (e.g., inductive heating) or chemical combustion to test the thermo-mechanical behavior of various components and subsystems. This should also help make the development plan more affordable with a shorter schedule.

B. Candidate Ground Test Facility Solutions

As previously mentioned, there were candidate facilities identified for most of the NTP development functions, which were once considered in past studies, but some have since been demolished. A candidate NTP facility database was put together as part of the Space Exploration Initiative (SEI) in the early 1990’s. A panel composed of NASA, DOE, and DOD members, with help from universities and industry, identified about 200 candidate facilities available at that time across the US¹⁹. The panel recommended having the reactor tests and full scale engine tests at the same location to share common infrastructure²⁰. The panel also recommended on focusing first on the reactor and full scale engine test facility since they will have long lead times before being operational²⁰. The NTP test

facility database was updated again in 2006 and re-evaluated in 2011²¹. The candidate facilities include ones which meet the test requirements as is, with minor modifications or a completely new design. A few candidate facilities currently being investigated are discussed.

One option to simplify the full scale NTP exhaust scrubber system is to use borehole ground soil to filter the hydrogen exhaust of radioactive particulates and noble gases. This is an extension of the strategy used for containment of underground nuclear weapons testing. The Sub-surface Active Filtering of Exhaust (SAFE) concept was proposed by Steve Howe in the late 1990's and shown in Fig. 15. Borehole locations at the Nevada Test Site and Idaho National Laboratory are currently being investigated. Hydrogen buoyancy has been known to rise through soil from past experiences. The primary concern about the concept is the amount of permeability in the soil to avoid a significant rise in back pressure during a long steady state burn of NTP. Factors affecting permeability include changes with hole depth, water (used to cool the NTP exhaust) saturation, turbulent flow, and hole stagnation pressure are currently being investigated. A few other secondary concerns have been identified, but initial modeling results show promise. Subscale test reports from the NTS have been gathered and are being analyzed for useful data to compare with models. A subscale test setup has been investigated with an estimated cost to better help verify the performance of the SAFE concept. Figure 16 shows a possible test rig which can be used for the subscale tests.

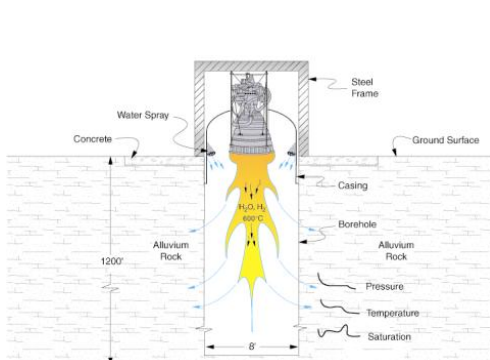


Figure 15. Schematic of SAFE Concept²².

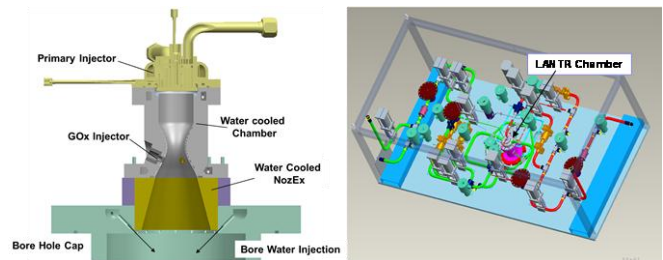


Figure 16. Hot hydrogen injection chamber built by Aerojet Corporation and used by NASA for Lox augmented NTR testing. Possible Test rig for SAFE subscale testing using hot gas chamber²².

A new candidate facility being investigated which could help the NTP development is the new Advanced Post Irradiation Examination (APEX) facility at INL and is shown in Fig. 17. The facility is scheduled to be operational in 2018 and could be used to inspect radioactive NTP engine components after full scale engine tests.

C. Trade Studies to Assess Ground Facility Candidates

When all the candidate ground test facility options have been identified, a trade study will examine the pros and cons of each one to determine the best candidates. Figures of merit can be used to compare each candidate. The figures of merit account for effectiveness/performance, safety, security, regulatory, cost, schedule, and stakeholder acceptance. In addition, a risk assessment can be made for each candidate to meet its operational NTP requirement.



Figure 17. Artist Concept Advanced Post Irradiation Examination (APEX) facility at INL²³.

VI. Other Development Needed

The duty cycle, environment, and requirements for many of the subsystems for a nuclear engine are different enough from a chemical engine that much of the non-reactor components are in the TRL 3 to TRL 4 range. Validation in a relative environment, in this case, one with radiation and representative duty cycles would be required to bring the TRL up to 5. While this was done to a great extent during the Rover/NERVA programs, so much has changed for all aspects of modeling, design, manufacturing, testing and at the contractor involvement that the experience from the Rover/NERVA can't be claimed as valid justification for declaring

technology to be at the TRL 5 or TRL 6 level. The lower TRLs should be factored in during early planning for technology development and when estimating the cost for those activities. This does not mean that these activities will be overly expensive, or difficult, merely that costs and difficulty will likely be underestimated and that failure to take these into account early in the program may show up as very costly delays, even jeopardizing engine readiness for critically timed missions. Below is a discussion of some factors that need to be considered at the onset of a nuclear engine development program.

A. Turbomachinery

The duty cycle for most chemical engines is an order of magnitude less in time than for a nuclear engine. That fact combined with the easy start and shutdown transients of a nuclear engine may call into question the use of typical rolling element bearings. Foil or hydrodynamic bearings may be a good choice. Turbopumps on nuclear stages may be required to ingest saturated propellant. Hydrogen, being a good neutron moderator, will be heated in the presence of the reactor. The propellant repressurization system will add significant heat to the cryogenic hydrogen in a 45 minute engine firing. As heat builds up in the propellant tanks, especially near the end of a longer engine operation, saturated conditions could develop. Ingesting saturated propellants can cause impeller cavitation and lead to impeller erosion, impeller imbalance and ultimately possible failure. The duty cycle for a nuclear engine also requires a long gradual shutdown to facilitate the cooling of the reactor. This may also have a special set of design requirements for the turbopumps that need to be address.

B. Valves

There are at least two areas of concern with valves on a nuclear engine and stage. The first is the leakage rate of propellant if hydrogen is used. Hydrogen, being the smallest molecule, leaks past valve seals. This is exacerbated by contaminants in the hydrogen, one of the most common is water. Studies have shown that even extensive purging doesn't remove all the moisture in a tank prior to use. This effect is common everywhere in the process of separating, transporting, and transferring hydrogen. Not all engine valves will be required to have a very low leakage rate, only the ones isolating the propellant during long periods of storage. It may also be possible to combine leakage of valves with other Cryogenic Fluid Management (CFM) techniques or isolate them to minimize the impact of the leakage rates.

The other area of possible concern is the possible lack of appropriate valve manufactures. The companies that have typically supported development of rocket engines are slowly disappearing or changing their manufacturing clientele, and thus their core manufacturing processes, away from that which is supportive of rocket engine needs. The development of new business relationships may be necessary and may even have to be concurrent with the development of new low-leak technology.

C. Nozzle Extensions

The primary difficulty associated with nozzle extensions is the testing in a relevant environment. It has been suggested that the extension be tested on a chemical engine, and that maybe a good plan for cost savings in the development of the nozzle extension. But failure to test a fully integrated engine will violate the "test like you fly" philosophy. Given larger area ratios of 100-200, the only way to test the nozzle integrated to the engine is the use of a steam-ejector stand. The cost of scrubbing the exhaust from a steam-ejector stand will be cost prohibitive. New evaluation criteria and possibly technology will be required to validate nozzle extensions.

D. Avionics, Actuators and Power Generation

The radioactive environment for the avionics, actuators and power generation needs to be considered. This includes instrumentation and the requirements of instrumentation and avionics. Classic open or closed loop control may prove to be problematic. Even though reactor manufactures and their supporting infrastructure are used to dealing with the problems associated with operating in a reactor environment, rocket engine companies and their support network are not. Early planning and consideration of technology needs will pay off in lower overall development cost and fewer schedule delays.

E. Analysis Tools

The suite of analysis tools required to integrate a reactor into a rocket engine does not exist in an integrated and validated form or process. Some parts of the analytical toolbox exist and have successfully been applied to empirical data; however, the broad set of analytical tools needed to successfully integrate a reactor into a rocket engine does not exist. The problem is amplified if a prime contractor is used to develop the nuclear rocket engine

since the prime will likely not be brought on board until after the Government Systems Requirements Review (SRR). Consideration should be given to bringing the prime on early or developing several primes analytical capabilities very early in the life of the Project/Program. These capabilities should include Neutronics, engine thermodynamic balance, reactor flow distribution, comprehensive reactor temperature prediction, flow induced vibration, thermal expansion, stress, strain, material deformation, material degradation and others as identified. This analysis may be done in a multi-physics tool, but such a tool would need to be integrated into a complete design process.

F. Cryogenic Fluid Management

CFM is another technology needing development in parallel to NTP for NTP to be utilized. Hydrogen has always been the best propellant option for NTP because it provides the best Isp. Figure 18 shows the comparison of Isp to a variety of other propellant options. Other propellant options may have better storability, density, etc... However, lower Isp can lead to a greater # of launch vehicles to deliver a greater IMLEO. The technical challenges involving the use of hydrogen includes being able to store the propellant with minimum boil-off for a few years and coupling the propellant lines between stages, thermal management, and zero-g liquid acquisition.

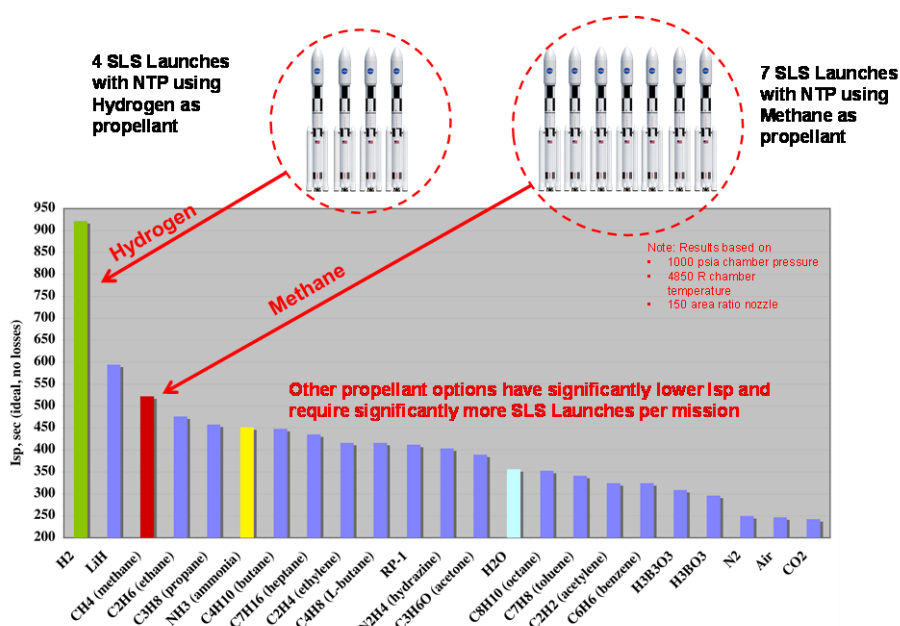


Figure 18. NTP Performance Comparison of Various Propellants.

All of these technologies need to be worked over the next couple of years to mature the technologies to TRL 5 level. It will be hard to justify an authority to proceed with full scale NTP development if too many critical technologies are not mature enough.

VII. Possible Prototype Flight Test

Based on previous discussions, it is impossible to have a complete flight like test capability on the ground. Therefore, a prototype flight test could demonstrate full nozzle expansion and radiate heat to space, perform thrust vector control with the engine operating, validate reactor operation without effects from facility surroundings, more accurately examine radiation effects on the stage throughout the mission, and exposure to space environment effects. The flight reaches earth escape velocity and can consist of multiple burns with different burn durations. Engine cooldown can also be examined. Ideally, the prototype flight test could perform double duty by undertaking a planned unmanned mission (e.g., asteroid reconnaissance).

A problem with flight tests is the difficulty with post-test examination of components to feedback on future engine designs. Options under consideration to address this include extra instrumentation to collect information, and the use of modern robotics to inspect the engine and stage at the end of the mission. After waiting for the radiation level to significantly drop, a “robonaut” could start taking the engine apart and examine components. The added flight inspection would provide additional data to help build higher confidence for human missions.

Lessons learned from the ARES 1-X flight demo could help the strategy for a NTP prototype. The ARES 1-X test flight project was completed in three years. Man ratings and added factors of safety and redundancy not needed for the test flight. Thus, a prototype flight test early in the development program may find significant redesigns needed for basic NTP operation and allow time for upgraded development engines to ground test the modifications before the next flight test.

VIII. Development Schedule and Cost Logic Flow

The paper has discussed many factors which influence the NTP development cost and schedule. Figure 19 shows a simplified logic flow on the approach to determine the final development plan and cost. There are two parallel paths that need to be worked with cross talk between them. One path involves the selection of the best test facilities, while the other path involves the engine DDT&E. Other considerations (e.g., political, environmental, and economic) must also be included. Both paths converge to the final plan and total development cost. Work has started on each block identifying objectives, tasks needing to be performed, and collection of useful data. The goal is to achieve a rough order estimate of the development plan and cost by the end of FY14.

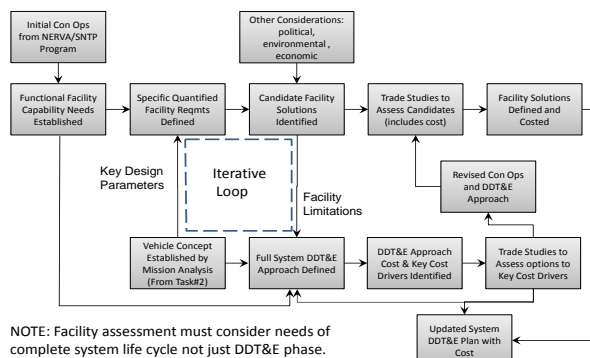


Figure 19. NTP Development Plan Logic Flow.

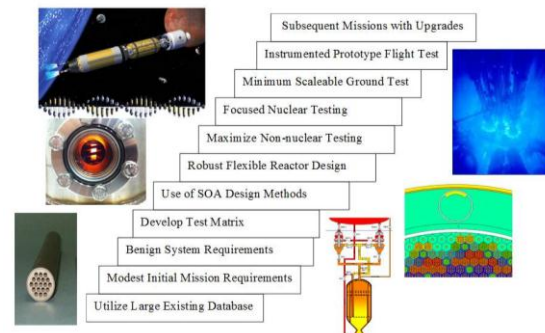


Figure 20. Conceptual Approach.

IX. Summary

The paper provided an overview of the affordable development and qualification strategy and discussed the following major sections:

- Major lessons learned and database from past NTP and chemical propulsion programs
- Important development needs for the NTP stage, engine system, subsystem (includes reactor and fuels), and components
- Ground testing challenges and limitations
- Other programmatic considerations
- Potential prototype flight test
- Development plan logic flow

A full paper could be written on each of these sections. However, enough information was provided to show the scope of complexity which is being implemented in the plans. Many people have been skeptical on the cost and schedule for NTP development and think it will cost too much and take too long for DDT&E. The current plan is to take into account everything that needs to be done for NTP qualification, acceptance, and utilization with respect to cost and schedule to build a complete and confident development plan. Accounting for all the factors which influence the development plan and quantify the factors based on experience, analysis, analogies or similarities, will build greater justification with less uncertainty to have an authority to proceed with NTP development. The

philosophy we are using is to keep the development plan as simple as possible with only “must haves” and not “nice to haves”. Figure 20 summarizes the conceptual approach for an affordable NTP development strategy.

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