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Heat Resistant Materials and Their Feasibility Issues For a Space Nuclear Transportation System*

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ABSTRACT

A number of nuclear propulsion concepts based on solid-core nuclear propulsion are being evaluated for a nuclear propulsion transportation system to support the Space Exploration Initiative (SEI) involving the re-establishment of a manned lunar base and the subsequent exploration of Mars. These systems will require high-temperature materials to meet the operating conditions with appropriate reliability and safety built into these systems through the selection and testing of appropriate materials. The application of materials for nuclear thermal propulsion (NTP) and nuclear electric propulsion (NEP) systems and the feasibility issues identified for their use will be discussed. Some mechanical property measurements have been obtained, and compatibility tests were conducted to help identify feasibility issues.

For direct nuclear thermal propulsion (NTP) needed for manned missions, high specific impulses are highly desirable and would require operating temperatures as high as 3200 to 3500 K in an hydrogen environment and/or high thrust-to-weight ratios that require materials with high strength-to-weight ratios commensurate with high-operating temperatures. The operating life of NTP systems would be on the order of 10 hours for these high temperatures of 3000 K or greater. Graphite with carbide coatings appear to be the materials generally needed for high-temperature components and super-alloys for lower-temperature pumps, turbines, and structural components. Some concepts employ tungsten-based alloys for power generation.

Another propulsion system used for cargo missions and based on nuclear electric propulsion (NEP) employs a nuclear reactor operating between 1200 and 2200 K that produces electric power that drives arc or ion thrusters. These systems are based on either closed Brayton cycles using hydrogen or helium/xenon coolants or Rankine cycle using liquid metals such as lithium. For cargo missions, NEP concepts need high specific impulses from the thrusters to reduce the weight of the system to allow more cargo and specific masses of less than 10 kg/kWe to reduce weight. NEP systems employ extensive use of the refractory metals molybdenum, tungsten, and tantalum based alloys for high temperature strength and compatibility with liquid metals.

IN A SPEECH on July 20, 1989 commemorating the 20th anniversary of the Apollo 11 Moon landing, President Bush established the basic framework for future exploration planning. He stated: "First for the coming decade - for the 1990's - Space Station Freedom - the critical next step in all our space endeavors. And next - for the new century - back to the Moon. Back to the future. And this time, back to stay. And then - a journey to tomorrow - a journey to another planet - a manned mission to Mars." On November 2, 1989, the President approved a national space policy which stated that a long-range goal of the civil space program is to expand human presence and activity beyond Earth orbit into the solar system. On November 20, 1989 NASA released its, "Report of the 90-Day Study of Human Exploration of the Moon and Mars", which identified nuclear propulsion (both nuclear thermal propulsion and nuclear electric propulsion as a key technology for the exploration of Mars.[1] Subsequently the Committee on Human Exploration of Space of the National Research Council (NRC) issued a report entitled, "Human Exploration of Space," which endorsed work on nuclear propulsion technologies.[2] In FY 1991, the Bush Administration has proposed the initiation of the Space Exploration Initiative (SEI) a focused, multi-decade program of lunar and Mars exploration missions.

To gather information on possible nuclear propulsion systems and to assess the nuclear propulsion technology, an NEP workshop was held from June 19-22, 1990 in Pasadena, California and an NTP workshop was held in Cleveland, Ohio form July 10-12, 1990. At the NEP workshop, 9 solid-core reactor concepts were presented of which 3 were based on closed Brayton cycle engines and 6 on liquid-metal-cooled Rankine systems. Variations were based on fuel modifications and on the power conversion technologies. At the NTP workshop 10 solid-core concepts were presented, again with the major variations in the fuel design.

From these NEP and NTP concepts, heat-resistant materials are identified along with their feasibility issues for applications to the development of a space nuclear transportation system. Since the feasibility issues are derived from the mission-requirements for the materials, preliminary mission requirements are discussed first along with the mission-derived requirements for the materials in the various concepts. Various heat-resistant materials are identified that are common to a number of reactor concepts and their feasibility issues are then discussed.

MISSION REQUIREMENTS

NASA's planning for future exploration of the Solar System includes unmanned (precursor) and manned missions to Mars and its moons, as well as a resumption of manned missions to the Moon to establish lunar bases. A significant portion of the cost for these missions depends on launch vehicle and on-orbit fuel requirements. One of the keys to reducing cost is to minimize the propellant mass in low-Earth orbit (LEO) required to achieve a transfer trajectory to accomplish orbit insertion, to effect a planetary landing and to return to Earth. Reduced propellant requirements in orbit translate to substantial cost savings because fewer Earth-to-orbit (ETO) vehicle launches are required to accomplish the mission. Nuclear propulsion offers the potential of reducing IMLEO by a factor of 2 or more compared to an all propulsive chemical transport system. Even more important is reducing the overall risk of the mission. Long duration flights to Mars present problems of life support, human considerations, radiation shielding and increased probabilities of system failures. One of the keys to reducing the risk of a mission to Mars is to reduce the trip time. Nuclear propulsion offers the potential of cutting the trip time in half compared to an all propulsive chemical transportation system. Thus, a key enabling technology to greatly reduce in-orbit propellant mass requirements and to reduce trip times is the development and use of a high-performance nuclear propulsion system.

Preliminary analyses has shown that specific impulse is an important parameter for Mars missions. A parameter to measure performance in mission analyses is the initial mass in low earth orbit (IMLEO). IMLEO is plotted as a function of thrust-to-weight for different values of specific impulse in Figure 1. Specific impulse has the largest impact on reducing the IMLEO, and although the higher the specific impulse, the lower is IMLEO, preliminary mission analyses indicates that a 850 to 925 second specific impulse is acceptable for a 434-day trip time. IMLEO decreases with increasing specific impulse so that fuel that can achieve the highest specific impulse such as 925 seconds would be most beneficial.

The thrust-to-weight ratio is not important for ratios greater than 7 to 10 for Mars missions (Fig. 1) because the launch is assumed from a low-earth-orbit from Space Station Freedom. The thrust-to-weight ratio becomes more important for such applications as orbital transfer vehicles (OTV).

The total burn time for a Mars mission is expected to be at the most 2 hours, and for a 5 mission cycle, the total life time is 10 hours. This 10-hour lifetime encompasses numerous start-ups and shutdowns for engine testing and propulsion maneuvers which requires the fuel to be capable of 25 multiple transients.

The performance requirements for fuel development are summarized in Table 1 for nuclear thermal propulsion along with the mission requirements that drive the fuel performance requirements.

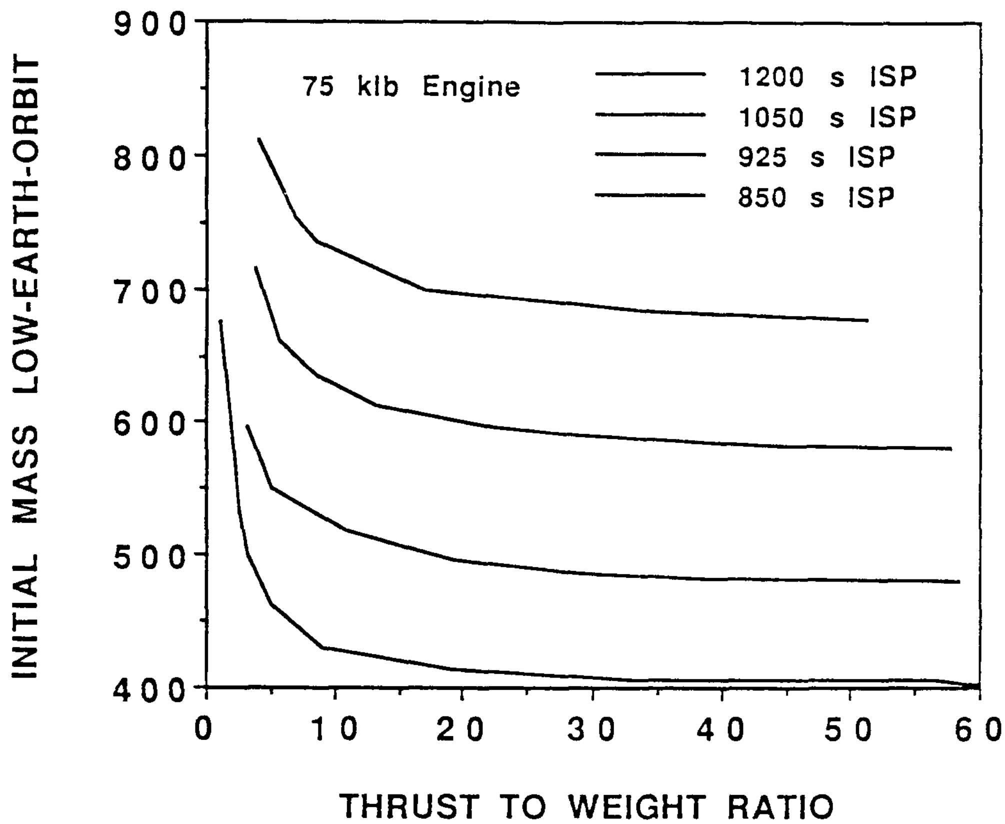

Figure 1 - IMLEO Performance as a Function of Thrust-to-Weight for Different Specific Impulses

Table 1 - Fuel Performance Requirements for Nuclear Thermal Propulsion Derived From NASA Analyses

925 second specific impulse	2700K gas temperature in chamber 3000K fuel temperature
10 thrust-to-weight ratio	Specific power greater than 10 kW/cm^3
10-hour operating lifetime	Minimum fission product release Maintain dimensional stability
25-cycle lifetime	Capability to withstand transient cycling Minimum fission product release Maintain dimensional stability
Capability of alternate propellants	Provide indigenous coolant capability

For nuclear electric propulsion, the fuel operates at lower temperatures, but for longer times than those for nuclear thermal propulsion. Since the major application for NEP is cargo transport requiring low thrust and very high specific impulse, the total lifetime is anticipated to be 15 years of which 4 years is the total operating lifetime. NEP is expected to experience 15 transient cycles during the reactor's lifetime. For three missions per system, the average mission duration is 1-1/3 years. Fission product release requirements are expected to be similar to those for nuclear thermal propulsion.

Analogous to the thrust to weight ratio for nuclear thermal propulsion, NEP systems must achieve a specific mass ratio of 10 kg/kW(e) or less. This ratio, to a certain extent, will be driven by the specific power density and also the fuel temperature which drives the efficiency of the system. The other part of the specific mass will be determined by the mass of the power conditioning equipment and the radiators.

The performance requirements for fuel development are summarized in Table 2 for nuclear electric propulsion along with the mission requirements driving the fuel requirements.

REVIEW OF NTP AND NEP CONCEPTS

To gather information on possible nuclear propulsion systems and to assess the nuclear propulsion technology, the NEP and NTP workshops were held.

The 19 concepts for both NEP and NTP systems are summarized in Table 3. These concepts are categorized as to the type of fuel, i.e., prismatic, particle, cermet, and pin-type fuels which indicate to a large extent the temperature limits of these systems and accordingly the temperature limits imposed on the materials. The major differences are in the operating temperatures and operating lifetimes shown in this table. These 17 concepts have certain commonalities as derived from the cycle type, coolant, and the operating temperatures which dictate materials for these systems.

MATERIAL SELECTION

The operating requirements dictate the need to use certain heat-resistant materials listed in Table 4. For example, the liquid-metal Rankine systems dictate the need for high-temperature strength refractory metals that are compatible with liquid metals. In some cases to reduce the mass of the system, advanced materials such as the carbon-carbon composites need to be developed, at least, in part to substitute for the heavy refractory metals. For the closed Brayton cycle NEP

Table 2 - Fuel Performance Requirements For Nuclear Electric Propulsion Derived From NASA Analyses

10 specific mass ratio	Specific power greater than 2 kW/cm^3
4-year operating lifetime	Minimum fission product release Maintain dimensional stability Fuel temperatures commiserate with lifetime
15-cycle lifetime	Capability to withstand transient cycling Minimum fission product release Maintain dimensional stability

Table 3 - Summary of NTP and NEP Concepts

CONCEPT	Cycle Type	Fuel Temperature (K)	Time	Coolant
PRISMATIC FUELS				
ROVER/NERVA	Open Brayton	2200 - 3000	10 hrs	Hydrogen
Advanced Dumbo	Open Brayton	2200-2800	10 hrs	Hydrogen
Enabler	Open Brayton Closed Brayton	3000 - 3600 1000 -1500 (NEP)	10 hrs 4 yrs	Hydrogen Xenon/Helium
STAR-:M Thermionic	Thermionic			Lithium
FOIL	Open Brayton	2200 - 2800	10 hrs	Hydrogen
NIMF	Open Brayton	2200 - 2800	10 hrs	Water Carbon Dioxide
PARTICLE BED FUELS				
Particle Bed	Open Brayton Closed Brayton	2500 -3600 1000 -1500 (NEP)	10 hrs 4 yrs	Hydrogen Xenon/Helium-Mercury
Pellet Bed	Open Brayton Closed Brayton	2200 -3100 (NEP)		Hydrogen Hydrogen/Potassium
Low Pressure NTR (INEL)	Open Brayton	2700 - 4200	10 hrs	Hydrogen
CERMET FUELS				
UO2 Cermet	Open Brayton	2200 -2800	10 hrs	Hydrogen
UN Cermet	Rankine	1500 -2200 (NEP)	4 yrs	Lithium/Potassium
PIN FUELS				
Thermionic	Thermionic	2200 -2800 (NEP)	4 yrs	Lithium
SP-100	Rankine	1200 - 1500 (NEP)	4 yrs	Lithium
LLNL Rankine	Rankine	(NEP)	4 yrs	Potassium/lithium
Torchlite	Thermionic	(NEP)	4 yrs	Lithium
Wire Core	Open Brayton	2200 - 2800	10 hrs	Hydrogen

systems which use carbide fuels, the basic components will depend on graphitic matrices with carbide coatings to protect the structural materials from the coolants and retard vaporization.

Carbon-Carbon Composite - Carbon-Carbon composites have been identified for NEP radiators for heat rejection in closed cycle systems, and these radiators based on refractory metals are massive contributing to as much as 60% of the mass of the system. Carbon-carbon composites offer a significant potential reduction to the specific mass of the system. Radiators are required with masses less than 1 kg/m^2 and heat rejection rates greater than 50 kW/m^2 at 1000 K. By increasing the heat rejection temperature to 1200 K, the mass of the radiator could be cut in half because of the radiation heat transfer. However, because of compatibility with liquid metals, the carbon-carbon composites

Table 4- Materials Development and Testing

Cermet Fueled Reactor	Particle Bed Reactor	Prismatic Fueled Reactor	Pin Fueled Reactor
W-Re Alloys	Mo-Based Alloys	C-C Composites	Mo-Based Alloys
Ta-Based Alloys	Stainless Steels	Carbide Coatings	Nb-Based Alloys
Nb-Based Alloys	C-C Composites	Ni-Based Alloys	W-Based Alloys
W-Based Alloys	Ni-Based Alloys		Rhenium
C-C Composites			Ta-Based Alloys

would have to be lined with refractory metals or ceramic such as lithium aluminum silicate. The goals are to decrease the mass of the radiators and reduce the area by increasing the operating temperature.

Another application of the carbon-carbon composites is in turbines for NEP systems that use these materials as a structural component in high-speed rotating machinery. Carbon-carbon composites are considered for the rotors and casings that are in contact with either hot hydrogen or inert gas environments.

An outstanding compatibility issue is the use of ceramic or refractory metallic liners to protect the carbon-carbon composites from reaction with the lithium reactor coolant or the potassium working fluid. Any defects or cracks in such liners will lead to attack of the composite and transport of the carbon to the metallic parts of the systems. Such effects could be catastrophic. In addition, the compatibility of ceramic silicates with high-purity, high-temperature molten lithium or potassium has not been verified. The potassium vapor lines which are coated carbon-carbon composite material pose the most serious compatibility issue. Potassium attacks carbon materials to form intercalation compounds with disastrous effects on structural integrity. Any gap or crack in the ceramic or metallic lining which exposes the carbon to potassium vapor could result in rapid structural degradation of the carbon-carbon containment.

Fabrication and design issues for the carbon-carbon composite components which are ceramic lined or metallic lined involve the actual fabrication of the composite materials with liners and the joining of these composite materials to each other and to refractory metals. These must be addressed through materials and structural testing. The thermo-mechanical fatigue durability of surface coatings is of concern when there are many startups or excursions from normal service temperatures. Cycling can introduce damage that leads to coating cracks which in turn causes exposure of the carbon-carbon composites. Methods to predict thermal fatigue life are often poor when only isothermal creep-fatigue environ-mental interaction information is used as a predictive tool.

Niobium-Based Alloys- The niobium-based alloys, in particular the Nb-1Zr alloy, is proposed for piping in the secondary loops and pressure vessels of Rankine systems that operate up to 1400 K in lithium and potassium and for radiator panels fabricated with carbon-carbon composite material containing Nb-1Zr heat pipes attached to a Nb-1Zr coolant manifold. Nb-1Zr is also used to contain boron carbide poison rods which are used for reactor safety rods. Thus the niobium-based alloys are used for a broad temperature range and need to be compatible with a wide variety of materials. Annular-linear induction electro-magnetic pumps fabricated from Nb-1Zr are also used to circulate Li coolant at temperatures near 1150 K.

Pure niobium is used as a collector operating from 1000 to 1200 K in thermionic elements. For 1200 K temperatures, niobium must possess high-creep strength and low emmissivity to obtain good thermionic performance.

Tungsten Based Alloys - Reactor radiation shield materials are fabricated from a tungsten alloy (W-3.5%Ni-1.5%Fe) as the gamma shield. This shield is a layered structure with alternating layers of the gamma and neutron shield materials. The performance of this alloy needs to be verified under temperature and irradiation conditions in a gamma field.

A thermionic device has been proposed using a tungsten emitter dispersed with small particles of HfC for enhanced creep strength at 2200 K compared with pure tungsten.[3] Based on early data, the creep strength would be higher than pure tungsten as long as the HfC particle size is less than 700 angstroms.

W-HfC alloys presents a major fabrication issue in forming this alloy into tubes or wire. A concentrated effort is required to develop the fabrication technology required to optimize the processing and properties of this material.

The stability of the HfC precipitate in the W-HfC alloy needs to be addressed. Data for HfC particle growth is based on approximately 100 hour data and suggests that carbide particle size can grow from 100 Angstroms in diameter to 700 Angstroms in less than 500 hours at 2200 K. These kinetics need to be verified for longer times and for different particle sizes.

The long-term compatibility of W-HfC fuel clad/emitter with irradiated UO2 at 2200 K needs to be verified. UO2 as well as some of the other chemical forms have high-vapor pressure which may result in dissociation and the transport of metallic uranium through the tungsten resulting in embrittlement and the degradation of performance.

A tungsten-25% rhenium alloy is proposed as a matrix material for a W-25Re/UN fuel cermet composite. These composites are expected to operate as high as 2200 K for periods of time up to four years in liquid lithium. Compatibility tests have been conducted that shows the dissociation of UN to uranium and nitrogen results in the reaction of liquid uranium or uranium vapor with rhenium in the W-25%Re alloy to form URe_2. The formation of URe_2 results in large volume expansions and could disintegrate the cermet. Kinetic studies are required to establish the temperature and time limits for this reaction.

Other compatibility concerns are possible preferential reaction and mass transfer of Re when W-25Re is exposed to molten lithium

Tantalum Based Alloys - A number of tantalum-based alloys are proposed for various components in the NEP systems. A boiler feed turbo pump is to be constructed of ASTAR 1511-C for the turbine disks and blades and T-111 for the stationary components. These components will be exposed to potassium vapor.

The Li in the primary circuit is pumped by an AC electro-magnetic (EM) induction pump. The refractory materials in these pumps include T-111 for ducting and piping. These pumps circulate the Li coolant from the reactor around the outside of the radiation shield to the boiler-reheater assembly to transfer thermal energy to the potassium working fluid. Expansion compensators in the primary loop are fabricated from T-111 alloy and carbon-carbon composite material discussed above.

These alloys have been fabricated previously as hardware for liquid-metal containment and other high-temperature applications with the exception of Astar 1511-C. Astar 1511-C has not been routinely produced and represents a high-risk approach because of the large amount of fabrication development and testing required for this developmental alloy. Even the other alloys are not currently commercially produced and are only done so in very large quantities as a best effort basis.

The tantalum-based alloys (ASTAR-811C, ASTAR-1511C, T-111, and T-222) have reasonable mechanical properties data bases except for 1511-C. Additional data will be required to reflect the mechanical properties of current fabrication practice as well as more extensive measurements for ASTAR-811C.

The T-111 reflector and control drum cladding needs evaluation for the effects of fluence and temperatures in the operating range. There is substantial unirradiated properties data available at temperatures of interest, but the effect of irradiation on these properties needs to be evaluated. The use of a high tantalum alloy may not be desirable because of transmutation effects if there is some other substitute available due to the high-energy-gamma radiation caused by neutron irradiation.

Molybdenum-Based Alloys - Mo-Re-based alloys have a number of applications for space nuclear power and propulsion applications. In one application Mo-Re is used as a fuel cladding containing uranium carbide fuel and operating at temperatures anticipated to be 917 K in a hydrogen. A core containment basket is again constructed of Mo-48% Re.

Mo-41%Re alloy is generally selected over the Mo-48%Re alloy due to the tendency of the latter to form a embrittling sigma phase at elevated temperature. The operating temperature for this cladding is not excessive, therefore, it is unlikely that an appreciable amount of sigma phase would form. Molybdenum and rhenium alloys of any composition are usually handled as special order by refractory metal suppliers. Processing development and joining studies will be required for the Mo-Re components since experience is limited with this class of materials. All the Mo-Re alloys are available from suppliers and are readily fabricated except the Mo-50%Re hot frit and the Re foam material.

Mechanical properties for the alloys are available except for the Mo-50%Re. This alloy will require testing and the development of a data base. The concern would be that the alloy will contain or form a sigma phase at elevated temperature service and embrittle. The DBTT of this material will have to be assessed.

The H2 compatibility of Mo-Re used in the reactor is a major unknown factor and will have to be determined under simulated environmental conditions.

Nickel-Based Alloys - Some of the concepts employ a few of the superalloys such as an iron-base superalloy such as A-286 or Incoloy 800H as the fuel element tie rods that provide support for the graphite fuel elements in the Enabler concept. Rotating drum radial reflectors fabricated from Incoloy 800H contain Be and B_4C.

The hydrogen compatibility of Inconel X-750 reactor vessel and the nickel- and iron-based superalloys will have to be verified. The effect of hydrogen on bearing surfaces is uncertain and needs to be determined.

A number of different alloys are used in turbines which drive generators in a few of the NEP concepts. Turbines have Mar-M-5O9 stator vanes, and some employ Mar-M-509 turbine blades. Hastelloy K is used for inlet scrolls on a case with outlet scrolls of Haynes 188. Commercially available flexible drive couplings of A286 alloy connect the turbines to the alternator. The lack of any detrimental hydrogen effects on the nickel-based turbine materials will have to be verified.

CONCLUSION

The development of advanced, qualified materials for a manned space transportation system is a challenging task. The use of carbon-carbon composites, although used presently in some aerospace applications, still will require development and adaptation to liquid metal systems with the use of refractory metal linings or coatings.

The technology of fabrication needs to be recaptured for the refractory metal alloys including the W-based alloys, Mo-based alloys, and the Ta-based alloys. Thermal, mechanical, and physical properties need to be measured and performance evaluated and established to qualify these materials for manned space flight.

Because the niobium-based alloys are used in the SP-100 program, these materials are fairly well established. Additional qualification would be required to push these materials to higher temperatures than 1350 K.

The superalloys are also fairly well established and do not present any significant feasibility issues. The major concern is hydrogen embrittlement at high temperatures.

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