DOD-MISC-001

SPACE NUCLEAR THERMAL PROPULSION PROGRAM

Compilation of new releases, news clippings, and journal articles

DEPARTMENT OF THE AIR FORCE
AIR FORCE CENTER FOR ENVIRONMENTAL EXCELLENCE (AFCEE)
BROOKS AIR FORCE BASE, TEXAS 78235-5000

INEL Technical Library (PRR)
Attn: Gail Willmore
1776 Science Center Drive
Idaho Falls, ID 83415

Dear Ms Willmore

Per our telephone conversation on 23 March, 1992, I am enclosing a compilation of news releases, news clippings, and journal articles on the Space Nuclear Thermal Propulsion program. Request you make these available to the general public through your reference desk (along with this letter), and ~~suggest a 3-4 hour time limit on checkout so~~ all interested parties have the opportunity to ~~view it.~~ All of this material is in the public domain and may be reproduced. Our intent in making this available is to provide an understanding of the technology and why it is being studied. However, since much of this consists of media articles, we cannot guarantee its accuracy.

Decisions yet to be made about this program include whether to proceed with the technology development and if so, where to conduct ground testing. These decisions will be based in part on an Environmental Impact Statement (EIS) that we are preparing. Since two sites at the Idaho National Engineering Laboratory are under consideration, we will be conducting a scoping meeting in Idaho Falls on Thursday, 9 April, 1992. It will be held at the Bonneville High School Auditorium at 7:00 PM. This meeting is open to the general public, and will assist us in determining the scope of environmental issues to be analyzed in the EIS.

Your assistance in this matter is greatly appreciated. If you have any questions on this matter, please call me at (512) 536-3806.

Sincerely

Scott A. Hartford

Scott A. Hartford, Capt USAF,
EIS Project Manager

You are welcomed to photocopy materials.

News Release

United States Air Force

AIR FORCE SYSTEMS COMMAND

OFFICE OF PUBLIC AFFAIRS, PHILLIPS LABORATORY, KIRTLAND AFB NM 87117-6008

January 13, 1992
PL RELEASE NO. 92-02
CONTACT: Rich Garcia
PHONE: (505) 846-1911

PHILLIPS LABORATORY ANNOUNCES PROGRAM IN SPACE PROPULSION

KIRTLAND AIR FORCE BASE, N.M. -- A technology program that could advance the state-of-the-art in space propulsion was announced today (Jan. 13) by Phillips Laboratory officials at the 9th Symposium on Space Nuclear Power Systems.

The program, called Space Nuclear Thermal Propulsion, will use a particle-bed reactor that is expected to more than double the specific impulse of the best current rocket engines. The goal is to develop a 75,000-pound thrust engine with a specific impulse goal of 1,000 seconds at a 30-to-1 thrust-to-weight ratio for exoatmospheric applications.

-MORE-

PROGRAM IN SPACE PROPULSION -- 2

The program is managed by the Air Force's Phillips Laboratory at Kirtland Air Force Base, N.M. The Department of the Air Force, Department of Energy, and NASA are also participating in the project.

The propulsion technology was selected because it offers potential for a wide range of military and civilian space missions. The Air Force has no plans to use the engine in the atmosphere. It may be used once a vehicle is in space, for example, as an advanced upper stage for space launch, orbit transfer vehicle, or a space propulsion vehicle for the President's Space Exploration Initiative (SEI).

A July 1991 report by the SEI's Synthesis Group (Stafford Report) cited nuclear thermal propulsion as an enabling technology for the manned exploration of space.

Department of Defense officials are working closely with members of the U.S. Congress, the Administration, and various regulatory agencies to ensure a safe, successful proof-of-concept, research and technology effort.

News Release

United States Air Force

AIR FORCE SYSTEMS COMMAND
OFFICE OF PUBLIC AFFAIRS, PHILLIPS LABORATORY, KIRTLAND AFB NM 87117-6008

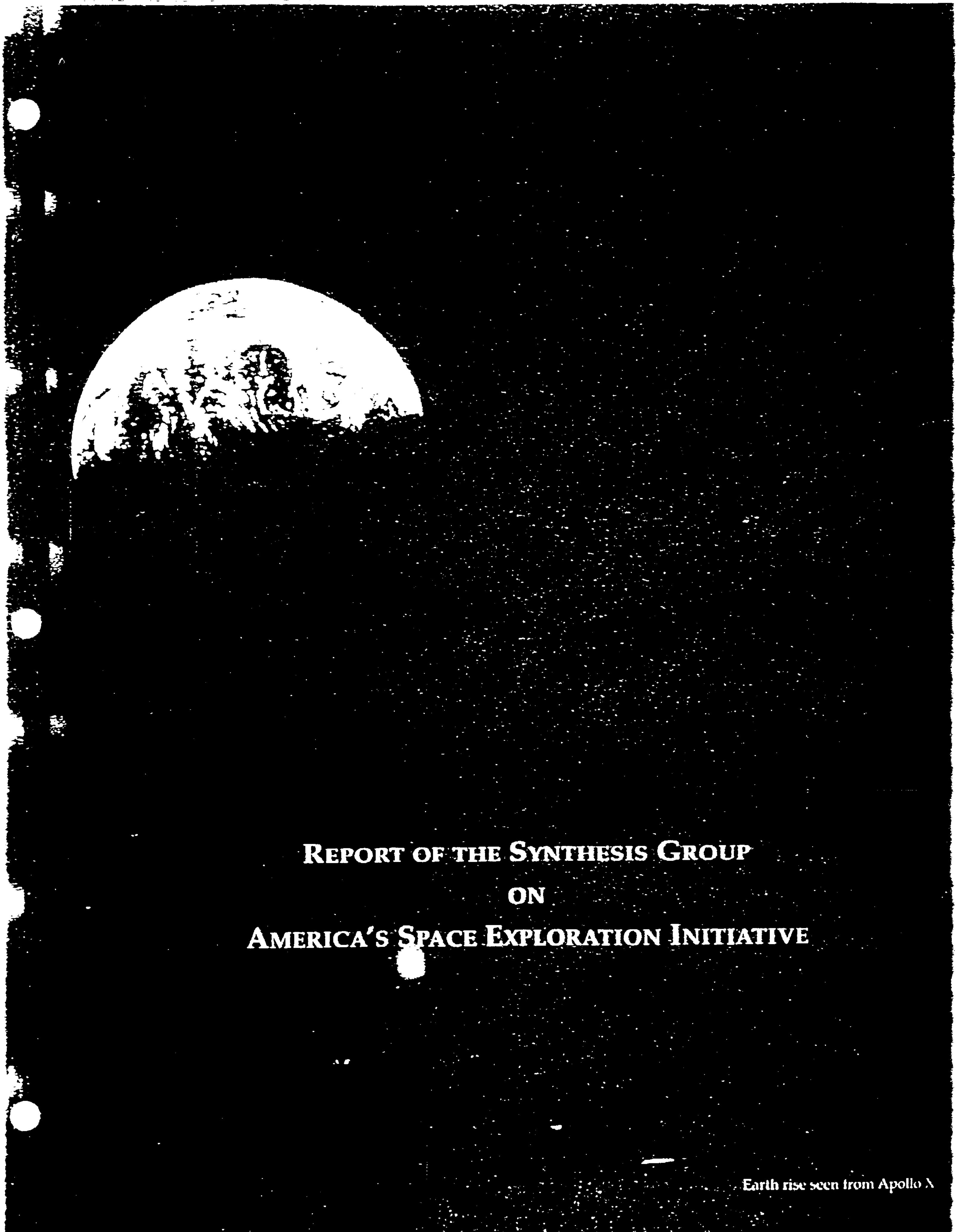
JANUARY 13, 1992
RELEASE NO. 92-2
CONTACT: KARI J. PASEUR
PHONE: (505) 846-1911

SPACE NUCLEAR THERMAL PROPULSION ENGINE

KIRTLAND AIR FORCE BASE, N.M. -- PICTURED IS A MODEL OF THE SPACE NUCLEAR THERMAL PROPULSION ENGINE WHICH THE AIR FORCE'S PHILLIPS LABORATORY IS DEVELOPING. THE BLACK CONE-LIKE STRUCTURE AT THE BOTTOM IS THE ROCKET NOZZLE. THE NUCLEAR PARTICLE BED REACTOR IS THE BLACK CYLINDER IN THE MIDDLE PORTION, AND THE ENGINE SUBSYSTEMS ARE THE BLUE CIRCULAR ASSEMBLY AT THE TOP. THE ACTUAL ENGINE WOULD BE 12 FEET HIGH. (OFFICIAL U.S. AIR FORCE PHOTO)

AMERICA AT THE THRESHOLD

AMERICA'S
SPACE EXPLORATION INITIATIVE



Report of the Synthesis Group on America's Space Exploration Initiative

Earth rise seen from Apollo X

EXECUTIVE SUMMARY

> "The challenges of the Space Exploration Initiative are great, but so is the quality of American talent and ingenuity, and so is the leadership of the American people. And . . . it is America's destiny to lead."
>
> *President George Bush*

Apollo 11 first placed America on the Moon on July 20, 1969. This extraordinary accomplishment confirmed the United States' technological ascendancy for a generation. On the 20th anniversary of Apollo 11, President George Bush announced a new vision for America in the 21st century — a vision that will return us to the Moon to stay, and onward to Mars by 2019. This vision, the Space Exploration Initiative, represents one of the greatest technological challenges the world has ever known.

Vision for America

The Space Exploration Initiative provides a focus that allows the United States to gain control of our destiny in space. In doing this, six "visions" guide and direct our space efforts. These are:

Knowledge of our Universe. We strive to understand the origin and history of our Solar System, the origin of life, and the ultimate fate of our universe. People are the best explorers, but they often need machines to help. *The Space Exploration Initiative is an integrated program of missions by humans and robots to explore, to understand and to gain knowledge of the universe and our place in it.*

Advancement in Science and Engineering. Returning to the Moon and onward to Mars requires the best engineering and scientific talent our nation can muster. Through a long range commitment to space, we stimulate our national education system and inspire students to learn. Motivated students are essential to excellence in education. *The Space Exploration Initiative will motivate and inspire the new generations on which our future as a nation depends.*

United States Leadership. The Space Exploration Initiative provides us with an opportunity to re-establish and maintain American preeminence in technological innovation and space leadership. Other nations have gained the initiative in certain areas and have become leaders in a tradition of space exploration that America pioneered. *Leadership cannot be declared . . . it must be earned.*

Technologies for Earth. America's recent history has demonstrated that our space program stimulates a wide range of technological innovations that find abundant application in the consumer marketplace. Space technology has revolutionized and improved our daily lives in countless ways, and it will continue to do so. Energy from space, advances in solar power and fusion fuels, useful materials for advanced communications, new resources, medical breakthroughs, and greater insight into the human potential are some of the direct benefits we can expect. *The Space Exploration Initiative provides focused goals to effect practical and beneficial technological change.*

Commercialization of Space. Initiatives by the private sector are goals of our National Space Policy. Space is a limitless, untapped source of materials and energy, awaiting industrial development for the benefit of humanity. *Commercial products, such as zero gravity derived materials, and service industries, like advanced global communications, all become increasingly feasible and profitable once routine, reliable and affordable access to space is available.*

Strengthened U.S. Economy. New technologies open new markets. An investment in the high technology needed for space exploration maintains and improves America's share of the global market and enhances our competitiveness and balance of trade. It also directly stimulates the scientific and technical employment bases in our country, sectors whose health is vital to our nation's economic security. *The Space Exploration Initiative is an investment in the future of America.*

Why the Moon?

Earth's closest neighbor in space, the Moon, is surprisingly complex. It is an object for detailed exploration, a platform from which to observe and study the universe, a place to live and work in the environment of space, and a natural source of materials and energy for an emerging space-based economy.

The Moon offers a record of four billion years of planetary history. Its violent birth and history of bombardment from space is closely related to events on the early Earth. The Moon provides a natural laboratory for detailed study of geology and planetary formation, the output of our Sun over its lifetime, and the elements of our universe. The Moon's 14 Earth-day night, crystal clear, airless sky and stable ground provide a superb platform for astronomy.

The Moon is the nearest object in space where people can live under conditions similar to those we will face on other planets. Thus, the Moon is a natural test bed to prepare for missions to Mars through simulation, systems testing, operations and studying human capabilities.

The Moon is a rich source of materials and energy for use in space. Abundant metals, ceramics and recoverable amounts of hydrogen, carbon and oxygen can provide propellants and human life support from the lunar surface. The 14 Earth-days of a lunar daytime provide abundant solar energy. Our Moon provides a rich scientific and economic waystation for human expansion into the Solar System.

Why Mars?

Of all the planets in our Solar System, Mars is the most like Earth. With a thin atmosphere, weather, seasons

and a 25-hour day, Mars has a diverse and complex surface, including ice and evidence of water. Although conditions on Mars cannot support life now, a variety of evidence suggests that Mars was warmer, wetter and had a much denser atmosphere early in its history. Life may have existed. If so, fossil evidence may be found.

Mars has undergone a complicated geologic evolution. Its surface consists of gigantic canyons, huge volcanoes, gorges carved by running water, vast regions of sand dunes and a polar ice cap. Understanding the periodic changes in climate that have occurred on Mars will help us understand the Earth's climate and predict its future behavior, a topic vital to the survival of life on Earth.

Architectural Considerations

At its closest point, Mars is 35 million miles from Earth. This distance increases to 230 million miles when we are on opposite sides of the Sun. By comparison, the Moon is only a quarter-million miles away — a three-day journey. The challenges of a Mars expedition stem from the distances, the long times away from Earth, the environment of deep space and Mars' unique characteristics.

A total Mars mission duration depends on both the round trip travel time and the time spent on the planet's surface. Conventional chemical propulsion missions will take about 230 days one way, and require long surface stays of about 500 days to allow the planets to realign before returning home. Advanced nuclear propulsion technologies can shorten the transit time, provide flexible surface stay times, significantly reduce the propellant mass to low Earth orbit and increase the available launch opportunities.

Shorter travel times are desirable to reduce the impact of the deep space environment on the crew and mission equipment. During the space voyage, expected hazards include radiation from galactic cosmic radiation and solar flares, the lack of normal gravity, psychological stress from long term isolation, and equipment degradation.

The challenges of a Mars trip will require several hundred tons of equipment and fuel for the expedition. Thus, we will require a heavy lift launch capability to minimize assembly in Earth orbit. Nuclear propulsion technology allows reduced weight, approximately one-half that of chemical systems, and achieves faster interplanetary trip times. At Mars, we need Earth-independent operations, since round trip communications times will vary from seven to 40 minutes. We also need improved long term life support systems that operate for lengthy time periods without resupply.

The planetary surface of Mars provides challenges different from those of the Moon. The planet is large — about one-third the size of Earth. It has a diverse topography, with 80,000 foot volcanos, three times as high as Mount Everest and as large as the state of Montana, and canyons as long as our continent is wide. Mars' atmosphere is mostly carbon dioxide and it is known to have periodic dust storms. These features will require unique power systems, landers, rover vehicles and human habitats.

Architectures

The foundation of the architectures reflects three areas of emphasis: human presence, exploration and science, and space resource development for the benefit of Earth. Different architectures vary with the degree of human presence, the level to which exploration and science are pursued, the extent to which space resources are developed, as well as the relative emphasis between lunar and Martian activity.

Architectures

I. Mars Exploration
II. Science Emphasis for the Moon and Mars
III. The Moon to Stay and Mars Exploration
IV. Space Resource Utilization

Four architectures have been identified and they provide significant differences across the possible areas of interest. They are:

Mars Exploration: The emphasis of this architecture is on Mars exploration and science. The first human mission to the Moon occurs in 2005. The lunar infrastructure is developed only to the degree necessary to test and gain experience with Mars systems and operations and to simulate Mars stay times. The Moon is explored while developing operational concepts for Mars.

Robotic precursor missions are used to scout the territory before committing to a landing site for Mars. The first human mission to Mars occurs in 2014, with a surface stay of 30 to 100 days. The next mission is planned for 2016 for a 600 day stay. This architecture is designed to be a minimal approach to achieving the Initiative objectives.

Science Emphasis for the Moon and Mars: The Moon and Mars are emphasized equally, and an early global assessment of both bodies permits a variety of initial missions designed to better understand global diversity. The first human mission to the Moon is 2003. Life sciences data required for Martian missions are generated through extensive operations on the Moon. Human-controlled robotics assist the planning and execution of human activity on the surface. Instrument emplacement focuses on early deployment of portable instruments which gather observation data independent of lunar location. In the latter stages of architecture implementation, emphasis shifts to larger scientific experiments and instruments after developing surface capabilities for construction, maintenance and operations. Continuous exploration activities yield a significant scientific return though the use of a balanced mix of human and robotic exploration techniques.

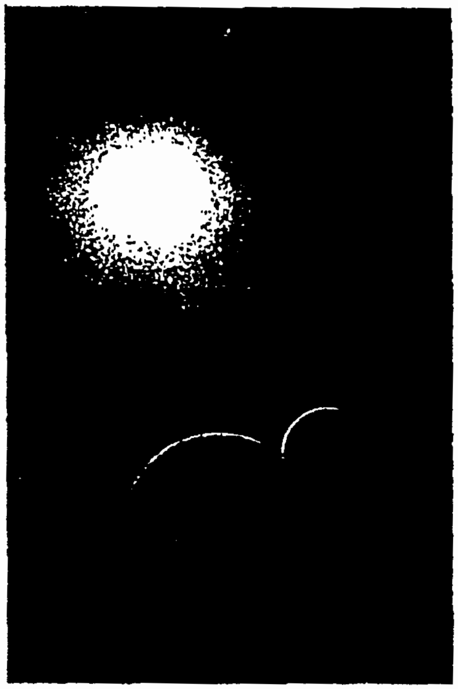
Subsequent to the establishment of the desired long term operational capabilities for exploration and science on the Moon, human missions to Mars take place beginning in 2014. All knowledge gained by the activities in lunar orbit, and on the surface becomes part of and is complementary to the dress rehearsal for the Mars mission.

The Moon to Stay and Mars Exploration: This architecture emphasizes permanent human presence on the Moon, combined with the exploration of Mars. One of the major objectives is to build towards life support self-sufficiency for breathing gases and food production on the Moon.

The permanent presence of humans on the Moon, beginning in 2004, gives us an impressive scientific capability. Science on the Moon will emphasize exploration and observation. For lunar exploration, extended traverses in pressurized rovers will permit detailed study of complex and puzzling lunar features and processes. Robotic assistants will extend human reach for great distances across the lunar surface. With a permanent human presence on the Moon, advanced and sophisticated astronomical observatories can be installed and maintained.

Extensive space and lunar surface operations are conducted on the Moon to provide the necessary life sciences and engineering data to prepare for future exploration missions to Mars. The first human mission to Mars is in 2014, with a surface stay of 30 to 100 days.

Space Resource Utilization: This architecture makes maximum use of available space resources to support the exploration missions directly. It also seeks to develop a large class of available resources for a broader range of transportation, habitation, life sciences, energy production, construction and many other long term



Beyond the Moon

activities. In preparation for the first human return mission, a robotic experimental resource producing plant is landed on the Moon in 2003. The first human mission to the Moon takes place in 2004 and to Mars in 2016. On Mars, the basic exploration would be done on the first two missions with the addition of more resource development, which could be expanded on missions beyond the first two. In the long term, this architecture may benefit Earth by providing Helium-3 to fuel Earth-based fusion reactors and beaming solar-produced electricity to Earth.

Transportation

After study of the various transportation options, it was concluded that chemical propulsion from low Earth orbit, as used in the Apollo program, is still the preferred way to get to the Moon. However, significantly heavier lift capability will be required to support any of the architectures. For the Mars transit from Earth orbit, the nuclear thermal rocket is the preferred propulsive system to allow significantly reduced mass to low Earth orbit, shorter transit times and greater operational flexibility.

Supporting Technologies

Technology will provide the tools necessary for safe and cost effective exploration of the Moon and Mars. Technology development is required in the following areas:

1) Heavy lift launch with a minimum capability of 150 metric tons with designed growth to 250 metric tons

★ 2) Nuclear thermal propulsion

3) Nuclear electric surface power to megawatt levels

4) Extravehicular activity suit

5) Cryogenic transfer and long term storage

6) Automated rendezvous and docking of large masses

7) Zero gravity countermeasures

8) Radiation effects and shielding

9) Telerobotics

10) Closed loop life support systems

11) Human factors for long duration space missions

12) Lightweight structural materials and fabrication

13) Nuclear electric propulsion for follow-on cargo missions

14) In situ resource evaluation and processing

At first glance, the implementation the architectural approaches outlin appears daunting. It is indeed co plex. But it is noteworthy t America's ability to return to t Moon and to begin the exploratior Mars depends on two fundamer technologies:

1) Restoration of a heavy lift launch capability

2) Redevelopment of a nuclear propulsion capability

This nation had both of these capat ties in the early 1970s. In additior these two areas, the 12 other te nologies identified, if successfu developed, offer the potential vastly enhancing the exploratior the Moon and Mars.

Organization and Acquisition Management

The Space Exploration Initiative represents a major management challenge as well as a significant technological challenge to this country. The capability exists in this nation to accomplish the Space Exploration Initiative within the combined resources of the government, industry and the academic community. It requires management that allows for crisp and timely decision making, plus the assured resources to reach its goals.

An Executive Order should be issued to cite the basic charter of the National Program Office for the Space Exploration Initiative Organization. It should define the leadership role of NASA and the cooperative relationships among various governmental departments and agencies. The Executive Order should clearly enumerate the staffing, budgeting and reporting relationships and responsibilities of the affected agencies.

The Synthesis Group reviewed numerous successful and unsuccessful major aerospace, industry and government programs, and studied various acquisition improvements and key factors that helped reduce the cost of the most successful aerospace programs.

In managing the Space Exploration Initiative, NASA should be authorized to tailor the existing procurement system and devise new procedures to fit the needs of this major new program.

The opportunity for a number of international cooperative ventures exists.

Commercial potential abounds within the framework of the Initiative. Launch services, communications satellites, robotics, production of materials in space for use in space and on the Earth, and electronics technology represent a few of these potential areas.

Recommendations

Specific recommendations are provided for the effective implementation of the Space Exploration Initiative.

RECOMMENDATION 1

Establish within NASA a long range strategic plan for the nation's civil space program, with the Space Exploration Initiative as its centerpiece.

> ". . . the jewel represented by the vision of a seemingly unattainable goal, the technologies engendered, and the motivation provided to our nation's scientists and engineers, its laboratories and industries, its students and its citizens. Hence that the Mission from Planet Earth be established with the long term goal of human exploration of Mars, underpinned by an effort to produce significant advances in space transportation and space life sciences."[1]

A strategic plan will provide decision points to allow flexibility during the life of the program, concentrate management activities of diverse departments, provide budget guidelines and identify technology pathways. The plan must be based on a detailed governmental (NASA, the Department of Defense, the Department of Energy) analysis of the Synthesis Group's four architectures. This analysis should result in further refinement to gain sufficient detail to support relative costing of the architectures. Existing and planned programs should be reviewed for their contributions to this plan. Industry effort should be limited to studying elements of the architectures. As the strategic plan's centerpiece, the Space Exploration Initiative complements the goals of Mission to Planet Earth.[2]

> "We propose . . . to accelerate the development of the NOVA nuclear rocket. This gives promise of some day providing a means for even more exciting and ambitious exploration of space, perhaps beyond the Moon, perhaps to the very end of the solar system itself."
>
> *John Fitzgerald Kennedy*

RECOMMENDATION 2

Establish a National Program Office by Executive Order.

This organization would include Department of Defense and Department of Energy personnel working directly for the National Program Office. With the multi-agency nature of the National Program Office, an Executive Order should be issued to cite the basic charter of the organization, the leadership role of NASA, and the cooperative relationship among various governmental departments and agencies. The Executive Order should clearly enumerate staffing, budgeting and reporting relationships and responsibilities of the affected agencies.

RECOMMENDATION 3

Appoint NASA's Associate Administrator for Exploration as the Program Director for the National Program Office.

This is required to ensure clean lines of management authority over a large, complex program while simultaneously providing a focus for NASA's supporting program elements.[2]

RECOMMENDATION 4

Establish a new, aggressive acquisition strategy for the Space Exploration Initiative.

The Space Exploration Initiative should standardize acquisition rules for the agencies executing the Initiative's various projects. The most streamlined processes available should be adopted for that standard. The Space Exploration Initiative is so great in scope that it cannot be executed in a "business as usual" manner and have any chance for success. The Space Exploration Initiative National Program Director should be designated as the Head of the Contracting Activity. This will allow the director to establish the optimum acquisition procedures within the Federal Acquisition Regulations. Multi-year funding should be provided.

RECOMMENDATION 5

Incorporate Space Exploration Initiative requirements into the joint NASA-Department of Defense Heavy Lift Program.

The Space Exploration Initiative launch requirement is a minimum of 150 metric tons of lift, with designed growth to 250 metric tons. Using Apollo Saturn V F-1s for booster engines, coupled with liquid oxygen-hydrogen upper stage engines (upgraded Saturn J-2s or space transportation main engines), could result in establishing a heavy lift launch capability by 1998.[2]

RECOMMENDATION 6

Initiate a nuclear thermal rocke technology development program.

The Synthesis Group has deter mined the only prudent propulsio system for Mars transit is the nucle ar thermal rocket. Sufficient testin and care must be taken to mee safety and environmental require ments.

RECOMMENDATION 7

Initiate a space nuclear power tech nology development program base on the Space Exploration Initiati requirements.

The program must concentrate o safe, reliable systems to a megawa or greater level. These nuclear pow systems will be required for use on the Moon before use on the Mars mission.

RECOMMENDATION 8

Conduct focused life sciences experiments.

Implement a definitive life sciences program, along with the necessary experiments and equipment, on Space Station Freedom, consistent with the recommendation of the Advisory Committee on the Future of the U.S. Space Program. These experiments are needed to reduce the uncertainties of long duration space missions.[2]

RECOMMENDATION 9

Establish education as a principal theme of the Space Exploration Initiative.

The Initiative will require scientists, engineers and technicians for its execution. It is a source of interest and expectation to those considering science and engineering careers. The Space Exploration Initiative can contribute directly to undergraduate and graduate education in engineering and science by re-invigorating a university research program in support of the Exploration Initiative as was done during the Apollo program of the 1960s and early 1970s.

RECOMMENDATION 10

Continue and expand the Outreach Program.

The Outreach Program has served a very useful purpose in the Synthesis Group's deliberations. The ideas from the Outreach Program will be turned over to NASA with the recommendation that they review them periodically. The Outreach Program generated not only ideas but also greater interest in the Space Exploration Initiative. Both features should be emphasized. The database should be refreshed with further outreach solicitations, perhaps every two years, and with increasing focus to specific program goals. The Space Exploration Initiative touches virtually every scientific field and engineering discipline. The Outreach Program should be extended to include all other entities that are affected by the program in addition to the aerospace industry. An informed public is vital to the Space Exploration Initiative, which will require a sustained commitment of the nation's resources.

Why Now?

America stands at the threshold. Our national space program is undergoing intense scrutiny. Many ask questions similar to those voiced during the heyday of Apollo — What is the point of large space ventures? How can we afford the great expenditures? What is the function of a human presence in space?

By offering direction and purpose, the Space Exploration Initiative will rejuvenate our sense of challenge, of competitiveness, and of national pride. The Space Exploration Initiative is a positive, social endeavor. In a world of uncertainty, it has the capacity to inspire people, to stimulate them and to cause them to reach deep inside to find the very best they have to offer.

Technology development and architecture analysis must precede any final concept validation effort. The Initiative can be started now with a modest commitment of funds.

Great nations have always explored and profited from new frontiers and territories. Space is the new frontier of the industrialized world in the 21st century. Benefits from space and the technologies needed to journey there become increasingly important in the next century. **As Americans, we must ask ourselves what our role will be in human exploration of the Solar System: to lead, follow or step aside?**

1 The Advisory Committee on the Future of the U.S. Space Program.

2 These recommendations are consistent with and expand upon those made by the Advisory Committee on the Future of the U.S. Space Program.

to-orbit concept. The National Aerospace Plane program should be vigorously pursued. The single-stage-to-orbit concept should be carried forward to demonstrate concept feasibility. Both of these efforts could hold promise for a cost effective personnel launch system to low Earth orbit.

begin here

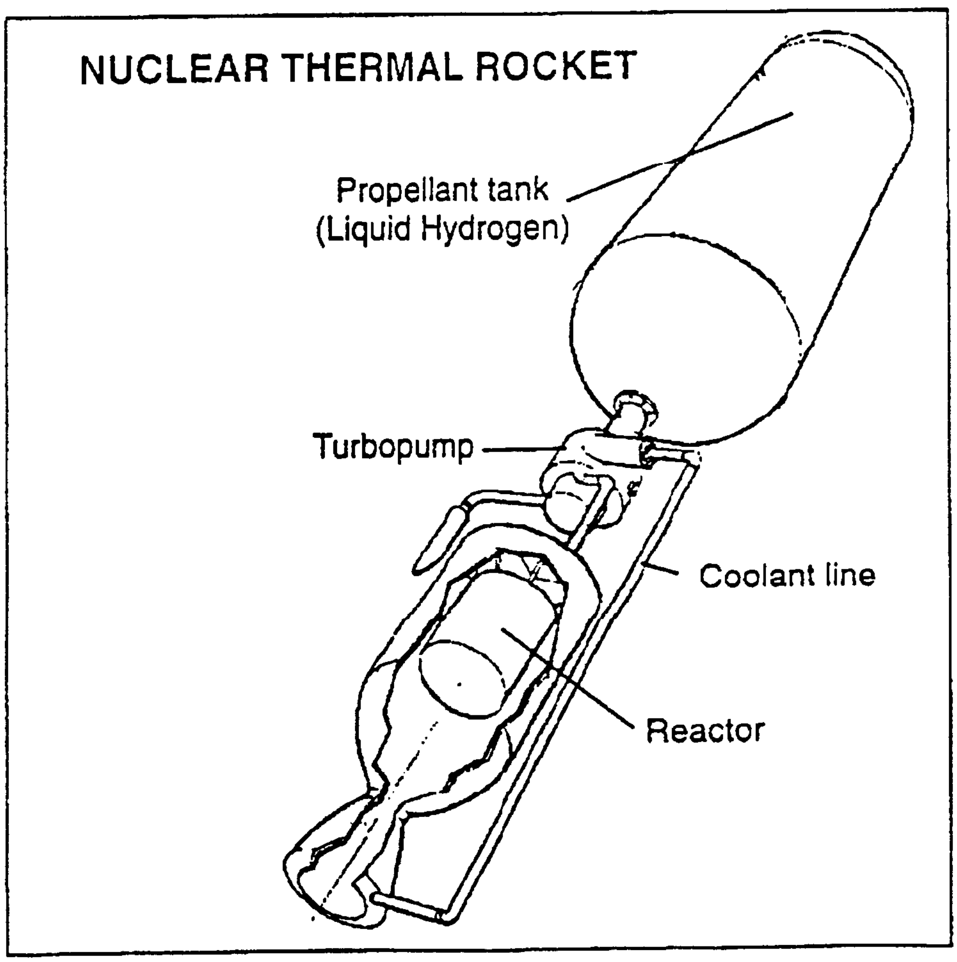
Nuclear Systems. The nuclear thermal rocket is a device which uses a nuclear reactor to heat propellant to high temperatures. The propellant is then expanded by a supersonic nozzle to produce thrust much in the same manner as a conventional rocket motor, as shown in Figure 2. However, since the nuclear thermal rocket can use a low molecular weight propellant (usually H_2), heated to high temperatures, substantial increases in performance over chemical systems are possible.

Nuclear thermal rockets underwent substantial development in the 1960s and the early 1970s under the Rover/Nuclear Engine for Rocket Vehicle Applications program. A series of full power reactor/engine tests resulted in propellant temperatures in excess of 2,700°K and a specific impulse of 845 seconds. One 1,125 MWt reactor power test was run continuously for one hour. In addition, a reactor power test demonstrated 28 automatic start-up/shut-down sequences and a thrust level of 250,000 pounds was demonstrated. Although no integrated rocket system was ever flight qualified or flown, the program did generate substantial test experience prior to program termination in 1972. Based on experience gained in this program and the Space Exploration Initiative requirements, nuclear thermal rockets, with further development, are the choice propulsion technology for the interplanetary phase of the Mars mission.

Since 1972, advances in materials and fuel technology hold the promise for higher temperatures leading to still higher performance engines. ☆Newer concepts, such as the compact particle bed reactor, offer potential for high power density reactor cores which could lead to substantially higher integrated thrust-to-weight ratios. A high thrust-to-weight ratio engine would be particularly attractive for a second generation upper stage of an advanced heavy lift launch vehicle.

To provide propulsion for Moon and Mars cargo missions, where transit time is not an important constraint, low thrust nuclear electric propulsion systems are attractive because of their very high performance levels; their specific impulses range from 3,000 to 10,000 seconds. Although the technology is usually described as new, some 30 electric thrusters have been flown in space to date.

Figure 2



While the development of nuclear electric thrusters is moderately well advanced, the main issue in the technology status of these systems is the lack of space-qualified nuclear power systems in the 1 to 5 MW range. A robust technology program to develop multi-megawatt nuclear systems for both surface and space application could result in the use of nuclear electric propulsion for Mars cargo missions. The major advantage of these systems is the very low propellant requirements for interplanetary missions. This directly translates into a cost savings due to a decrease in the amount of propellant needed in low Earth orbit.

Promising nuclear electric thrusters include ion and magnetoplasmadynamic engines. Ion engines use a noble gas such as Xenon or Argon as a propellant. Ion systems have specific impulses approaching 10,000 seconds, but this benefit is offset by a low thrust level. Magnetoplasmadynamic thrusters have demonstrated high performance with specific impulses ranging from 3,000 to 6,000 seconds.

Baseline

Chemical systems, such as liquid oxygen-hydrogen or liquid oxygen-kerosene (RP-1), are the primary high thrust systems for Earth-to-orbit operations and lunar missions.

For low thrust missions such as lunar ascent and descent, storable liquid systems are utilized (nitrogen tetroxide-unsymmetric dimethylhydrazine, etc.). Numerous storable propellant systems have demonstrated the necessary throttling for ascent and descent applications. High performance systems such as liquid oxygen-hydrogen need to demonstrate long term storability.

Parametric studies for piloted Mars transfer missions show that chemical propulsion is an undesirable option since the initial mass to low Earth orbit requirements exceed 1,100 metric tons in addition to providing limited launch opportunities and requiring longer transit times. The piloted Mars transfer vehicle uses a nuclear thermal rocket propulsion system with a high thrust to weight ratio (approaching chemical propulsion systems). The initial Mars cargo missions will also use the same high thrust-to-weight nuclear thermal rocket propulsion system and provide further inflight verification prior to the piloted flight. Follow on cargo missions may use nuclear electric propulsion.

Near term Earth-to-orbit and lunar cargo transfer will use a conventional cryogenic chemical propulsion system.

Development Programs

Propellant management in zero gravity has several technology problems and issues which need to be resolved, such as tank staging and whether to use wet or dry transfer. To meet the timetable for returning to the Moon, handling experiments should be completed by 1999 and, therefore, be initiated soon. It must be emphasized that although no new physics is involved and all propellant management issues are engineering problems only, actual demonstrations will be a significant challenge.

Advanced development in chemical propulsion technologies, such as the large pintle-controlled injector and the liquid/liquid platelet injector concept, holds promise for reductions in cost without major performance penalties

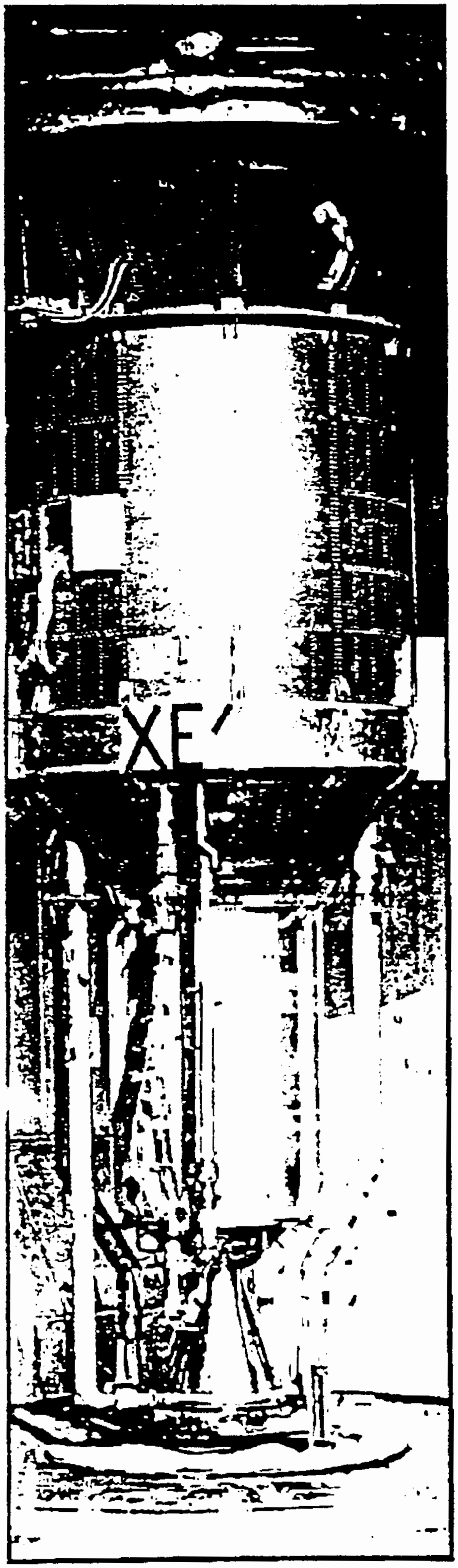
In order to provide a flight qualified nuclear thermal rocket for the 2014 Mars mission, an aggressive development program must be initiated.

Testing of an integrated nuclear thermal rocket presents a challenging engineering and political problem. The safety issues regarding operation are principally concerned with accidental release of radioactive material. Location of potential Department of Energy ground test sites are very isolated and the amount of radioactive

Nuclear Thermal Rocket Performance Goals

- **Engine specific impulse ≥ 925 s**
- **Thrust-to-weight ratios approaching those of chemical systems**
- **Start/stop cycles ≥ 10**
- **Highly reliable, environmentally sound, and inherently safe**

Figure 3: NERVA Engine



material in the engines assures that even if an accident released 100% of the fuel, radiation levels outside the test site boundary would be below accepted national nuclear safety standards. In addition, as demonstrated in the Rover/Nuclear Engine for Rocket Vehicle Applications (NERVA) program (Figure 3), exhaust scrubbers can further guard against the possibility of inadvertent release. Development tests can be designed to meet all applicable nuclear safety requirements and licensing criteria.

The issue of using a nuclear rocket in a flight test is more complex. Social and political perceptions, not just technical realities, are involved. Design of an engine is such that under normal operating conditions, there is virtually no radioactivity in the exhaust stream, as all fission products are contained within the fuel particles. There is a minimum radiation risk prior to the time the reactor is run for the first time, which occurs at trans-Mars injection, leaving Earth orbit. Thus, while the reactor is on the launch pad, it contains only the natural radioactivity levels associated with the uranium fuel.

When the engine is operated in space to provide thrust, the operating time is relatively short compared to terrestrial power reactor systems. This method of operation produces fission byproducts which are predominantly short-lived. The radioactivity in the engine after completion of thrust is far less than contained in a comparable terrestrial power reactor. However, the decay of these radioisotopes releases secondary radiation such as gamma rays. It is the radioactivity associated with this process which poses minimal and short-term consequences in a terrestrial accident situation. Use of nuclear engines for upper stages and missions beyond Earth orbit permits further minimization of risk by allowing a wider selection of trajectory profiles and abort options.

The amount of radioactive materia in the rocket engine prior to the nucle ar engine's start would be orders c magnitude less than radioisotop thermoelectric generators which hav already been safely launched (mos recently, Ulysses). The issue of mee ing all the necessary safety and env ronmental standards will be a sub stantial challenge. The program mus be dedicated to this aspect if the tech nology is to gain public acceptance.

Power

Requirements

The functional electrical pow requirements are shown in Table] Transportation to the Moon requir power for about seven days for th round trip in addition to time in lun orbit, whereas transportation to Ma involves trip times on the order of year plus orbital and surface oper tions of up to two years. In case where solar flux is very high, gre care must be taken to control therm heating. This results in continuo rotation of the spacecraft to sprea the thermal load and affect orient tion of solar panels and radiators.

Surface activities needing pow include habitats, laboratories, ba power and vehicles. Habitats mu have their own highly reliable pow source for safety. Base power includ power for mining, in situ operation fabrication, emergency power f habitats and power for regenerati of fuel cells. Habitat power must highly reliable, greater than 99.5 while base power can be about 95 reliable. Power units should be ma operational with a minimum of su port activities, have lifetimes compa ble with the base, be serviceable ar if nuclear, be refuelable and dispc able. Evolutionary system designs a preferable to specific point desig without growth potential.

Options

Power can be supplied using electr chemical energy storage devices, ph

END

News Release

Pete V. Domenic[i]
United States Senato[r]

FOR IMMEDIATE RELEASE
January 13, 1992

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DOMENICI ANNOUNCES EVOLUTION OF EXCITING NEW SPACE PROPULSION TECHNOLOGY

PHILLIPS LAB TO LEAD DEVELOPMENT OF SPACE ROCKET

ALBUQUERQUE -- New Mexico Senator Pete Domenici today announced the development of a newly declassified nuclear propulsion technology that could revolutionize the space industry.

Domenici, R-N.M., announced that the Phillips Laboratory at Albuquerque is managing the development of Space Nuclear Thermal Propulsion (SNTP) technology. This program could lead to the building of a safe nuclear rocket engine that could more than double payloads and greatly reduce the cost of space launches.

"This giant leap in technology can be equated to the progress made when man went from riding horses to driving automobiles," Domenici said.

"The Space Nuclear Thermal Propulsion technology, at its present pace, could eventually enable us to launch more powerful rockets carrying bigger payloads for less money. It is an exciting technology that can take man to worlds in outer space that have been closed to us," Domenici said.

The Senator said the SNTP program -- technology which has just been declassified -- is being managed by the Air Force's Phillips Laboratory with the participation of Sandia National Laboratories and a number of private companies. Both NASA and the Department of Energy are also interested in the technology.

It will take approximately eight years for the Air Force to complete construction and ground testing of a SNTP engine before it could actually be used to launch payloads into space. Although the SNTP engine would be about the same size as a conventional upper stage rocket engine, it will have at least twice the performance levels of a conventional engine. Scientists believe payloads could be increased as much as tenfold, compared with the conventional engine.

--MORE--

"Employing a safe SNTP rocket could save the United States as much as two-thirds the cost now incurred in rocket launches," Domenici said. "If the SNTP proves to be feasible, the Department of Defense alone could save $1 billion annually."

For example, launching a 40,000 pound payload now requires a Titan IV, costing about $250 million per launch. The same payload could be carried with the SNTP rocket engine in a much smaller Atlas II, which cost about $80 million.

Domenici said that the SNTP program through ground tests will cost $800 million if development efforts meet all technical and unprecedented safety requirements. Annual funding is projected to be about $40 million per year through 1997, followed by up to $80 million a year into the next century. About $130 million has been spent in previous years on this technology in other programs.

During a news conference to announce the SNTP program, Domenici also announced that work is progressing on efforts to expedite the purchase of an unfueled Russian TOPAZ II Space Nuclear Reactor.

Domenici is working with the Defense Department to remove other agency objections to this bargain purchase of the Soviet nuclear-powered satellite. The satellite contains Soviet technology not available in the Free World.

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Las Vegas SUN, 1/13/92 (2B)
(Circulation: 34,011 daily)

Nuclear rockets returning

Program may be located at NTS

By Mary Manning
LAS VEGAS SUN

The nation's nuclear-powered rocket program will be revived in the Southwest, 20 years after Nevada Test Site scientists placed the giant engines on the shelf, Air Force officials announced today.

No experimental site was announced, but the Test Site, 65 miles northwest of Las Vegas, has been explored as a location for testing the nuclear engines.

"It is our understanding that the Nevada Test Site is one of the front-runners for that program," said Larry Werner, a spokesman for Sen. Harry Reid, D-Nev. No date has been set for a decision, he said.

The program will cost between $10 million and $15 million for preliminary design and construction, Werner said. Construction could begin this year and last from 12 to 18 months.

NASA inspected the Nevada Test Site in March as part of a review to revive the rocket engine testing.

The Atomic Energy Commission, now the DOE, experimented with nuclear engines at the Test Site in the 1960s and 1970s in the Rover program. President Richard Nixon grounded rocket experiments in 1972 over environmental concerns and cuts in funding.

Gov. Bob Miller said today he received a limited briefing on the project a few months ago.

"I have been and am encouraging the federal government to look at alternative uses at the Nevada Test Site in case of cutbacks in nuclear testing," Miller said. "This may be a way to involve Nevada in space exploration.

"From the limited information they gave me, it seemed to me to be a much more advanced and sophisticated program with much better safety features built in."

The secret project's revival surfaced in April when The New York Times reported that the program, code-named Timberwind, was part of SDI, the space defense initiative.

The nuclear engine program has now been moved to the Bush administration's Space Exploration Initiative, the Air Force said. Scientists are trying to develop a nuclear rocket reactor that will double the thrust of the best current rocket engines.

The Air Force Systems Command at Phillips Laboratory on Kirtland Air Force Base in Albuquerque announced the development at a University of New Mexico space propulsion conference attended by Air Force, Department of Energy and National Aeronautics and Space Administration officials.

The Federation of American Scientists, a private group based in Washington that has opposed the Star Wars anti-missile program and some uses of space reactors, first disclosed the project to The New York Times.

The Defense Department had launched plans for the secret nuclear rocket project and planned testing the engines at Saddle Mountain in the southwest section at the Test Site.

Another flight test is being considered over water around Antarctica.

The SDI, or Star Wars program, has longed to launch hundreds of large weapons and sensors too heavy for conventional rockets, including massive lasers, particle beams and homing rockets.

Rather than the current nuclear power packs used in NASA's deep space probes, the new generation would be a real reactor that splits atoms rather than a battery-like device that simply uses natural radioactive decay.

Operating some of the future lasers would require tons of exotic fuels.

The goal of the program is to build a special type of nuclear reactor that would power engines far more energetic than any rocket engines now in use, allowing large and heavy payloads to be lofted high above the earth.

Nuclear rockets appeal to scientists on the theory they can take the long haul over conventional ones, whose engines are powered by chemical reactions often involving the explosive burning of oxygen and hydrogen.

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Las Vegas Review-Journal, 1/14/92 (1A)

(Circulation: 139,735 daily; 212,283 Sunday)

NTS may test nuclear rockets

Idaho and Nevada are being considered for the testing of nuclear-powered rockets for use in space.

By Keith Rogers
Review-Journal

ALBUQUERQUE, N.M. — Nevada and Idaho are being considered for testing of a nuclear-powered rocket for military uses and space exploration, government officials said Monday.

Selection of the Nevada Test Site for the $800 million rocket development program would help guarantee the future of the test site, Gov. Bob Miller said in a telephone interview.

Energy Secretary James Watkins will decide where the rocket will be tested, according to Energy Department spokeswoman Joanne Johnson. That decision is expected within a few months.

"This program will be unprecedented in safety while it is unprecedented in opportunity."
Sen. Pete Domenici

The once-secret Space Nuclear Thermal Propulsion project was unveiled by Sen. Pete Domenici, R-N.M., during a scientific gathering.

Domenici likened the prospects for the first nuclear-powered booster rocket to the era of history when automobiles replaced horse-drawn carriages.

"This program will be unprecedented in safety while it is unprecedented in opportunity. We have been stalled in space for a number of reasons," not the least of which are economics and an affordable, powerful booster, said Domenici, a member of the Senate Appropriations Committee.

He said the project, secret since funding began in 1988, was declassified because recent breakthroughs convinced scientists "it clearly has a great deal of civilian applications."

If studies continue to show promise as they have during the project's infancy at Phillips Laboratory at Kirtland Air Force Base in New Mexico, the new rocket would cost one third as much as today's U.S. rocket launches, saving the Pentagon $1 billion a year in lifting military hardware into orbit, Domenici said.

Reusing the booster also is being studied. Scientists hope the rocket not only can be used for launching so-called "Star Wars" hardware, but also for powering human flights to Mars and other planets, according to Air Force and NASA officials at Monday's briefing.

They described the new rocket engine as 10 to 30 times more efficient in space than conventional rockets. It also would be cheaper to build and could deliver payloads faster and farther. Essentially, a bed of nuclear fuel pellets would heat hydrogen to 5,000 degrees Fahrenheit, and the resulting hot, light gas would be forced out of nozzles, driving the spacecraft forward.

Domenici's comments came during a press briefing at the Ninth Symposium on Space Nuclear Power Systems, sponsored by the University of New Mexico. Some 600 scientists and engineers from government, industry and universities, including a team of Soviet space experts, attended the conference.

While Air Force Lt. Col. Roger Lenard, a project official, would not say which two Energy Department sites were being considered for testing, Gov. Miller confirmed that the Nevada Test Site was one. The other, the Idaho National Engineering Laboratory, was confirmed by Sen. Harry Reid, D-Nev.

Reid said he received a number of classified briefings about the project and met with contractors at the test site, which he said would be ideally suited for the rocket testing program.

"We've done it there before," he said. "This is the kind of work we're looking for, the kind of work we need. I'm pulling for Nevada and I hope we get it."

Reid said he was satisfied the testing would not pose any environmental or safety problems at the test site and he believes the program would be consistent with the facility's mission.

"They were very encouraging about the design being such that it had virtually no risk whatsoever... If Nevada is selected, we would want to make sure it was safe."
Bob Miller
Governor

Scott Peyron, a spokesman for Idaho Gov. Cecil Andrus, said Andrus has not been briefed about the project.

But Miller said he had been briefed by Lenard on the safety and environmental aspects of the project several months ago.

"They were very encouraging about the design being such that it had virtually no risk whatsoever," Miller said.

He cautioned, though, "If Nevada is selected, we would want to make sure it was safe."

Lenard said, "Our design goal is to make these (rockets) release no fission products at all ... If we can't make it safe and reliable, we aren't going to do it."

Before tests could be conducted, the Energy Department would have to prepare an environmental impact statement for public review to comply with federal law. The agency, NASA and the Department of Defense are partners in the venture with Phillips Laboratory managing development. Two national labs — Sandia Albuquerque and Brookhaven in New York — also have contributed to the project.

Energy Department figures show the rocket engine testing program will cost between $10 million and $15 million for preliminary design and construction startup costs.

Since 1988, $132 million has been spent on the project, not counting between $65 million and $120 million that will be spent on it this year, Lenard said.

Miller said the project "would provide the economic alternative" to reducing or eliminating test site programs, such as nuclear weapons testing, which is expected to dwindle in light of arms reductions in the United States and the formerly Soviet republics.

"We have a great many scientists and technicians who are employed at the test site that could be relocated. This type of program will keep some of this expertise in our area," Miller said.

The Department of Energy has a $1 billion annual budget for its Nevada operations and employs about 8,500 scientists, engineers, technicians and support personnel, most at the test site, 65 miles northwest of Las Vegas.

During the 1960s and until 1973, a nuclear-powered rocket was developed at the test site under a project dubbed, NERVA — Nuclear Engine for Rocket Vehicle Application.

Chris West, an Energy Department spokesman in Las Vegas, said the engine was successfully developed and tested in the southwest portion of the Nevada Test Site, but it was never used for lack of a mission.

Domenici said the new nuclear-powered rocket project will take eight years to construct and test before it could be used to launch payloads.

He said the United States is also trying to purchase from the Russians TOPAZ II — a space nuclear reactor.

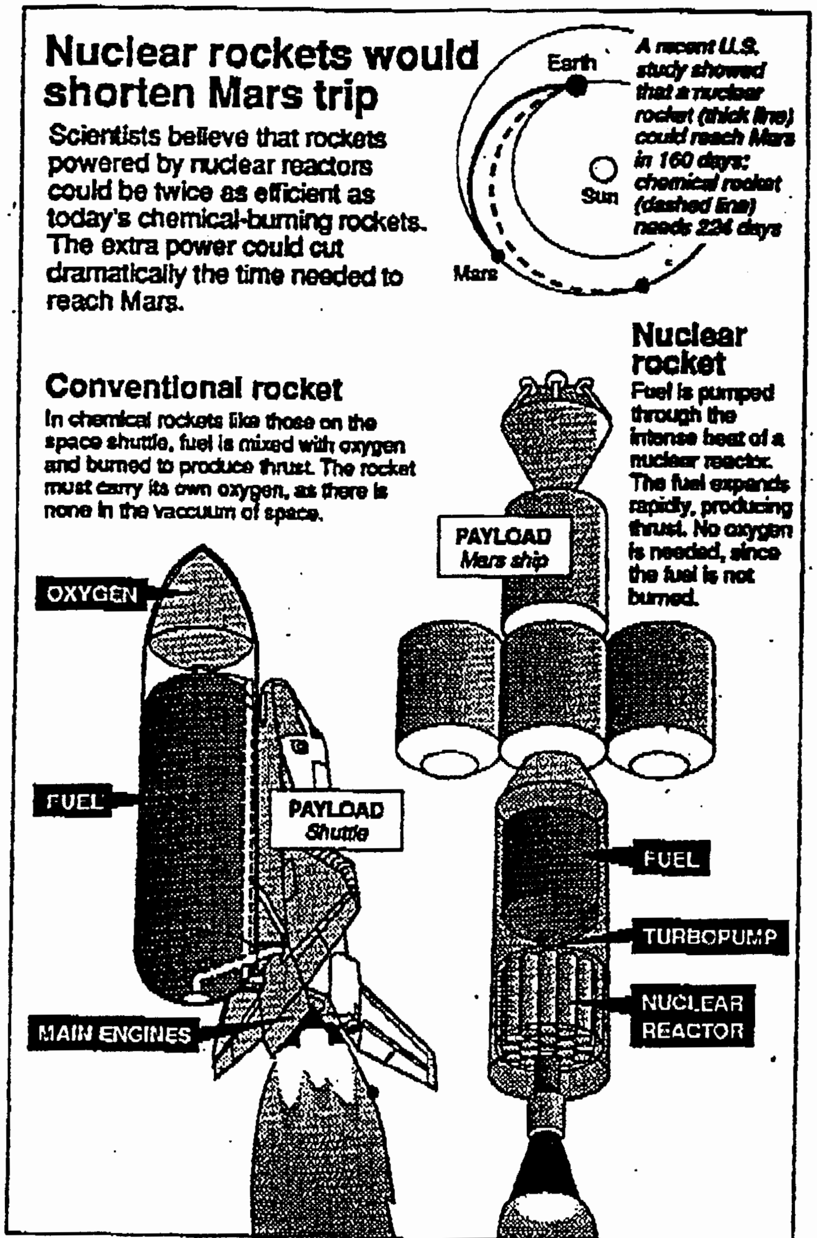
In addition, he said he is working with the Pentagon to buy the Soviet nuclear-powered satellite, which employs Soviet technology that has not been available in the free world.

Domenici said, however, there is no current effort to include Soviet scientists in a joint venture.

Nikolai N. Ponomarev-Stepnoi, first deputy director of the Russian Atomic Energy Academy in Moscow, said, though, "We are ready to participate in this program. This is up to our American colleagues.

"All in all we worked some 30 years in this direction, and we have achieved high results, in some cases exceeding the Americans," he said through a translator during a break in the conference.

Donrey Washington Bureau writer Shaun McKinnon contributed to this report.



Source: *The Illustrated Encyclopedia of Space Technology*, Synthesis Group report on America's Space Exploration Initiative AP/Karl Tate

Associated Press

Col. Peter J. Marchiando, commander of the Phillips Laboratory at Kirkland AFB, N.M., looks at a model of a nuclear thermal propulsion engine Monday in Albuquerque. Plans for such an engine were discussed.

ALBUQUERQUE JOURNAL Tuesday, January 14, 1992

Astronauts May Rocket To Mars

Trips Will Be Powered With Nuclear Energy

By Rex Graham

JOURNAL STAFF WRITER

Within the next few months, Phillips Laboratory in Albuquerque will begin testing components of a powerful experimental nuclear rocket intended to take astronauts to Mars in the next century.

The rocket technology grew out of secret Star Wars research already under way at Phillips, the U.S. Air Force's space-research superlab.

Part of the technology was declassified and described Monday by Sen. Pete Domenici, R-N.M., and laboratory officials during the opening minutes of the Ninth Symposium on Space Nuclear Power Systems.

"This is an enormously significant event as it pertains to man and space," symposium chairman Domenici told 300 journalists, Air Force officers and aerospace company representatives crowded into an Albuquerque Convention Center meeting room.

The University of New Mexico is the primary sponsor of the symposium, which is held in Albuquerque.

The engine is considered crucial for a Mars mission because a conventional chemical rocket would take 230 days to travel the 35 million miles to Mars at its closest point to Earth. The nuclear rocket could do the job in one-third the time, according to a federal feasibility report.

Air Force Lt. Col. Roger X. Lenard, project manager of the Space Nuclear Thermal Propulsion technology at Phillips, said $132 million has been spent on the engine since 1987 and $51 million will be spent this fiscal year on research and construction. He said $65 million to $125

MORE: See ASTRONAUTS on PAGE A3

Astronauts May Rocket To Mars

CONTINUED FROM PAGE 1

million a year needs to be spent on the effort to have the engine ready in eight years.

The eight-year target date is needed to get an astronaut to Mars by about 2016, the date recommended by a federal panel on the feasibility of sending an astronaut to Mars.

Officials said the project will create new jobs for Albuquerque, but no one could say how many.

While Phillips will manage the work, Sandia and Brookhaven national laboratories as well as aerospace companies Grumman Corp. and United Nuclear Corp. will be involved in the research and development effort.

Lenard

The heart of the rocket engine will be 100 pounds of radioactive uranium-235 made into black BBs. The tiny pellets, about one-half millimeter in diameter, will be encapsulated in ceramic. When the pellet bed is allowed to get hot during a launch, it will heat the hydrogen propellant to 5,000 degrees Fahrenheit, which will then roar out the back of the rocket and provide thrust.

Phillips officials said an environmental impact statement has been completed, but not yet cleared for release to the public.

Domenici said all environmental and safety standards will be met or exceeded. "It will be unprecedented in safety," he said.

Domenici said every part of the engine will undergo a rigorous "proof of concept" procedure before it ever makes its way to a launch pad.

Chemical rockets are envisioned to lift astronauts into Earth's orbit before the nuclear engine would be turned on to send the spacecraft zipping toward Mars.

Gary L. Bennett, deputy director of NASA's Transportation and Platforms Division, said at the symposium that his agency is looking at "two or three" nuclear thermal propulsion systems.

Las Vegas SUN, 1/14/92 **(1A)**

(Circulation: 34,011 daily)

Rocket plan a 'sham'

Scientist group: It's a cover for military

By Mary Manning
LAS VEGAS SUN

Plans to revive a nuclear-powered rocket program to explore the cosmos are merely a smokescreen for a top-secret military leap into space, a scientific think tank says.

"It's an exclusively military program and they are using space as a fig leaf to cover it," said Steven Aftergood of the Federation of American Scientists, based in Washington, D.C.

New research into a nuclear rocket engine for deep space exploration was announced Monday at the ninth annual Symposium on Space Nuclear Power Systems in Albuquerque, N.M.

The program, now characterized as a potential joint venture with Russian scientists in an effort to send a man to Mars, had its roots at the Nevada Test Site in the 1960s. It was shelved by President Nixon in 1972.

But the Federation of American Scientists said Monday that the supposedly new nuclear rocket program – code-named Timberwind – actually has been retired because of security leaks.

In its place, the scientists said the Air Force has launched a new secret program known as LT, an abbreviation of the new classified code name.

Testing could be performed at the Nevada Test Site or the Idaho National Laboratory, Air Force officials said. But the Air Force has not chosen a testing location.

University of California-Santa Cruz physicist Joel Primack called the rocket tests risky.

"The danger is the nuclear reactor will melt or even explode during the tests," Primack said.

Best estimates say it will take about eight years and $800 million to build and test the nuclear engine.

Current rocket engines use chemical propulsion, burning a fuel such as liquid hydrogen and an oxidizer to provide thrust, said Gary Bennett, deputy director of the Transportation and Platforms Division at the National Aeronautics and Space Administration.

In a nuclear thermal propulsion engine, hydrogen is injected into an atomic reactor that heats it. The hydrogen is then expelled out a nozzle at a high velocity.

"The hotter you make it (the hydrogen), the faster you go," Bennett said.

It is thought that nuclear reactors could cut travel time by 40 percent – a round-trip to Mars in about 300 days, including a 14-day stay, as opposed to 500 days via chemical rocket.

Although members of the Nevada congressional delegation have been briefed on the project, details remain unavailable.

"(The Air Force) seems determined to proceed further along the path of excessive secrecy," Aftergood said. "Public confidence is essential for a successful space nuclear program. Unfortunately, this program reeks of deception."

The Federation of American Scientists requested an environmental assessment of the Saddle Mountain experimental site at the Nevada Test Site, but never got it, Aftergood said.

"We were unable to respond to the request based on national security considerations," said Department of Energy spokesman Chris West.

West, meantime, expressed enthusiasm about the revival of the nuclear rocket program, which ultimately could send a man to Mars.

"I'm pretty excited about civilian aspects of it," West said. "That's why NASA's in it."

that a joint program with Russian scientists may be part of the nuclear rocket project. The Russians are believed to be ahead of the United States in nuclear-propelled rocket research.

The Strategic Defense Initiative Organization, a government body, is proposing to launch a nuclear reactor-powered spacecraft to explore the solar system by buying several Soviet Topaz II space reactors.

But the Soviet rockets don't conform to U.S. safety standards and could never receive launch approval, according to the Federation of American Scientists bulletin. Under certain circumstances, the Soviet engines could accelerate out of control, a mirror incident to the 1986 Chernobyl nuclear reactor accident, the bulletin said.

Post Register, Idaho Falls, ID 1/14/92

Nuclear propulsion project announced

Associated Press

ALBUQUERQUE — Astronauts traveling to Mars would get there quicker using a nuclear space propulsion system to help drive space ships after launch, experts said Monday.

"Nuclear propulsion is clearly a good way to do it," said Gary Bennett, deputy director of the Transportation and Platforms Division at the National Aeronautics and Space Administration in Washington, D.C.

The space nuclear thermal propulsion technology program, announced at the 9th Symposium on Space Nuclear Power Systems here that ends Thursday, will be managed by the U.S. Air Force's Phillips Laboratory at Albuquerque.

The lab will work with the U.S. Department of Energy and NASA on the project, portions of which were declassified Monday.

"This giant leap in technology can be equated to the progress made when man went from riding horses to driving automobiles," said Sen. Pete Domenici, R-N.M.

Lt. Col. Roger Lenard, program manager of Phillips Laboratory's space nuclear thermal propulsion program, said portions of the project were declassified because it's hard to implement "breakthrough technology in a classified world."

Bennett, appearing with Domenici and Lenard at a news conference, said current propulsion units use a fuel like liquid hydrogen and an oxidizer that are burned, providing thrust.

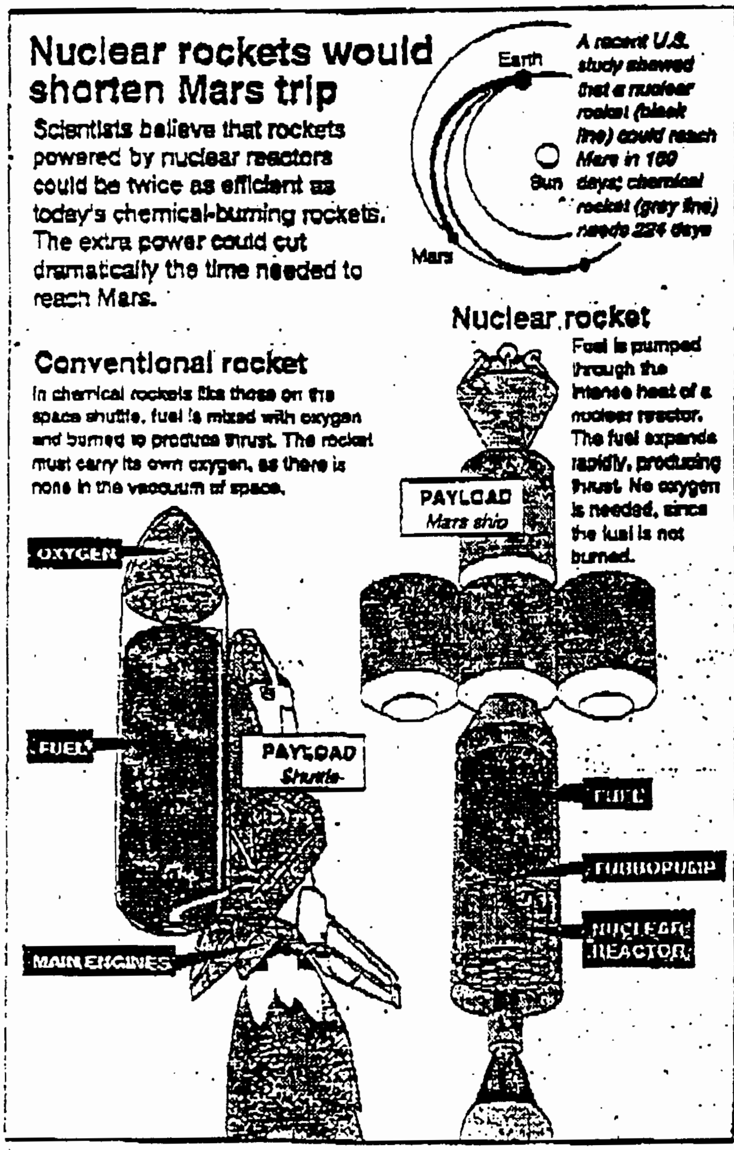
But in a nuclear thermal propulsion unit, hydrogen is injected into a nuclear reactor that heats the hydrogen, which is expelled out a nozzle at a high velocity.

"The hotter you make it (the hydrogen), the faster you go," Bennett said.

Laboratory work already has been conducted on such a system, but Bennett declined to elaborate.

Nuclear rockets would shorten Mars trip

Scientists believe that rockets powered by nuclear reactors could be twice as efficient as today's chemical-burning rockets. The extra power could cut dramatically the time needed to reach Mars.



Source: *The Illustrated Encyclopedia of Space Technology*; Synthesis Group report on America's Space Exploration Initiative — AP/Karl Tate

Domenici said it would take about eight years for the Air Force to complete construction and ground testing of a nuclear thermal propulsion engine before it could actually be used.

THE ALBUQUERQUE TRIBUNE / **INSIGHTS**

WEDNESDAY, JANUARY 15, 1992

Kirtland base unlikely to be rocket test site

The construction of a nuclear rocket test facility could cost as much as $1 billion, placing it in the big science competition for tax dollars, a Sandia National Laboratory analyst said today.

The test site likely will be at the remote Nevada nuclear bomb test facility near Las Vegas, where Los Alamos National Laboratory led a now-defunct nuclear rocket development and testing program in the 1960s.

Kirtland Air Force Base, where two of the rocket development prinçiples — Sandia the Phillips Laboratories — are located, "could not be absolutely ruled out" for test facility, but the base is not likely to be selected, Air Force officials said.

Such a facility would be used to conduct a myriad of tests of rockets being designed to power spaceships to the moon and Mars and for military missions in Earth orbit.

George Allen, a Sandia scientist who helped analyze existing test facilities as a member of Department of Energy, Pentagon and NASA panel, said today that the cost could range from several hundred million dollars to $1 billion.

Speaking at the Symposium of ninth annual Space Nuclear Systems in Albuquerque, Allen said the test facilities would have strict environmental and safety safeguards and would acccount for as much as 30 percent of the entire rocket development program, he said.

Lawrence Spohn

Las Vegas Review-Journal, 1/15/92 (1A)

(Circulation: 139,735 daily; 212,283 Sunday)

Governors of Nevada, Idaho wary of nuke-powered rocket

☐ Bob Miller and Cecil Andrus, who are battling the nuclear storage issue, are cautiously optimistic.

By Keith Rogers
Review-Journal

The governors of Nevada and Idaho, whose states are candidates for a Department of Energy nuclear-powered rocket project, welcomed the plan with some reservations Tuesday even though both are warring with the agency about nuclear waste.

Idaho Gov. Cecil Andrus said, "Yes. It sounds like that's the type of research and development we'd be interested in, but I'd have to know more about it."

Andrus said he first learned from a reporter Monday the Energy Department's Idaho National Engineering Laboratory near Idaho Falls was, along with the Nevada Test Site, being considered for testing a nuclear-powered rocket engine.

"It's good business. It's good economics. We've got an existing science research laboratory and qualified personnel to do the work," he said.

Andrus said he will meet next week with Energy Department officials about the future of the Idaho National Engineering Laboratory.

He has been quarreling with the agency about his reluctance to allow storage in Idaho of medium-level tranuranic wastes from the nuclear weapons complex and abroad.

"We're not in the business of storing nuclear waste from around the world," Andrus said during a telephone interview.

"We have always said we will handle wastes we have generated, but not the waste generated in Rocky Flats and Fort St. Vrain (both in Colorado), New York, the Taiwan public service utility, or those fuel rods that are currently stacked up in Australia," Andrus said.

Nevada Gov. Bob Miller, who adamantly is opposed to Department of Energy's plans for locating a high-level nuclear waste dump at Yucca Mountain, 100 miles northwest of Las Vegas, said a proposal by the same agency to test nuclear-powered rockets nearby has economic advantages — if it is safe.

"I don't think there is any comparison in the risks. It's kind of like comparing apples and oranges," Miller said.

He said he has been told by officials proposing the rocket project that it has "significant safeguards."

However, Miller said, "There is nothing to lead me to believe the dump will be safe at all."

He estimated the amount of radioactive material that would be buried in the Yucca Mountain repository — 77,000 tons of high-level nuclear waste mostly from civilian power reactors — is about the same as remnants from 2 million nuclear tests.

"And it will be transported on the roads on a daily basis," Miller noted.

But, he said he is encouraging the federal government to look for alternatives to the test site, 65 miles northwest of Las Vegas, where all U.S. and British nuclear weapons test devices are detonated below ground.

The nuclear-powered rocket project stands to bring hundreds of millions of dollars to the state to test the rocket engine, which federal officials say would be used to thrust into space heavy military payloads and power spacecraft carrying humans to the moon and Mars.

A surprise announcement this week by Sen. Pete Domenici, R-N.M., that the project had been declassified, revealed the Phillips Laboratory at Kirtland Air Force Base in New Mexico, and two national labs — Sandia Albuquerque and Brookhaven in New York — already have spent $132 million on the project since 1988.

Rich Garcia, a spokesman for the project, said altogether $800 million will be spent on constructing facilities and testing the rocket engine during the next eight years.

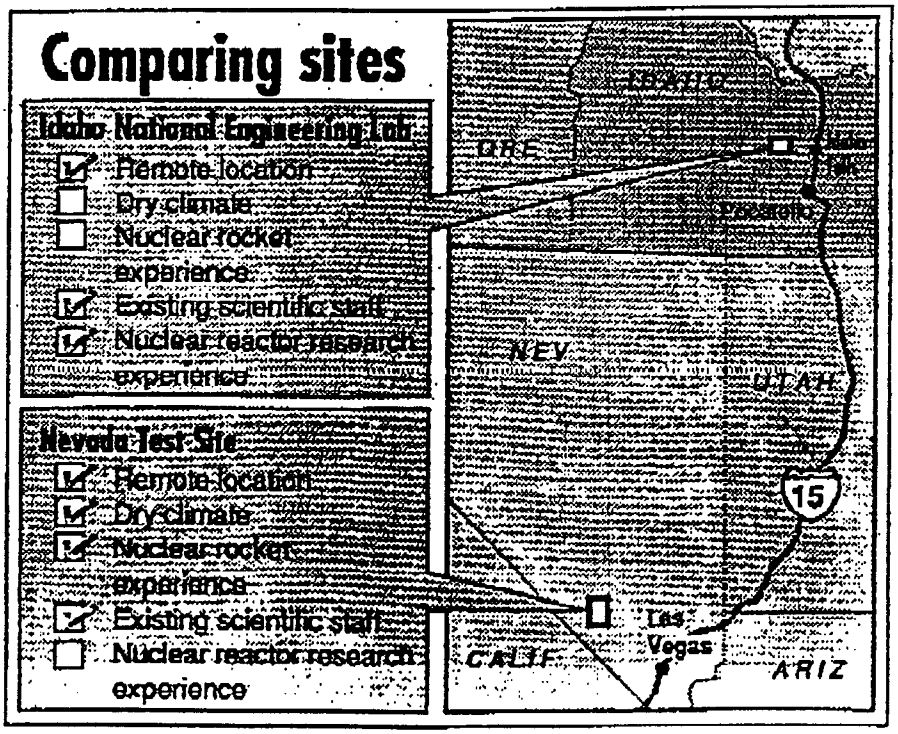
A statement by Domenici says annual funding for the project is projected to be about $40 million a year through 1997, followed by as much as $80 million a year "into the next century."

At a news briefing in Albuquerque, N.M., on Monday, Domenici said $65 million to $120 million would be spent on it this year, with the figure probably closer to $65 million.

Garcia said, "I know there are discrepancies in some of the figures. It just depends on how you interpret them."

Chris West, a spokesman for the Energy Department's Las Vegas office, said an official had inquired Tuesday about the possibility of the University of Nevada, Las Vegas, participating in some of the research.

"Obviously in an $800 million program the university community would be part of that," West said.



Post Register, Idaho Falls, ID 1/15/92

Andrus would welcome rocket testing program

Associated Press

LAS VEGAS — The governors of Nevada and Idaho have expressed cautious optimism about a federal plan to develop a nuclear-powered rocket.

Testing of the rocket would likely be conducted at the Nevada Test Site, 65 miles northwest of Las Vegas, or the Energy Department's Idaho National Engineering Laboratory near Idaho Falls.

Idaho Gov. Cecil Andrus says the project sounds like the type of research and development the state would be interested in.

Nevada Gov. Bob Miller says the plan for the nuclear-powered rocket would have economic advantages, if it is safe.

Miller says he's been told by those supporting the program that the project would have "significant safeguards."

Miller has adamantly opposed a nuclear waste dump proposed by the federal government for Yucca Mountain, 100 miles northwest of Las Vegas.

"I don't think there is any comparison in the risks," he said of comparing the safety of the rocket program and the nuclear waste dump. "It's kind of like comparing apples and oranges."

The nuclear-powered rocket project stands to bring hundreds of millions of dollars to the state where the tests of the rocket engine are conducted. The federal government says the rocket would be used to thrust heavy payloads into space and power manned spacecraft to the moon and Mars.

Las Vegas Review-Journal, 1/16/92 (8B)

(Circulation: 139,735 daily; 212,283 Sunday)

Opinion

The art of misdirection

The possibility of the Nevada Test Site being used to develop a nuclear powered rocket is good news to the 8,500 employees there. It represents the first concrete proposal to secure the future of the test site in the post-Cold War world, an important goal for the Southern Nevada economy.

The test site, though, is only a finalist for the program, which would develop a more efficient rocket engine to power manned space flights or launch military payloads. Idaho is also in the running.

But, irony of ironies, how do state officials, given their rabid opposition to a potential nuclear waste dump at Yucca Mountain, justify their tentative support for ground testing in the Nevada desert of a nuclear rocket engine?

"Apples and oranges," said Gov. Bob Miller.

That's debatable. Nevertheless, the issue highlights the precarious high-wire act state officials must perform to rationalize their various positions on things nuclear. The test site, where they detonate nuclear bombs, is good. Nellis Air Force Base, where they stockpile nuclear weapons within a few miles of thousands of people, is good. A program to test nuclear engines, which entails enough risk that test flights of a prototype rocket will occur near Antarctica, is good.

But storing nuclear waste at Yucca Mountain is so evil that the state's full weight must be unleashed to stop it.

Miller, for instance, said Tuesday that officials proposing the rocket program — at least in part under the auspices of the Department of Energy — assure him it has "significant safeguards." Yet it is precisely such assurances from the DOE about a high-level waste dump at Yucca Mountain that elicit howls of derision from state officials.

The governor also praised the economic benefits of the (yet-unstudied) rocket program, while a state commission on economic development refuses to study the potential ramifications of Yucca Mountain.

It's true that Yucca Mountain and the rocket program are only tangentially related. It's also true that Congress singled out Yucca Mountain as the lone potential waste site. And it's legitimate to ask whether one state should have to house all the nation's high-level nuclear waste.

Trouble is, the site selection process and the nation's nuke waste policy represent only minor components of the state's argument against Yucca Mountain. Rather, state politicians have, in large part, preyed upon an irrational fear of things nuclear and an inherent distrust of the DOE to whip up the masses against the nuke dump.

In doing so, they create a logical vacuum for their own embrace of other nuclear-related or DOE projects.

New Thermal Propulsion Gains To Speed Rocket Production

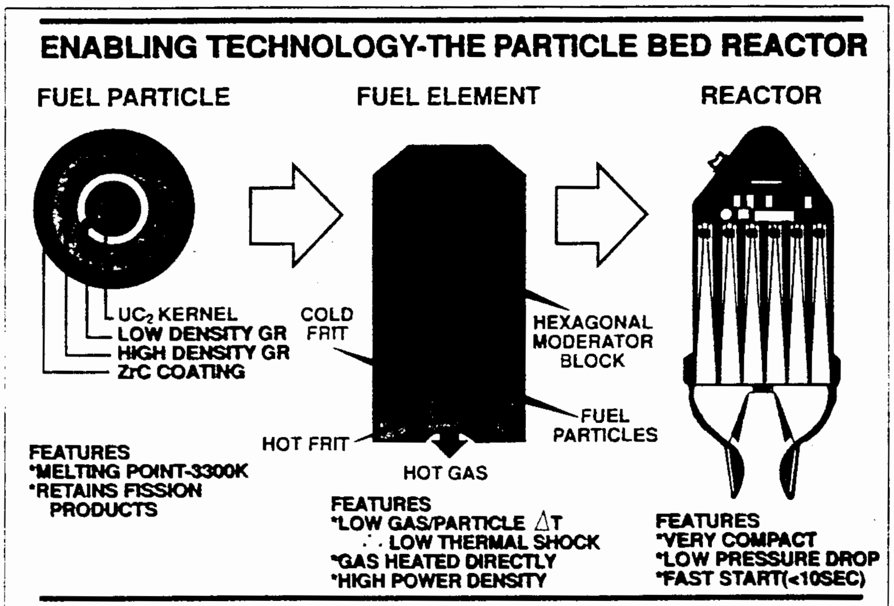
BRECK W. HENDERSON/ALBUQUERQUE, N. M.

Technical breakthroughs in nuclear thermal propulsion, which the U. S. Air Force has claimed, could accelerate initial production of a practical, high-performance nuclear rocket.

Officials from the Air Force Phillips Laboratory here revealed many previously classified details of its Space Nuclear Thermal Propulsion (SNTP) program at the 9th Symposium on Space Nuclear Power Systems last week.

U. S. Sen. Pete V. Domenici (R.-N. M.), chairman of the symposium, endorsed the program, saying "SNTP will do for man in space what the automobile has done for man on Earth." He pointed out the potential for reducing the cost for orbiting payloads for all purposes and the value of technology spinoffs from the program.

The SNTP program draws components of several research efforts into one project directed by Phillips, officials said, but at least part of the program was code-named Timberwind and directed by the Strategic Defense Initiative Organization (AW&ST Apr. 8, 1991, p. 18). Sandia National Laboratories here, Brookhaven (N. Y.) National Laboratory, NASA and the Energy Dept. also will participate.



Model of a potential space nuclear thermal rocket was displayed at the 9th Space Nuclear Power Symposium. The system is designed to have 75,000-lb. thrust and 1,000-sec. ISP.

The SNTP program is developing a rocket with a particle bed reactor that would produce about 75,000 lb. of thrust with hydrogen propellant heated to about 3,000K (5,000F). This would give it a specific impulse (ISP) of 1,000 sec. and a 30:1 thrust-to-weight ratio.

Lt. Col. Roger X. Lenard, SNTP program manager at Phillips, said these ambitious operating parameters are made possible by a number of technical "breakthroughs":

■ Power Density. Tests on hardware developed so far indicate an extremely high power density of 40 megawatts/liter is possible, Lenard said. The reactor portion of the rocket must be light and compact to realize the full advantages of the propulsion system.

■ Fuel kernels. In a particle bed reactor, the enriched Uranium 235 fuel is formed into beads of about the size of a grain of sand (0.5 mm.) in order to increase the surface area-to-volume ratio for efficient heat transfer.

Each particle is composed of a fuel kernel surrounded by a special coating to withstand the high temperature, prevent fission products from mixing with the propellant and minimize erosion from the flow of hydrogen gas. Engineers have fabricated new forms for the kernels that are stable at temperatures in excess of 3,000K, Lenard said.

■ Particle coatings. Lenard said his team is developing coatings to allow the kernels to work at high temperatures.

■ Cold frit. The hydrogen propellant is heated from 100K to 3,000K in a few centimeters of travel over the fuel particles. They are placed in fuel elements, which are cylindrical containers with a hollow flow channel in the center. The hydrogen is admitted radially to the annular region containing the fuel particles via a cold frit or filter that has been engineered using platelet technology pioneered by Aerojet.

■ High-temperature turbine. Program scientists also are fabricating parts for a turbine that can withstand 2,750K, Lenard said.

About $130 million has been spent since work began in 1987 with the goal of building and ground-testing a working propulsion system in about eight years.

The rocket also could be an important element of the Space Exploration Initiative that would be used to take astronauts from low-Earth orbit to the Moon or Mars

Officials estimate the complete program will cost about $800 million. The Air Force's Fiscal 1992 budget for SNTP called for $44 million, but Domenici said Congress has appropriated more than $65 million.

Lenard would not discuss the missions for which the Air Force is planning to use a nuclear thermal propulsion system, but he said employing the nuclear rocket to launch payloads directly from Earth has been ruled out, contrary to earlier descriptions of Timberwind.

Safety and environmental protection are top priorities in the SNTP program in response to public concerns, according to officials. "The technical breakthroughs are nice, but the real issue is safety. It's been a huge part of the development program," Lenard said.

A nuclear rocket used as an upper stage on a conventional booster could reduce launch costs significantly. "The payload of an Atlas could be multiplied by three or four using a nuclear upper stage," Lenard said.

The rocket also could be an important element of the Space Exploration Initiative that would be used to take astronauts from low-Earth orbit to the Moon or Mars. None of these applications would require firing the rocket inside the Earth's atmosphere.

The SNTP program has come as somewhat of a surprise to nuclear propulsion specialists at NASA and the Energy Dept., although the particle bed technology is not new and is an option being considered by NASA's office for space nuclear propulsion at Lewis Research Center in Cleveland.

Stan Borowski, a NASA nuclear propulsion scientist, said, "If they can get the operating parameters as stated, then it's an exciting development."

However, NASA needs a propulsion system that would operate differently than a military system. To send astronauts to Mars, a nuclear rocket would have to burn continuously for about 30 min., whereas an Air Force rocket would burn for only a few seconds at a time (AW&ST Dec. 2, 1991, p. 38). "We need long lifetime, robustness and a minimum of radioactive release," Borowski said.

He would like to see three concepts developed far enough for a technology run-off among an advanced NERVA design, a design using solid ceramic-metallic fuel called CERMET and the particle bed design.

Steven D. Howe, program coordinator for nuclear propulsion at Los Alamos (N. M.) National Laboratory, said there are still technical questions about controlling the flow of propellant around the fuel particles. The most advanced test of SNTP fuel elements to date, the Pulsed Irradiation of a Particle Bed Reactor Fuel Element (PIPE) test, was shut down prematurely when hydrogen flow was blocked and the element overheated.

Lenard said there was some melting and damage to the fuel element because carbon particles from the electrical brushes of support equipment blocked hydrogen flow. "There was no problem with the fuel particles, and we learned a lot from the tests," he said.

NASA and the Energy Dept. have not had the opportunity to evaluate the Air Force technology, but are forming teams and looking for money to begin the effort.

Prime contractor for the Air Force on SNTP is Grumman Space Systems Div. Subcontractors include Babcock and Wilcox, Aerojet, Garrett Fluid Systems Div., Hercules, General Dynamics, United Nuclear and L-Systems. □

Russians to Offer Their Nuclear Thermal Propulsion Technology to U. S.

ALBUQUERQUE, N. M.

Russian scientists attending the 9th Symposium on Space Nuclear Power Systems here say they, too, have much of the technology needed to construct a nuclear thermal propulsion system.

The Russian system is designed to develop about 5,000 lb. of thrust with a specific impulse (ISP) of 950 sec. It operates at about 3,000K (5,000F) and can burn continuously for up to 1 hr. The device is 4 meters (13 ft.) high and 2 meters (6.5 ft.) in diameter and weighs 2 metric tons (4,400 lb.).

Last year, the Russians chose the symposium as the occasion for announcing they had agreed to sell the U. S. scientific establishment a working copy of their Topaz 2 space nuclear power supply (AW&ST Jan. 14, 1991, p. 54). Consummation of the $10-million contract has been delayed by the U. S. State Dept., but U. S. Sen. Pete V. Domenici (R.-N. M.) said he thinks objections have faded and delivery will occur soon.

The University of New Mexico here, where the Topaz 2 will be studied, already has constructed some of the facilities, according to Nikolai N. Ponomarev-Stepnoi, deputy director of the Kurchatov Institute of Atomic Energy in Moscow.

The Russian nuclear propulsion system uses solid fuel rods, not the particle bed system in the U. S. Air Force's space nuclear thermal propulsion program. Ponomarev-Stepnoi said a complete propulsion system has not been ground-tested, but noted that much testing has been conducted in special nuclear reactors that have made it possible to develop the important components. Engine components also have been researched and mockups constructed.

Russian scientists see some U. S. programs, such as the space exploration initiative, that could benefit from their technology and are anxious to find roles. "Our technology supersedes American technology in some areas, and it would reduce costs if it were used," Ponomarev-Stepnoi said.

The Russian effort has developed fuel elements that are more advanced than American designs as well as advanced high-temperature, carbide-based ceramic composite materials for use in the reactor, he said.

The team of scientists who worked on the technology is still together, but in the crisis-plagued former Soviet Union, "the government does not pay much attention to this kind of work," Ponomarev-Stepnoi said.

"So long as we believe we will cooperate with the West, the team will stay together. But if the West doesn't show some activity, it will be very difficult to keep them from taking jobs in the Third World," he said. □

January 24, 1992

ASTRO NEWS

Phillips Lab develops program; decreases space launch costs

The Phillips Laboratory at Kirtland AFB, N.M., along with other laboratories and agencies, is managing development of a technology program expected to decrease space launch costs while increasing launch capability.

Pictured is a model of the Space Nuclear Thermal Propulsion Engine which the Air Force's Phillips Laboratory is developing. The cone-like structure at the bottom is the rocket nozzle. The nuclear particle bed reactor is the cylinder in the middle portion, and the engine subsystems are the circular assembly at the top. The actual engine would be 12 feet high. (Official U.S. Air Force Photo)

Designed to advance the state-of-the-art in space propulsion, the space nuclear thermal propulsion program will use a particle-bed reactor that should more than double the specific impulse of the best current rocket engines, laboratory officials said.

The goal is to develop a 75,000-pound thrust engine with a specific impulse goal of 1,000 seconds at a 30-to-1 thrust-to-weight ratio for exo-atmospheric applications.

Officials announced plans for the program at the ninth symposium on space nuclear power systems Jan. 13.

While propulsion technology was chosen for its potential for a wide range of military and civilian space missions, the Air Force has no plans to use the engine in the atmosphere, officials said. It may be used once a vehicle is in space, for example, as an advanced upper stage for space launch or an orbit transfer vehicle.

Phillips Lab is managing the program. The Air Force, Department of Energy and NASA are also participating. **(AFNEWS)**

Las Vegas Review-Journal, 1/26/92
(Circulation: 139,735 daily; 212,283 Sunday)

Nuke rocket put on the front burner

☐ Scientists aim to refine the idea for a trip to Mars, and Nevada or Idaho may provide the testing ground.

By Keith Rogers
Review-Journal

A statue of a warrior with outstretched arms and hands gripping the legs of an eagle in flight greets travelers arriving at Albuquerque International Airport.

The 13-foot-tall bronze work, titled "Dream of Flight," is a metaphor for scientists who envision a nuclear powered rocket that would thrust humans at record speeds on journeys to Mars, or lift "Star Wars" payloads into orbit.

The idea of using fission reactions to heat propellants to power rockets is not new, having been explored by Soviet researchers 30 years ago. But scientific breakthroughs at Phillips Laboratory on Kirtland Air Force Base, which overlaps the Albuquerque, N.M., airport, could land a major, $800 million project at the Nevada Test Site, 65 miles northwest of Las Vegas, according to Gov. Bob Miller and Deputy Energy Secretary W. Henson Moore.

The Idaho National Engineering Laboratory is another site that could host ground tests of the rocket, a venture expected to last eight years, Moore said during an interview last week.

But he said "there may be a third or fourth" site involved in the selection process because an environmental impact statement, or EIS, which could take 18 months to complete, is supposed to consider all possible sites.

Interviews with project officials show great promise for its success. Miller and Idaho Gov. Cecil Andrus have expressed interest in hosting the experiments, although they said they have some reservations about potential safety and environmental problems.

Given the uncertainties with rocket experiments, heightened by the explosion of the 1986 Challenger space shuttle that killed six astronauts and a New Hampshire schoolteacher, the thought of a nuclear powered rocket makes anti-nuclear activists shudder.

"We definitely want an EIS so the public can be informed," said Chris Brown, Southern Nevada coordinator

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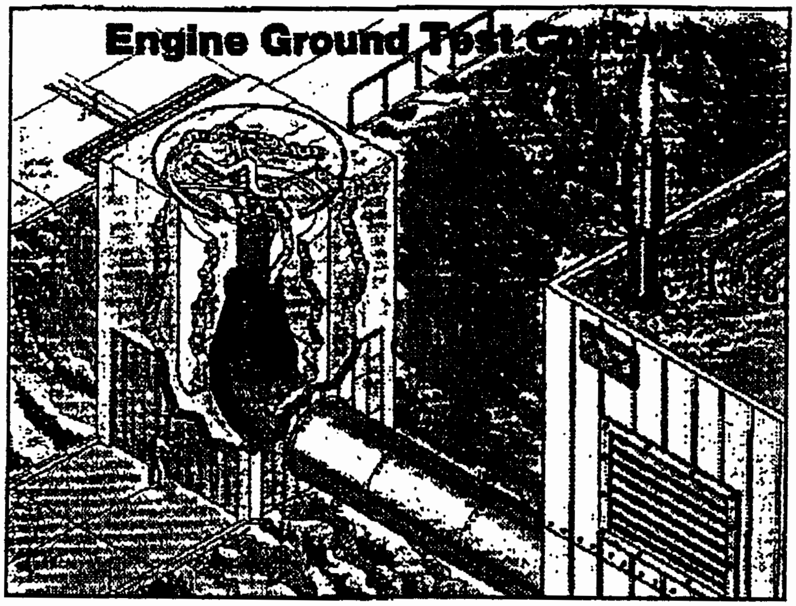
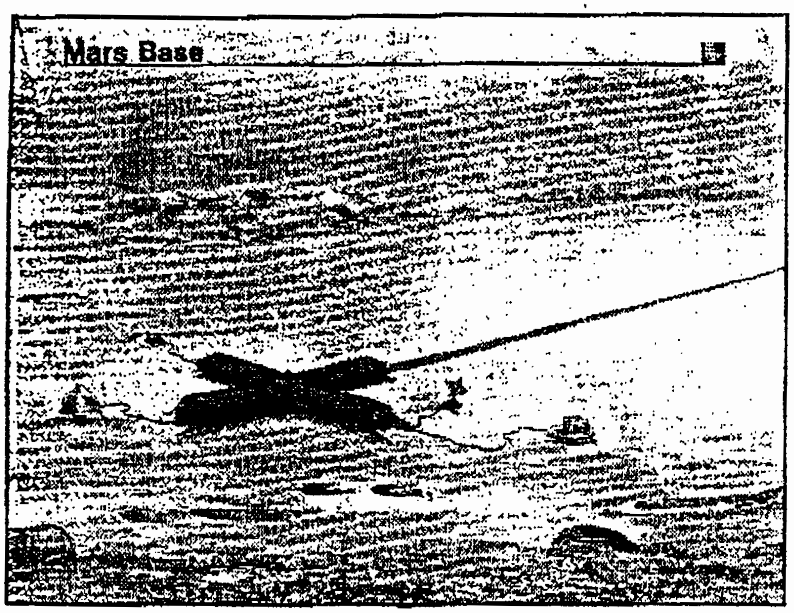


Air Force drawing

A test facility for nuclear powered rockets depicts the engine in an upright position with exhausts channeled to a filter room and burned off exiting a stack.



Lawrence Livermore National Laboratory drawing

A Mars base made of inflatable modules covered with Martian soil for radiation protection is likely cargo for a nuclear powered rocket in some National Space Council plans.

Rocket—

From 1B

of Citizen Alert, a statewide environmental watchdog group.

"The other thing that concerns us is this overall design. You put a source like hydrogen next to a nuclear reactor and you can have a big mess," Brown said.

Steven Aftergood, senior research analyst for the Federation of American Scientists, a private research and advocacy group in Washington, D.C., that examines space policy issues, said he wonders about the side effects of the rocket's ground tests.

"In some ways, ground testing of a nuclear engine may be the most environmentally sensitive issue of the whole program because we're not talking about what happens in space but what happens in Nevada," he said.

"What are the plausible accident scenarios at a ground test facility?" asked Aftergood. "As far as actually using a nuclear rocket, there is another set of questions."

Launching a nuclear powered rocket "should not be extraordinarily dangerous," said Aftergood, an electrical engineer. "A uranium reactor is not highly radioactive at launch. It's only after it has been used."

Aftergood, whose group in April was the first to reveal the government's secret, nuclear rocket work, code-named Timberwind, said he is "offended by the secrecy that has surrounded and continues to surround this program."

The Air Force continues to keep secret an EIS it prepared on the nuclear rocket project, most of which was declassified this month, he said.

Aftergood said the so-called declassified project is actually a descendant of Timberwind, along with another classified program known only as "LT."

He charged the Air Force is using the rocket's possible role in expeditions to the moon and Mars as a guise to cover its future military missions.

Sen. Harry Reid, D-Nev., said he has "been following this (project) awhile through classified briefings."

"We have been told there have been a number of studies to make sure the environmental problems are not a concern," he said. "I don't see any problems with it at all at the test site."

But a Bush administration official said nuclear powered rockets would play a major role in carrying out the National Space Council's moon-Mars initiative President Bush announced in 1989.

"The preponderance of opinion is that a space nuclear propulsion system is really vital to making a Mars mission affordable, and bring it to an acceptable level of risk," the official said.

The space council has estimated a nuclear powered rocket could carry astronauts to Mars in one-quarter the time as conventional, chemical propulsion systems. The trips also would be safer because astronauts would endure less time in zero gravity conditions, and receive less exposure to harmful, cosmic rays.

Air Force Lt. Col. Roger Lenard, manager of the Space Nuclear Thermal Propulsion Program at the Phillips Laboratory, explained the differences between a nuclear rocket engine and a conventional engine, and why scientists believe nuclear powered rockets are safer.

First, Lenard said, rockets powered by solid fuels have motors, while liquid fueled rockets are powered by engines.

Most rockets also have more than one engine, he said. For example, the Saturn V rocket used in U.S. moon expeditions had five engines. The space shuttles, however, have three liquid oxygen/hydrogen engines and two very large rocket motors.

In the case of a nuclear powered rocket, energy from a controlled, fission reaction — the splitting of uranium atoms — would be used to heat a propellant, Lenard said. The propellant would be hydrogen stored in its liquid state in a tank above a bed of uranium-235 "kernels," he said.

These kernels serve the same purpose as pellets of nuclear fuel, which make up fuel rods in nuclear power reactors. Instead of rods, Lenard said, radioactive kernels containing carbide and coated with a non-reactive ceramic material are arranged in a bed that would heat propellants, in this case hydrogen gas.

A goal of the rocket testing program is to make sure uranium does not react chemically with hydrogen gas when the gas passes over the bed of kernels and is heated to 5,000 degrees Fahrenheit.

This hot hydrogen would expand in a thrust chamber, and, in turn, be forced out of a nozzle, driving the spacecraft forward, according to Air Force drawings.

"It is essentially a very powerful heater," Lenard said.

Most of the ground tests would focus on the ability of the ceramic shells surrounding the kernels to withstand great temperatures, he said.

Current designs call for the nuclear engine only to be used above Earth's atmosphere, more than 60 miles high. "We would always use some form of conventional rocket to get it above Earth's atmosphere," Lenard said.

Theoretically, this would prevent any chance of fire or explosion because pure hydrogen gas cannot burn without oxygen in the vacuum of space, even with a hydrogen leak.

The Challenger explosion was caused by a leak in a joint of the solid rocket booster, which has been redesigned extensively.

A nuclear engine, capable of producing 75,000 pounds of thrust, would contain tens of thousands of uranium-235 particles in each fuel element. And a rocket of that power capacity would contain 61 fuel elements, Lenard said.

What would happen to the nuclear waste produced by the fission reactions?

It would stay in a high orbit for thousands of years and, by that time, would have decayed to a safe, stable level many times over, according to Air Force estimates.

The waste would be cold both radioactively and in temperature, Lenard said. "All of the radioactivity would have decayed down

Rocket—

to the level of what it was on the pad," he said.

"For each engine, we burn two grams of uranium for every 100 seconds it operates. We'll carry about 40 kilograms (of uranium-235) just to get the reactor to operate," Lenard said. "We have no intention of using an engine for more than one mission."

A Soviet nuclear powered Cosmos satellite operated for long periods in relatively low orbits and became radioactive before crashing to Earth. It virtually disintegrated as it fell in Canada's Northwest Territory in 1978.

In contrast, a U.S. nuclear rocket would run for very short periods at higher orbits.

"You would use very little fuel, creating little waste with very short half-lives — half-lives that could be measured in weeks or hours," said Lenard.

The waste would be fission byproducts such as xenon, krypton and strontium. A "slight" amount of plutonium-238 would be produced "and would burn off almost immediately," said project spokesman Rich Garcia. "Essentially you're not going to have plutonium as a byproduct."

Lenard said the nuclear rocket engine is especially appealing for missions to Mars, because such a mission would require much maneuvering. "You may have multiple starts and stops. You need thrust to get out of Earth's orbit, then thrust to get into Mars orbit, then thrust again to get out of it."

Work on the Mars mission, according to the National Space Council, has amounted to refinement of some four proposals from various institutions, including aspects of one made in 1989 by physicist Lowell Wood and two of his associates at the Lawrence Livermore National Laboratory in Livermore, Calif.

Wood is the same visionary behind the "Brilliant Pebbles" antimissile plan, an orbiting shield of many yard-long, conventional rockets equipped with special wide-angle lenses and computers that guide them toward enemy missiles in space and destroy them by colliding with them.

Although a Livermore lab spokesman said Wood "doesn't have the time or, frankly, the inclination to do (an) interview" about the space exploration project, which has been abandoned by the lab, a Bush administration official said Wood's idea for inflatable space modules to house astronauts is still alive.

These tough, Kevlar bladders, which Wood has called "community-size space suits," might be some of the gear that nuclear powered rockets would shuttle to Mars, the official said.

Since 1989, the space council has spent a relatively modest amount on Mars expedition plans, "barely tens of millions of dollars," the official said. Those plans explore a number of scenarios, including using the moon, or a space station as a steppingstone to reach Mars, which could occur from 2011 to 2016, according to previous NASA calculations.

The price tag for all of this, including nuclear powered rocket development and production, would range in the tens of billions, perhaps hundreds of billions, of dollars, according to space council estimates. That is considerably more than the $10 billion that Wood calculated his "Great Exploration" would cost, partially because the current project diverts from his idea of using off-the-shelf technology for slower, chemical rockets instead of faster, nuclear powered ones.

Ground tests, which could be completed at the end of eight years, would be essentially engine stand tests, Lenard said. During the tests, an engine would be mounted upright and hydrogen exhausts from the nozzle would be channeled through a high-efficiency filter system to scrub it clean of any contaminants. Then the hydrogen would be burned off.

Evaluations are still being made to determine if the waste from testing in the engine would be classified as low-level or high-level defense waste, he said.

The amount of waste would be relatively small because only grams of nuclear fuel would be used up in the reaction, resulting in tens of grams of waste, Lenard said.

"We may do two or four tests a year. We may then do 10 or 20 kilograms of fuel in the subscale testing, so I think the total amount of uranium involved would be less than 200 pounds per year," he said.

Besides testing the durability of the kernel coatings, Lenard said another technical challenge of the test program would be to ensure the reactor can operate safely and reliably through its life span.

As for space missions involving humans, Lenard said he doubts shields to minimize radioactive exposure to the astronauts would be as much of a problem as providing protection from naturally existing radiation in space.

"The radiation encountered in space far exceeds that which would be encountered in a nuclear rocket engine. Even with minimum shielding, it does not appear to be an intractable problem at all," he said.

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Nevada Test Site could play major role in rocket experiments

By Keith Rogers
Review-Journal

The Department of Energy's No. 2 official does not foresee any surprises ahead for the Nevada Test Site other than the possible addition of a nuclear powered rocket project that could lift the nation into a new era of space exploration.

Deputy Energy Secretary W. Henson Moore said the rocket project would not replace any of the test site's national defense programs such as testing nuclear warheads, but it would continue an unusual space research program that has been secretly under study by the Air Force.

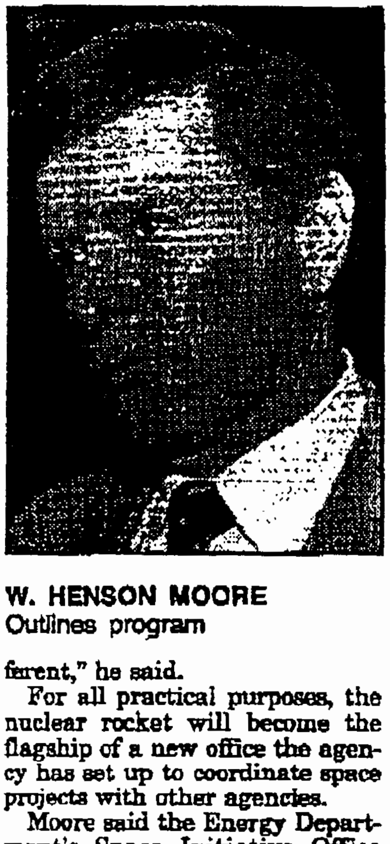
"It's not a huge program," Moore said last week, following a private meeting with Nevada Operations Manager Nick Aquilina at the agency's Las Vegas office.

Construction of a facility to conduct ground based engine tests would cost about $40 million, with an additional $200 million to operate the project through its life span, he said.

The nuclear rocket project, alias the Space Nuclear Thermal Propulsion Program, is "a little bit unusual," Moore said.

"We're trying to put it in the mode of usualness. When it comes to anything nuclear, DOE is supposed to have the lead. The military often hasn't tried to run a nuclear project on its own.

"They say, 'You guys design it, build it, test it and deliver it to me.' But this one started off different," he said.



W. HENSON MOORE
Outlines program

For all practical purposes, the nuclear rocket will become the flagship of a new office the agency has set up to coordinate space projects with other agencies.

Moore said the Energy Department's Space Initiative Office "only has three or four people in it."

"It's an effort to coordinate first within the department. But the need is coming from the president's space council and NASA," he said.

Another Energy Department project is to develop small nuclear reactors to power deep space probes, such as those for the Galileo mission, he said.

Despite a new emphasis on space work and the world's political climate changing toward disarmament, Moore said the main mission of the test site, 65 miles northwest of Las Vegas, will remain testing nuclear weapons.

"In our mind, as long as we're going to have nuclear weapons, we're going to have to keep testing" to ensure that the U.S. weapons are safe and reliable, Moore said.

Warheads slated for dismantling will not likely wind up at the test site. "We do all our dismantling at the Pantex plant" in Texas, he said.

A question mark in the disarmament picture is what the new Commonwealth of Independent States will do, even with help from U.S. weapons designers. In a historic speech last year, President Bush promised help to the Soviet Union when he challenged the superpower to disarm some of its nuclear weapons.

"I think they need help," Moore said of the Russians. "I heard at one point they never built their nuclear weapons with the idea of dismantling them.

"It takes money to take a weapon apart, and resources are very scarce. It's much cheaper for the Russians to leave these weapons assembled. You've got to pay their technicians and their scientists to work on them," he said.

Moore said there is a "very realistic fear" among U.S. officials that the thousands of Russian bomb builders and designers will be recruited by other nations that don't have peace in mind.

"So far nobody knows. We're worried about it," he said.

In 1992, Moore said the agency's biggest challenge will be to show the American public progress that has been made since Energy Secretary James Watkins set out to change the agency's mind-set.

One of the goals is to establish credibility that had been lost through 40 years of environmental neglect in the effort to make nuclear weapons.

This year "ought to be the year we show across-the-board the results of three years of planning and change of direction," he said.

"This will be the year the K reactor will start up. This will be the year of progress at Yucca Mountain. This will be the year we see the laboratories at Rocky Flats (Colo.) open up again," he said.

"So this is the year of fruition, to show we knew what we were doing, the proof in the pudding.

"It's been a long tough road. The toughest part has been that the department was run a certain way throughout its history. ... The reason was our work was secret and we didn't" have to comply with environmental laws, he said.

"We see it changing. The rules and regulations are in place. The money is being spent. People are being hired. But it will be another three or four years when you can safely say the place has been institutionalized," Moore said.

Taking care of business?

How America may be blowing an important deal with Moscow

Ten years ago, Yuri Kravinsky, a senior nuclear engineer at the Central Design Bureau for Machine Building in Leningrad (now St. Petersburg), requested permission to emigrate to Israel. Kravinsky had been one of the primary designers of a nuclear-powered Soviet surveillance satellite called Topaz II. The project was classified top secret. His KGB minders feared that Kravinsky's intimate knowledge of Topaz would be utilized by their cold-war adversaries; they denied his request.

Now a free man, Kravinsky sat in his New York apartment a year ago and listened in amazement to news that his old bosses not only had lifted the veil of secrecy surrounding Topaz but had offered to sell the technology to the United States. The Air Force and the Strategic Defense Initiative Office jumped at the opportunity.

Today, despite the fact that Kravinsky's enthusiasm is shared by many on both sides of the Atlantic, the prospect of such a historic joint venture is just that. The State Department has thrown a roadblock in the way of the sale. An interagency panel is studying the matter -- to death, critics suggest.

Sales job. *At a science symposium in New Mexico last week, a Russian makes his pitch.*

Brain drain. Is the United States missing a bet? Very possibly. Not only is the Topaz technology considered vital to future U.S. defense needs, but the project would be a powerful signal of American willingness to invest in the economic affairs of the former Soviet Union. Perhaps most important, this and other joint ventures would be the best way Washington could stem the brain drain of Soviet nuclear scientists to nations with competitive space industries in Europe and Asia, or to Third World nations intent on developing their own nuclear-weapons programs.

Two major areas of potential cooperation are space-based nuclear-power and nuclear-propulsion systems. Investment in both areas is being "considerably cut down" in Russia, says Vladimir Vasilkovsky, deputy chief of the Department of Nuclear Reactors at the Ministry of Atomic Power and Industry in Moscow. "That is why we hope cooperation with the United States will help us utilize our brain power to mutual benefit."

The Topaz sale was supposed to have been completed last year when a team of U.S. officials arrived in St. Petersburg to inspect the equipment a final time. Pentagon officials had already spent $1 million to modify a specially developed Topaz test facility, and the Air Force had issued detailed testing criteria. Months later, the Topaz equipment remains in a warehouse in St. Petersburg, gathering dust, while the State Department ponders what policy it should adopt toward imports of Russian technology. Department officials say sensitive projects should be fully considered before they are approved.

Some believe there is still hope to salvage the sale. "Topaz could serve as a model for joint ventures," says Frank Thome, an American scientist deeply involved in the Topaz purchase, "if the government chose to do that." If the government so chooses, it will have to work hard to resurrect the Topaz sale and turn things around quickly. ■

BY DOUGLAS PASTERNAK IN NEW MEXICO

AT SIXES AND SEVENS

The case of the phony reactor

One day after New Year's, on Jan. 2, 1992, a group of U.S. Customs agents found themselves in an echoing freight-storage facility at Los Angeles International Airport peering at a mysterious steel contraption. Puzzled, the federal agents pulled out a copy of a reference book, Jane's Space Directory. Soon they had an answer: The thing seemed to be a functioning nuclear reactor. "The customs agents were suddenly taken aback," said Edward J. Britt, vice president of International Scientific Products, which represents a consortium of four Soviet nuclear-research institutes. "It looked like a real nuclear rocket."

In fact, the object was no more than a harmless mock-up of a Russian experimental nuclear thermal propulsion exhibit. It was to be showcased last week in Albuquerque, N.M., at a symposium on space-based nuclear-power systems. The technology could benefit a U.S. Defense Department program underway to develop a similar system.

The tale of the phony Russian reactor does not bode well for the kinds of exciting joint ventures Washington and Moscow tout in such glowing terms. The reactor model is hung up in red tape; it never made it to Albuquerque.

Mixed signals. It is not the first time Moscow scientists have been frustrated trying to do business with America. A year ago, the Nuclear Regulatory Commission refused to allow the Soviets to take their own satellite home after displaying it at Albuquerque. It took a full six months to get the satellite liberated.

The case of the reactor model may prove more troublesome. The Customs Service finally kicked the matter over to the State Department. State Department officials say they were not properly notified about the importation of the reactor model. The issue is now under review. "The Russians are incensed," says an equally incensed Britt. He worries that the Russians may now offer their advanced nuclear-power and propulsion systems to Europe or Japan. Complains a bewildered Russian scientist: "We just wanted to pursue a joint venture."

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Air Force may issue statement on nuke rocket

☐ A Utah lawmaker wants information on the impact testing a rocket in Nevada could have on his state.

Associated Press

SALT LAKE CITY — The Air Force expects to release a classified environmental impact statement on proposed studies into a nuclear rocket engine, a spokesman said.

The information has been requested by Rep. Wayne Owens, D-Utah, who expressed concern that Utahns may be exposed to radiation if ground tests are conducted on the rocket in Nevada and an accident occurred.

"We are working to declassify a number of documents related to the program. When we get everything resolved, the environmental impact statement will be released, fairly near term," Maj. Dave Thurston, spokesman for the secretary of the Air Force, said Thursday.

But, Thurston said Friday, "We cannot give you a time frame."

Meanwhile, an aide to Sen. Orrin Hatch, R-Utah, called the Air Force program a "lousy idea" unlikely to attract much congressional support.

"Orrin has always opposed it, even when it was classified," Bob Lockwood, Hatch's staff counsel for trade and defense, said.

Since 1987, the Air Force has spent $130 million on the system — code-named Timberwind and known officially as the Space Nuclear Thermal Propulsion program — to develop a nuclear-powered engine that could be used for military purposes as part of the Strategic Defense Initiative or interplanetary space flights and explorations to the solar system's outer reaches.

A prototype engine is being developed at the Air Force's Phillips Laboratory in Kirtland, N.M., and ground tests are scheduled to begin in 1994.

Phillips Lab spokeswoman Kari Paseur said a ground-test site has not been selected, but Owens and others believe the Nevada Test Site, 65 miles northwest of Las Vegas, will be used.

Mindful of Utahans' exposure to fallout from open-air atomic testing in the 1950s and early 1960s, Owens has demanded the Air Force disclose documents supporting contentions the engine tests can be conducted safely.

The Air Force will, Thurston said, "but there are elements that need to be studied carefully to make sure classified information is not revealed. We're being especially careful about that. We're talking new technology."

Lockwood said, "It's as lousy an idea to test nuclear rockets in the atmosphere as it was a lousy idea for the Army to put a (high-level biological-warfare laboratory) at Dugway Proving Ground. ...There are times when even the strongest friends of the Defense Department will draw the line."

He said Hatch favors research into improving technology for chemical-propulsion engines, like those developed in Utah by Hercules and Thiokol.

AVIATION WEEK & SPACE TECHNOLOGY/February 3, 1992

INDUSTRY OBSERVER

RADIOACTIVE WASTE DISPOSAL

NUCLEAR SPECIALISTS have identified a possible spinoff from the space nuclear thermal propulsion (SNTP) system that the U. S. Air Force is developing at the Gen. Samuel C. Phillips Laboratory at Kirtland AFB, N. M. (AW&ST Jan. 20, p. 20). The extremely high power density developed inside a ground-based version of the SNTP particle bed reactor would make it suitable for "burning" high-level nuclear waste from weapons and commercial reactors. The waste would transmute into easier-to-store, low-level radioactive byproducts. A group of scientists from Brookhaven (N. Y.) National Laboratory conducted the initial study, but details of how such a process would be harnessed remain to be worked out.

Las Vegas Review-Journal, 2/10/92

(Circulation: 139,735 daily; 212,283 Sunday)

Opinion

Public information

Both Idaho and Nevada have expressed interest in hosting ground tests for a nuclear-powered engine designed for space flights or military purposes. The tests for the previously top-secret project are set to begin in 1994, but the Air Force and Department of Energy have yet to select the site.

Critics of the plan include members of the Utah congressional delegation, who worry that residents of their state may face harmful exposure to radiation if the engine is tested in Nevada and an accident occurs. Testing of things nuclear in Nevada understandably worries some Utahns, who were exposed to the fallout of above-ground nuclear blasts in the '50s and '60s.

The DOE and Air Force insist the dangers are minimal, and that was apparently enough to convince Nevada Gov. Bob Miller and his Idaho counterpart of the project's potential economic benefits. But the Utah delegation still frets.

"It's a lousy idea to test nuclear rockets in the atmosphere. . . . " said a spokesman for Utah's Republican Sen. Orrin Hatch. Utah Rep. Wayne Owens has also expressed concern.

The worries have validity. The potential for danger does exist — witness that the more extensive testing of the rocket itself would occur near Antarctica.

But the Air Force could go a long way toward alleviating fears if it would release an environmental impact statement it conducted on the rocket engine studies. The document was previously classified for defense purposes, but that's no longer necessary.

Air Force officials vow that the study "will be released, fairly short term," a spokesman said. He refused, though, to outline a time frame. Such vague promises only exacerbate the political posturing. Owens has threatened to hold up the project until safety studies are public. Nevada Sen. Harry Reid has accused him of demagoguery.

If Nevadans and Utahns are to make sensible, informed decisions involving the safety of this proposal, the Air Force mustn't wait for declassification proceedings to slog through the military bureaucracy. Those potentially affected by the proposal deserve immediate answers.

USAF NUCLEAR PROPULSION PROGRAM FACES ENVIRONMENTAL, TECHNICAL OBSTACLES

Although the Air Force's highly classified nuclear propulsion program is slowly emerging from the world of secret military projects, the Air Force has yet to release an environmental impact statement on engine tests scheduled to be carried out in the Nevada desert. One of the engine's components recently failed during a non-nuclear test, illustrating the technical challenges inherent in the program, sources said. Critics charge that the Air Force has used secrecy as a shield for the program's shortcomings and has made the program public in order to win further congressional funding.

Air Force officials "have been using classification to cover up an unproven design," a source familiar with the program charged. "They don't really have this race car that they claim." This source said a firm was hired by the Air Force last year to analyze the program and "presumably to bless it." When the report criticized the nuclear engine's design, it was immediately classified "top secret," this source said.

An Air Force source said the reason for the secrecy surrounding the program is the need to keep sensitive information out of the hands of competitors. The Commonwealth of Independent States, according to an Administration source, has a very advanced nuclear propulsion program of its own.

The Air Force last month publicly unveiled the Space Nuclear Thermal Propulsion (SNTP) program -- formerly called Timberwind -- which would ground test a nuclear propulsion engine in preparation for a decision on whether to pursue a nuclear propelled rocket. Rep. Wayne Owens (D-UT) sent a letter Jan. 24 to Air Force Secretary Donald Rice criticizing the Air Force for not releasing its environmental impact statement on the ground testing, despite Freedom of Information Act requests. An Air Force spokesman said the service will respond to Owens' letter, and is "working to declassify those documents." The environmental information has to be screened for classified data, according to the spokesman.

The Federation of American Scientists has reported that a late-January non-nuclear test of one of the engine components was unsuccessful. "A recent SNTP Nuclear Element Test (NET-0) failed, in a significant setback to the program, when graphite particles came loose and blocked propellant flow," according to the February issue of the organization's newsletter. The Air Force, according to a source at the Federation of American Scientists, argues that the experiment's heat source caused the failure rather than an "inherent flaw" in the engine concept. Even so, this source said, the test "suggests that the system is highly vulnerable." The Air Force could not be reached for comment on the report.

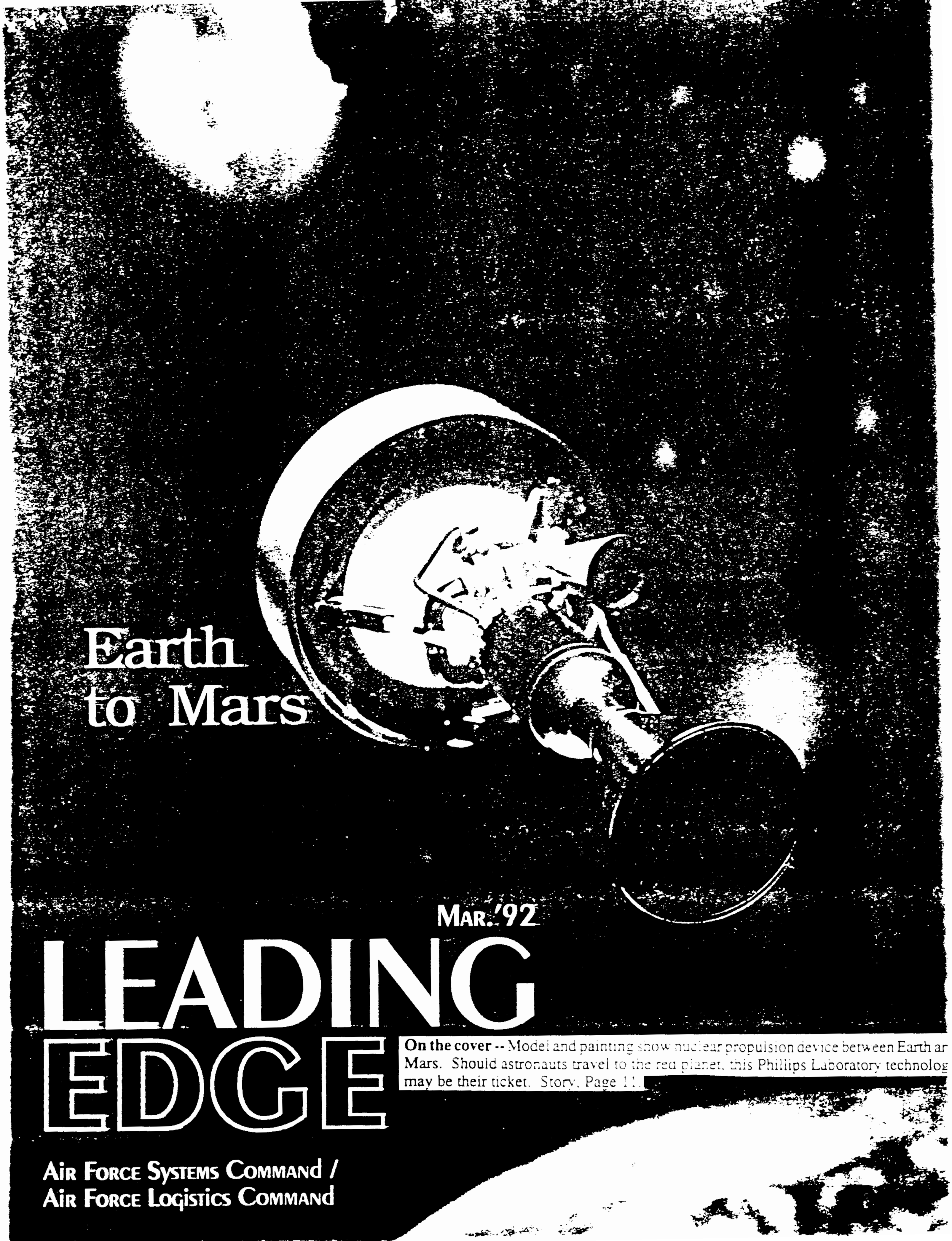
In the realm of environmental and health concerns, the program is plagued by a history of accidents and environmental damage from other nuclear programs carried out in the Nevada desert. During the 1960s, the Air Force, together with several other U.S. agencies, aggressively tested a nuclear propulsion design in the Nevada desert under a program called *Nuclear Engine for Rocket Vehicle Applications* (NERVA). The experiments on several occasions resulted in the release of radioactive materials. During one NERVA test in 1965, the engine ran out of hydrogen coolant, causing the fuel elements to melt and "spew out."

Although none of the incidents should be considered a nuclear disaster, according to a veteran of the NERVA program, "we were not as environmentally conscious back then as we are today." The design of the SNTP's "particle bed," where the nuclear reaction would occur, is "more susceptible to radioactive release than the old NERVA" design, this source said. The difference is that today there is a system for capturing radioactive gas that might be released and cleansing it, according to this source.

Sources said the Air Force is beginning to take the wraps off the program because congressional appropriators made this a condition for releasing $100-million to build a test stand for SNTP. The Air Force estimates the total cost of nuclear propulsion ground testing to be $800-million. Congress, according to one source, is also pushing the Air Force to work together with NASA on the program.

Environmentalists and propulsion scientists also have raised concerns about boosting a nuclear reactor through the atmosphere, although the Air Force emphasizes that the rocket would be propelled by conventional means until it is beyond the atmosphere, assuming the program progresses beyond ground testing. One scientist said that if the reactor is used to power the second stage of the rocket, as it would in most military missions, the reactor would have to return to earth, raising environmental concerns.

Observers also are concerned about the quality of the "peer review" in the SNTP program. Two of the members of the Defense Science Board are paid by the Air Force to do technical work on the program as well as to review it, creating a clear "conflict of interest," one scientist charged. -- *Ben Iannotta*



On the cover -- Model and painting show nuclear propulsion device between Earth ar Mars. Should astronauts travel to the red planet, this Phillips Laboratory technolog may be their ticket. Story, Page 11.

Ticket to Mars

If mankind's next giant step is to Mars, then Air Force nuclear propulsion technology may well be the ticket for getting there.

Closer to Earth, nuclear propulsion could decrease routine space launch costs while increasing payload capability. It would be used only outside the Earth's atmosphere and could propel vehicles farther and faster.

Early this year, the Air Force revealed the technology development program at the 9th Symposium on Space Nuclear Power Systems. Phillips Laboratory at Kirtland AFB, N.M., manages the program, with participation by the Department of Energy, NASA and other government labs and agencies.

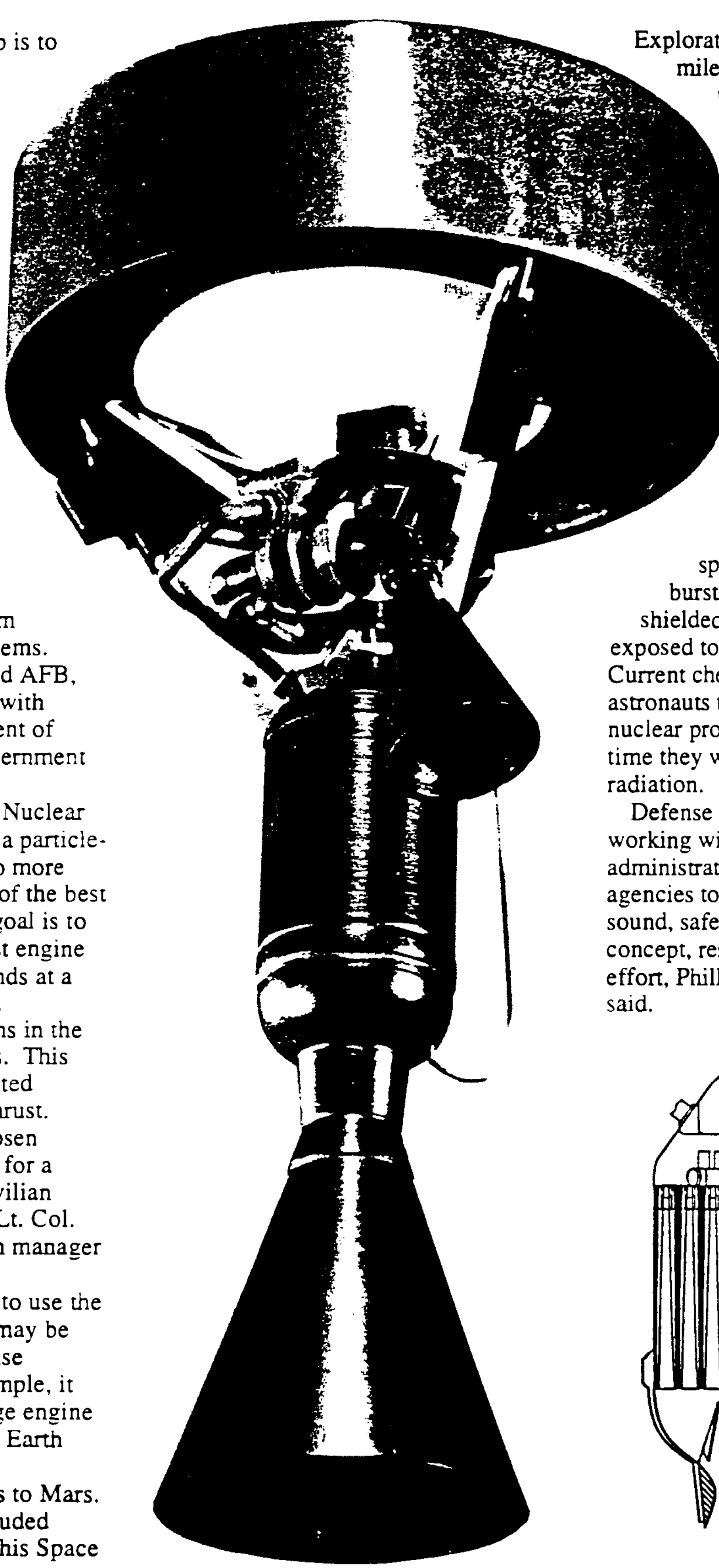
The program, called Space Nuclear Thermal Propulsion, will use a particle-bed reactor that is expected to more than double the performance of the best current rocket engines. The goal is to develop a 75,000-pound thrust engine that could fire for 1,000 seconds at a 30-to-1 thrust-to-weight ratio.

Put simply, nuclear reactions in the engine would produce hot gas. This expanding gas would be directed through a nozzle to provide thrust.

Nuclear propulsion was chosen because it offers the potential for a wide range of military and civilian space missions, according to Lt. Col. Roger X. Lenard, the program manager at Phillips Laboratory.

The Air Force has no plans to use the engine in the atmosphere. It may be used once a vehicle is otherwise launched into space. For example, it could be used as an upper stage engine to propel satellites into higher Earth orbits.

And it might take astronauts to Mars. Last year, President Bush included manned missions as a goal of his Space Exploration Initiative. At 48 million miles, Mars is 200 times farther than the distance manned spacecraft traveled to reach the moon.



Nuclear propulsion's performance gains will be needed for people to make the longer Mars trip, according to a report by the Space Exploration Initiative's Synthesis Group.

One concern is the background radiation present everywhere in space, as well as radiation bursts from solar flares. Even in shielded spacecraft, astronauts are exposed to some health hazards. Current chemical rockets could take astronauts to Mars, but the faster nuclear propulsion would minimize the time they would be exposed to space radiation.

Defense Department officials are working with Congress, the administration and various regulatory agencies to ensure an environmentally sound, safe, successful proof-of-concept, research and technology effort, Phillips Laboratory officials said.

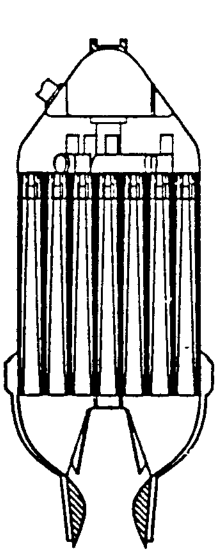
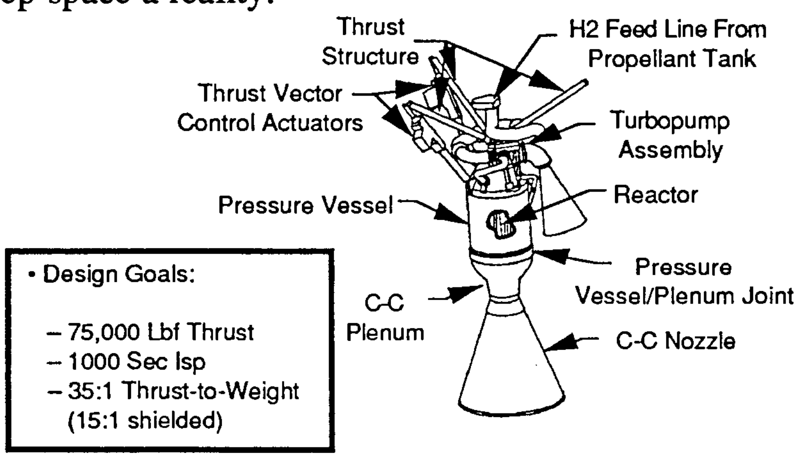


Diagram shows fuel elements in nuclear reactor, enclosed by pressure vessel corresponding to mid-section of model of nuclear propulsion device

Space Nuclear Thermal Propulsion (SNTP) Program
Technology Summary

What is it?

The SNTP nuclear rocket is a safe, reliable and high performance propulsion system which is in the proof of concept phase. The key to a rocket's performance is hot gas. Conventional chemical rockets burn a fuel and oxidizer mixture called propellant. This burning, or combustion, creates the hot, high pressure gas which is expanded through a rocket nozzle to produce a propulsive force on the rocket. Scientists use a measure of efficiency called Isp, or specific impulse, to compare rocket performance. Isp is found by measuring the overall thrust produced by the rocket and dividing by the propellant weight flow rate. The final number is expressed in units of "seconds", an unusual but very effective way to measure the rockets efficiency and performance, akin to an automobile's fuel mileage rating. The space shuttle boasts the highest Isp to be produced by chemical rockets, 450 sec. Scientists think rockets must achieve double this to make travel into deep space a reality.

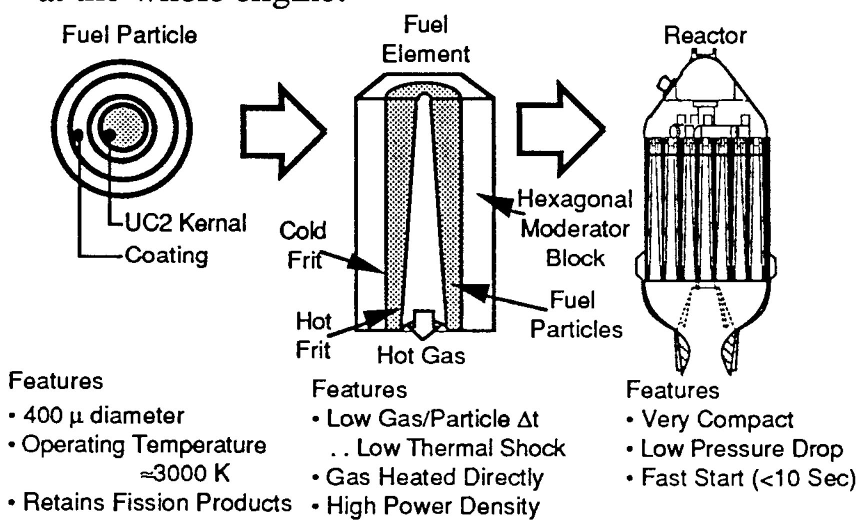


The SNTP nuclear rocket uses hot gas but there is no combustion. Instead liquid hydrogen is pumped through a compact nuclear reactor where it is heated, vaporized and expanded through a nozzle. Because no conventional combustion is taking place the nuclear rocket does not have to carry a supply of oxidizer, typically liquid oxygen, which increases the propellant mass flow rate and causes the Isp to plummet. Using pure hydrogen as a propellant enables the nuclear rocket to achieve Isp of 1000 seconds and beyond.

Thrust to weight ratio, or T/W, and payload capacity are some other parameters that are used to evaluate propulsion systems. T/W is a measure of how powerful a rocket is in comparison to its own weight. A very powerful rocket is useless if it is so heavy that it cannot lift a reasonable payload. Nuclear propulsion schemes in the past have been daunted by very unfavorable T/W and/or payload capacity. The SNTP concept uses a very compact reactor design called the Particle Bed Reactor, or PBR. Because of this size advantage the PBR-based nuclear rocket can develop a T/W of 35:1 (15:1 shielded) and 75000 pounds of thrust which rivals current chemical propulsion systems.

How does it work?

The PBR reactor is a nuclear heater. Instead of burning fuel and oxidizer, the hydrogen propellant is heated from -400°F to nearly 5000°F by flowing through a nuclear reactor. Let's take an inside-out look at the whole engine.



At the heart of the system is the nuclear fuel particle. The radioactive material, uranium carbide, is molded into tiny particles about the size of large grains of sand and then coated with an extremely resilient, high temperature resistant material. This ensures that virtually no fission products are present in the rocket exhaust. The fuel is packaged into cylindrical fuel elements. The fuel particles within each element are sandwiched between two porous filters called frits. The cold hydrogen enters the element through the cold frit and exits the element through the hot frit. The element produces heat by nuclear fission within the particles.

Nuclear fission takes place when a radioactive element like U235 is bombarded by neutrons and splits into two fission products. The reaction also releases 2 neutrons and energy. The neutron flux necessary to maintain this reaction can be externally applied or can be supplied by the reaction itself. When elements are combined in close proximity to each other they form a critical assembly, the geometry and mass of which enables a self-sustaining nuclear reaction. The SNTP reactor consists of 61 elements arranged in a cylindrical geometry. Like a commercial nuclear reactor, control rods are used to start and stop the fission by absorbing neutrons. The hydrogen propellant flowing through the reactor acts as a coolant.

How can it be used?

SNTP is a technology demonstration effort and does not specifically target one application or mission. The technology being developed may open doors in the areas of space travel, power generation and disposal of nuclear waste.

The high Isp of the PBR-based rocket enables increased payload capacity and/or faster transit times. The PBR would enable more payload to orbit than a similarly sized all-chemical rocket. Once a payload is in orbit a PBR-based nuclear rocket may be used to transfer payloads from one orbit to another. The PBR will enable 2 to 4 or more times the payload transfer capability of current systems. In the area of space exploration the PBR will enable manned missions to Mars and the outer planets. The PBR enables a faster and safer mission because the crew will spend less time in transit. Some believe that without the PBR a Mars mission is not possible.

...spin-off applications

The PBR is also the heart of the Closed Brayton Cycle (CBC) Continuous Electric Power System. The

CBC reactor can be used as both a ground based and space based continuous electric power generator. The power output is scalable from 10's kWe to 10's MWe. Unlike the PBR-based nuclear rocket, the CBC reactor is designed to operate at relatively low temperatures. This means that for continuous commercial use there is a considerable temperature safety margin.

Another promising concept that has been investigated is the PBR-based Nuclear Waste Converter. This application provides the capability to convert long half-life high energy nuclear waste into low energy nuclear waste by bombarding the waste with high energy neutrons within the PBR core.

Is it safe?

Safety to man and the environment is the SNTP program's top priority. If the SNTP program cannot meet stringent safety and environmental standards *we will not do it*. Most of the technology used in the PBR reactor is conventional. For example many of the exotic materials used to house the high temperature gases within the rocket are borrowed from current aircraft turbine engine technology.

Perfection in every aspect of the program is the key to success. Extensive analysis is followed by a comprehensive program of testing. Once the component technologies such as fuel particles, hot and cold frits, moderator, design algorithms and control laws have been tested then subsystem integration will commence. This phase will include fuel elements, pressure vessels, nozzles, turbo pumps etc. Finally a working reactor will be ground tested.

The program is both internally regulated and also subject to external review. The program has continually maintained a high level of effort in responding to all safety requirement at both the state and federal levels.

In Conclusion...

SNTP is developing technology to determine the feasibility of nuclear thermal propulsion. Based on the current test results and analysis the program has a high probability of success. Safety to both man and the environment are the top priorities. The PBR will enable higher payload missions at far lower costs than conventional technology and open a broad envelope of previously impossible missions, in addition to new power schemes and nuclear waste disposal systems.

Hearing Notes...

The scoping hearings you will be attending will discuss the proposed test sites at either the Idaho National Engineering Laboratory (INEL) or the Department of Energy (DOE) National Test Site (NTS).

A previously classified Environmental Impact Statement (EIS) was prepared under the direction of the Department of Defence (DoD) and the Defence Science Board (DSB) with congressional concurrance. The SNTP EIS process has been declassified.

Also included in this package is additional program briefing material and copies of some relevant scientific papers. We look forward to your input and comments.

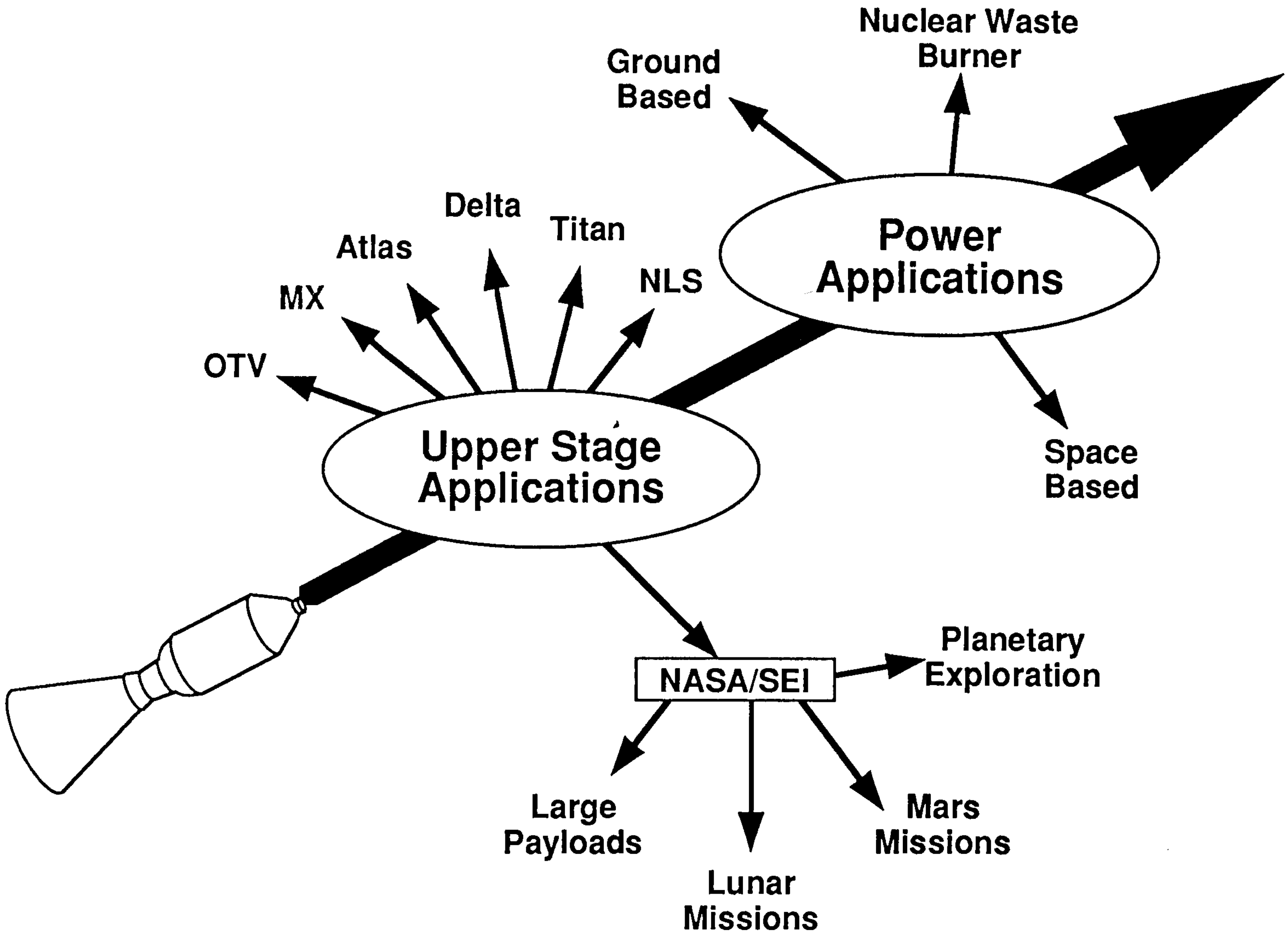
Program Goal

• To Safely Demonstrate the Practicality and High Performance Capabilities of Space Nuclear Thermal Propulsion Systems via Rigorous Ground Testing

Program Description

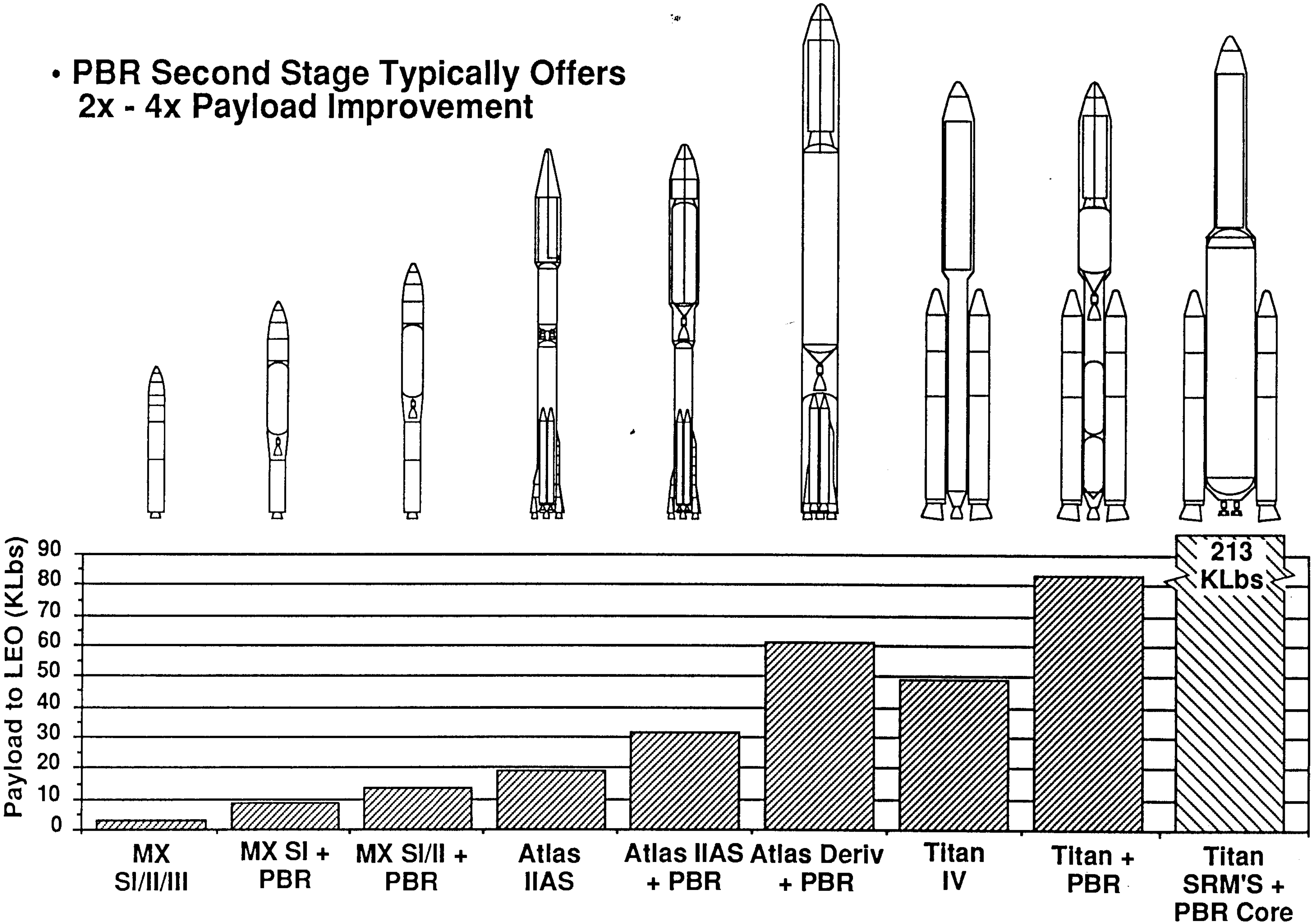
- Technology Program to Develop Advanced Nuclear Rocket Engine
  - Twice the Isp of H_2/O_2
  - Thrust-to-Weight Comparable to H_2/O_2
- Wide Variety of Potential Applications
  - Interceptors, OTV's, Upper Stages, Planetary Missions
  - Complements NLS, NASP, and SSTO Programs
- Program Priorities
  - Safety
  - Reliability
  - Operability
  - Performance
- DoD/Industry/National Laboratory Team
  - NASA & DOE to Join Program in FY '92
- Program is Hardware/Test Oriented
  - Progress is Exceeding Expectations

Evolution of the PBR ~~System~~ Technology



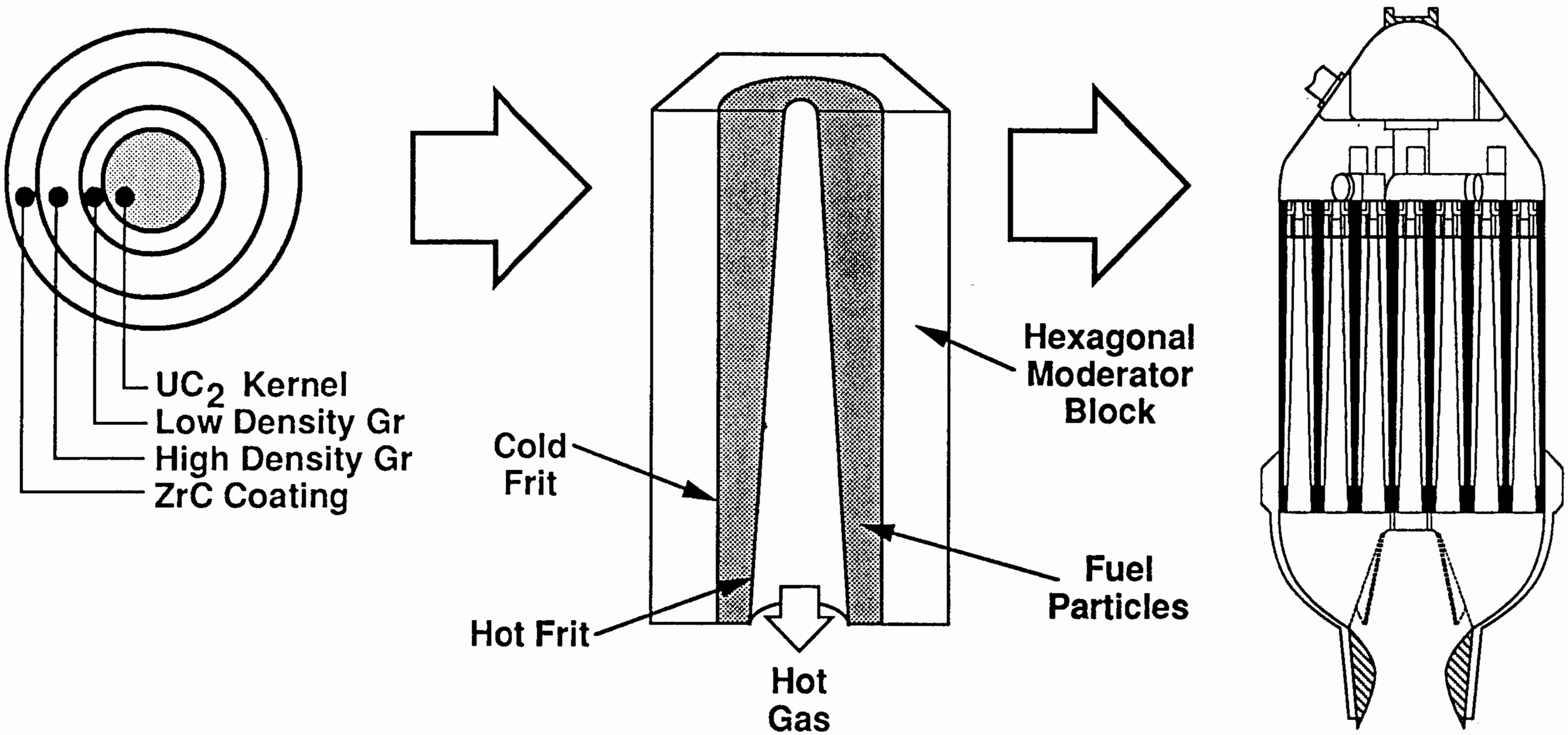
Typical Second Stage Applications

• PBR Second Stage Typically Offers
  2x - 4x Payload Improvement



Enabling Technology - The Particle Bed Reactor

Fuel Particle | **Fuel Element** | **Reactor**

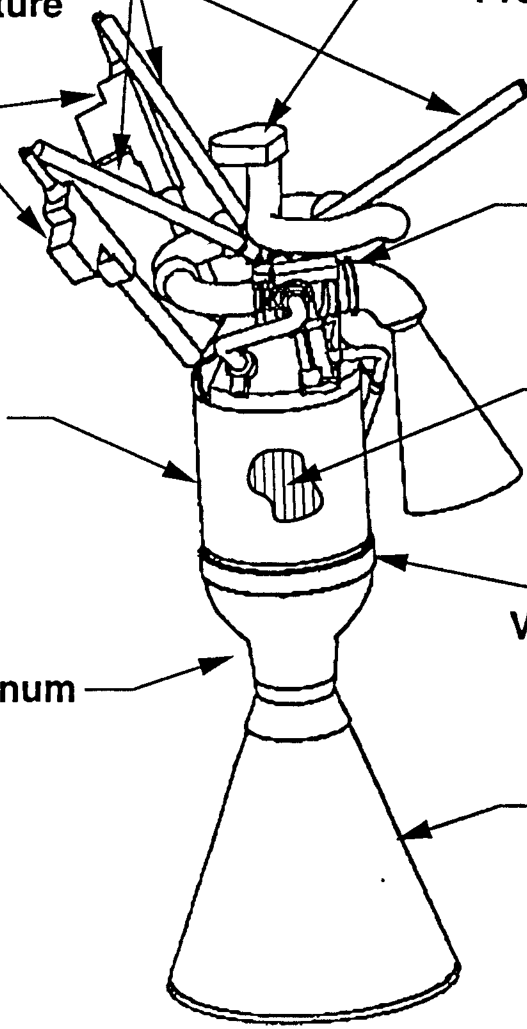


Fuel Particle Features
- 400 μ diameter
- Operating Temperature ≈3000 K
- Retains Fission Products

Fuel Element Features
- Low Gas/Particle Δt
  ∴ Low Thermal Shock
- Gas Heated Directly
- High Power Density

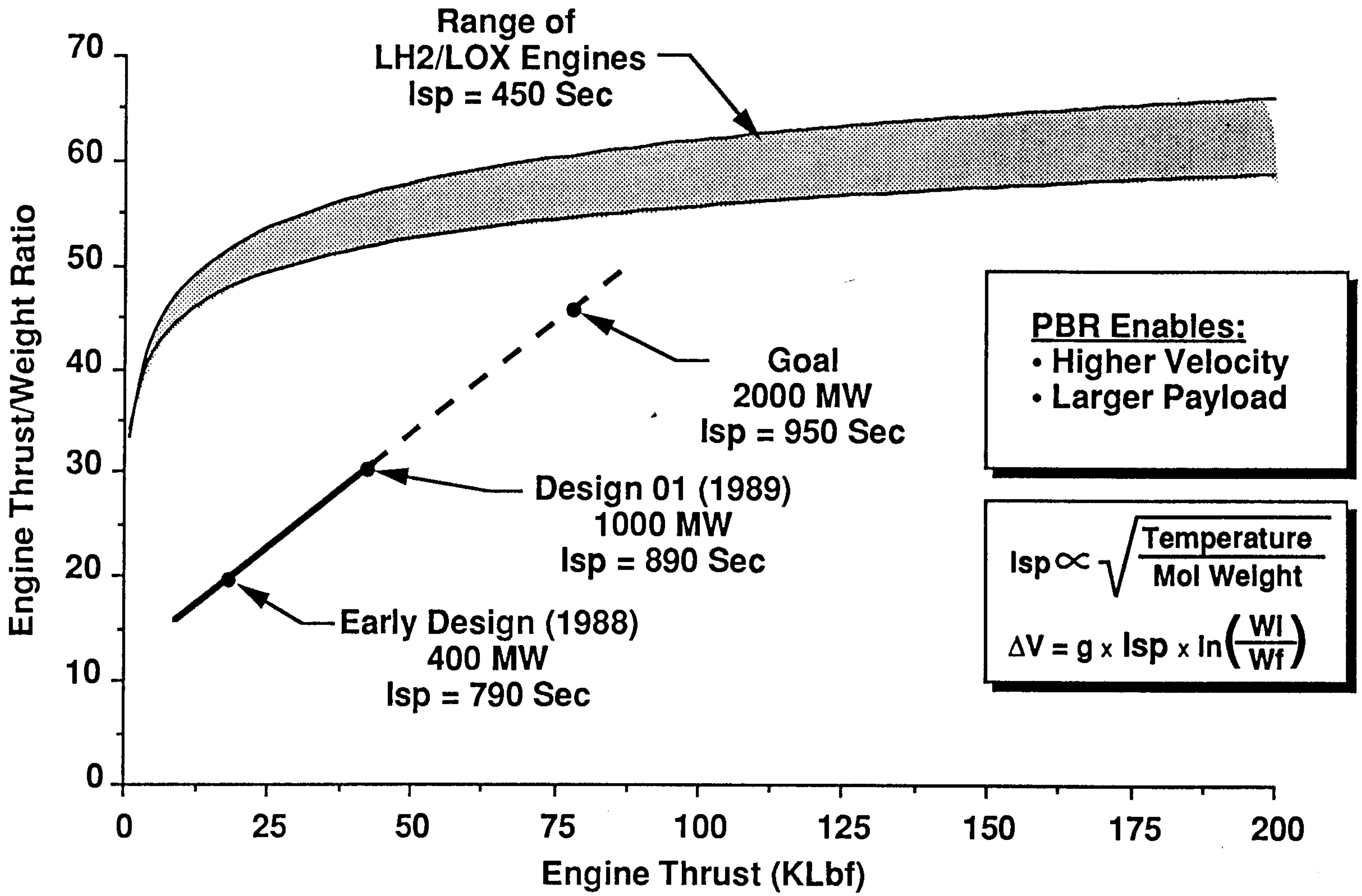
Reactor Features
- Very Compact
- Low Pressure Drop
- Fast Start (<10 Sec)

PBR Engine Description

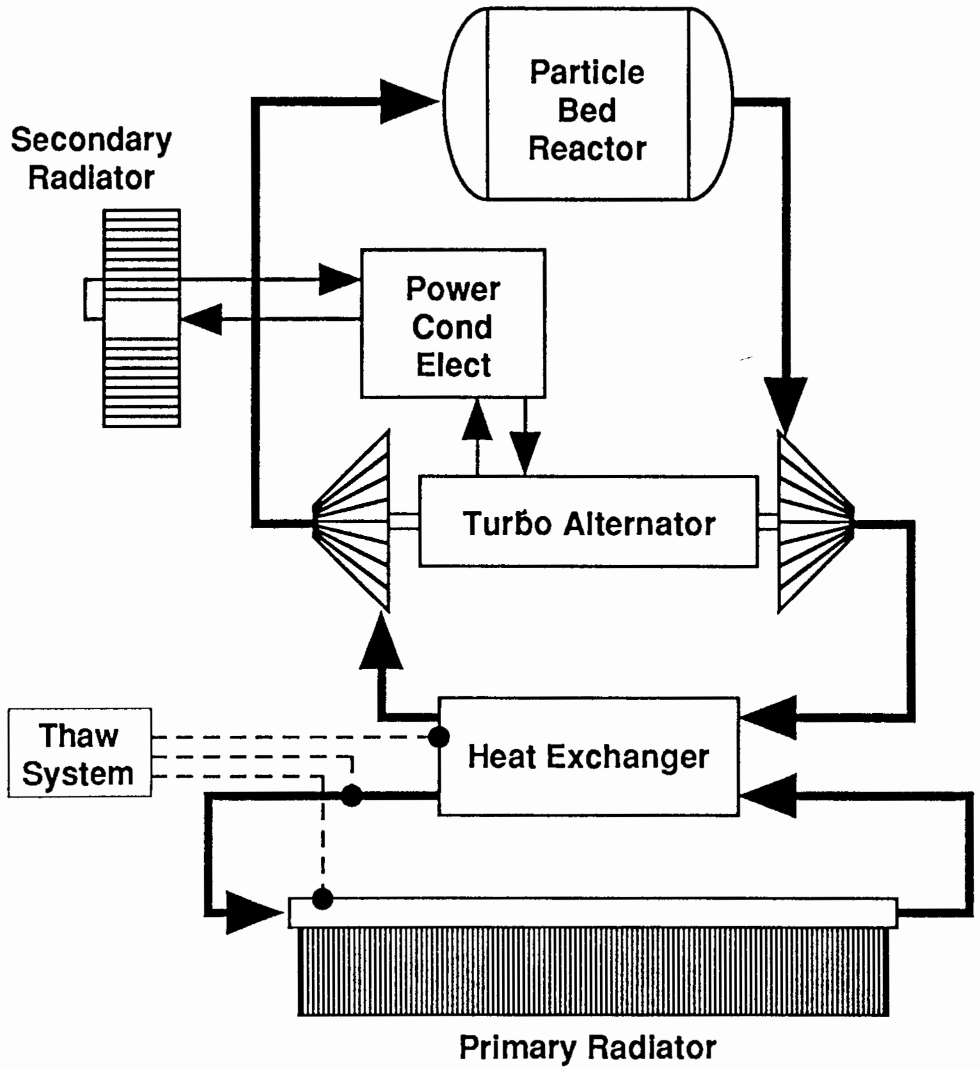


- Design Goals:
  - 75,000 Lbf Thrust
  - 1000 Sec Isp
  - 35:1 Thrust-to-Weight (15:1 shielded)

Technology Comparison



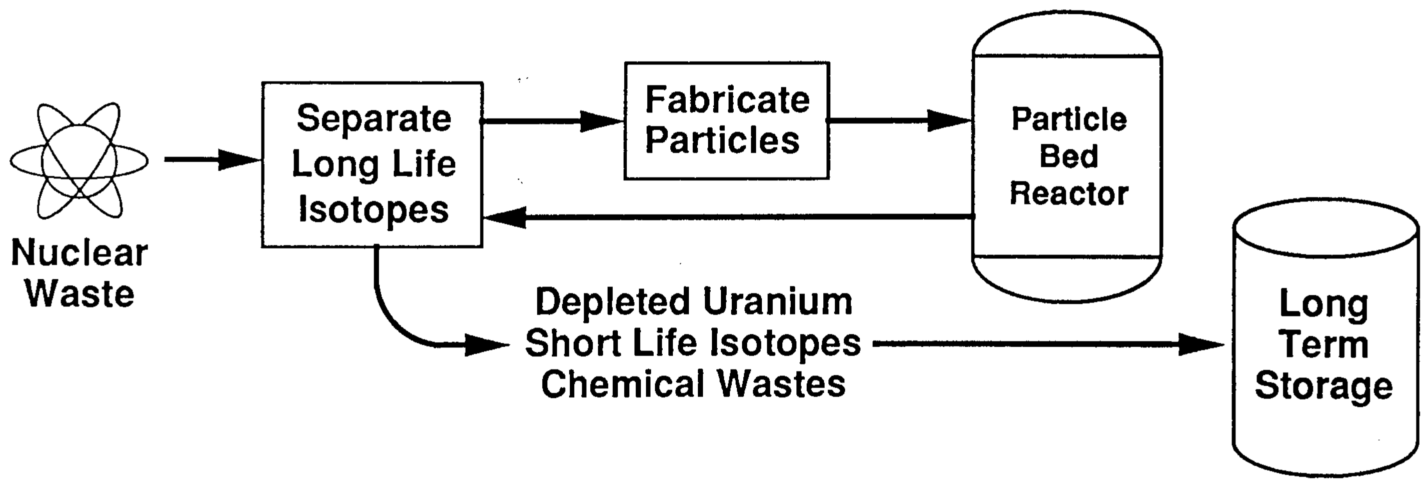
Closed Brayton Cycle Power System Schematic



Nuclear Waste Burner

- Transmute Long-Life Radioactive Isotopes Into Short-Life Isotopes
  - Decay to Negligible Radiation Levels in ~300 Years
  - May Be Safely Stored Using Current Technology

- PBR Offers Advantages Over Other Candidate Systems (Commercial Light Water Reactors)
  - Very Low Radioactive Inventory (1/100 That of LWR)
  - Rapid Destruction of Actinides/Reduction in Total Inventory
  - Compact and Remotely Locatable
  - Many Attractive Safety Features
  - Potentially Lowest Cost Candidate



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Fast Missions to Mars With a Particle Bed Reactor Propulsion System

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AIAA/NASA/OAI Conference on
Advanced SEI Technologies
September 4-6, 1991 / Cleveland, OH

FAST MISSIONS TO MARS WITH A PARTICLE BED REACTOR PROPULSION SYSTEM

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Abstract

The paper discusses the advantages offered by a nuclear thermal rocket based on the Particle Bed Reactor for the manned exploration of Mars. Since the advantages of high specific impulse are recognized, the paper focuses on the benefits of high engine thrust-to-weight (T/W) and high specific impulse (Isp) when applied to high energy manned Mars transits. Specifically, the projected engine T/W (10:1 with crew shielding) enables short opposition class mission durations, with round-trip transit times on the order of 240 days, at initial masses of under 1000 tonnes for a mission centered about the 2016 Earth-Mars opposition. This represents a 60 day improvement over a mission with a low T/W nuclear thermal rocket. Conjunction class missions also benefit substantially, with one-way transit times as short as 60 days feasible. These short transits offer enormous benefits to the crew, including less exposure to cosmic radiation and zero-gravity.

Other advantages include engine-out capability, elimination of the need to develop aerobrake and Earth reentry capsule technologies, increased robustness of the propulsion system, and habitat/vehicle reusability. In addition, fast transits are possible even in difficult opportunities.

The analysis, directed at determining the benefits of high engine thrust-to-weight to high energy missions, was based on ground rules derived from the NASA 90 day study and other sources. The recently released Stafford Synthesis Group report establishes a set of ground rules that do not necessarily agree with those employed in this paper.

Nomenclature

AB	Aerobrake
BNL	Brookhaven National Laboratory
C3	$= V_\infty^2$
ECCV	Earth Crew Capture Vehicle
EOC	Earth Orbital Capture
ETO	Earth-to-Orbit
ETV	Earth Transfer Vehicle
HLLV	Heavy-Lift Launch Vehicle
IMLEO	Initial Mass in Low Earth Orbit
Isp	Specific Impulse
LEO	Low Earth Orbit
MCV	Mars Cargo Vehicle
MLI	Multi-Layer Insulation
MOC	Mars Orbital Capture
MTV	Mars Transfer Vehicle
MULIMP	Multiple Impulse Trajectory Code
NASP	National Aero-Space Plane
NERVA	Nuclear Engine for Rocket Vehicle Applications
NTP	Nuclear Thermal Propulsion
NTR	Nuclear Thermal Rocket
PBR	Particle Bed Reactor
SEI	Space Exploration Initiative
SSF	Space Station Freedom
TMI	Trans-Mars Injection
TEI	Trans-Earth Injection
T/W	Thrust-to-Weight Ratio
V_∞	Excess Hyperbolic Velocity
ΔV	Change in Vehicle Velocity

I. Introduction

President Bush and the National Space Council have identified the manned exploration of Mars as a major milestone in Man's conquest of space. Such an undertaking poses many unique challenges and risks. Significant among these is the enormous distance that has to be traversed - a distance analogous in trip time to that traversed by Columbus in his journey to the new world. Traversing such a distance would require many months if current technology was applied, increasing risk to both the crew and to the mission as a whole. Technology that would noticeably reduce the time required for a round-trip mission would greatly reduce the hazards to the crew associated with prolonged exposure to radiation, weightlessness, and confinement, would improve the reliability of the vehicles, and would improve the prospects for mission success.

The NASA astronauts recognize the need for rapid transits. Nuclear Thermal Propulsion (NTP) is the most promising near-term candidate technology for achieving these rapid transits. Recent work performed by various contractors for NASA has acknowledged NTP as the propulsion system of

* Member AIAA

choice, since it can be developed in the near term and offers large improvements in transit time over current chemical propulsion systems, due to its much higher specific impulse. The recent Stafford Synthesis group has identified NTP as the propulsion system of choice for all manned Mars missions and for Lunar exploration.

NTP technology was demonstrated in the 1960's by the NERVA/ROVER program to a specific impulse (Isp) greater than 800 seconds, and modern materials technology will permit even higher performance. However, the NERVA was very heavy, with a thrust-to-weight ratio (T/W) <4:1. In contrast, the best chemical engines can generate Isp's of about 480 sec, at a T/W of 50 or more.

One of the most promising candidates for NTP is a propulsion system based on the Particle Bed Reactor developed by Brookhaven National Laboratory (BNL). A propulsion system based on the PBR offers the high Isp of NTP, but approaches the T/W of chemical engines. Recent studies at Grumman and BNL have indicated that Isp's of 1000 sec and engine T/W ratio's of 20-40:1 are achievable.

The goal of achieving short transit times must be moderated by other considerations. These include minimizing cost and risk. Cost can be controlled by keeping initial mass in low earth orbit (IMLEO), an accepted yardstick for Earth-to-orbit (ETO) costs, to an acceptable level. Other cost/risk reducing measures include minimizing the number of new development programs and minimizing complexity.

The advantages of high Isp are known and accepted, so the focus of the paper will be to demonstrate the additional advantages offered by a combination of high Isp and high engine T/W, especially when applied to fast, high energy missions.

II. Mission Definition

Low vs High Energy Missions

Transits to Mars can be loosely categorized as low or high energy, the energy in this case being the propulsive impulses required to get the vehicle from one planet to the other. Two impulses are required for a one-way transit. The first is required to escape the gravity well of the Earth and embark on a trajectory to Mars. This impulse is most effective when applied at orbital periapsis i.e. the point closest to the planet. This impulse (ΔV) adds to the vehicle's orbital velocity at that point (V_p), and the sum is identified as V_{final}. If V_{final} is greater than escape velocity (V_{esc}), then the vehicle will hyperbolically depart the planet's gravity well and enter the sun's gravitational sphere of influence.

As the vehicle departs the planet's gravity well, it decelerates with respect to the planet. The vehicle's velocity reaches a minimum value once it is at the effective edge of the planet's gravitational field. This value is known as the excess hyperbolic velocity, or V_∞, and determines what heliocentric trajectory the vehicle will assume. V_∞ is defined by the relationship:

$$V_\infty^2 = V_{final}^2 - V_{esc}^2 = C3$$

C3 is the square of V_∞, and is a measure of the vehicle's energy. If C3 is 0, the vehicle has just barely reached escape velocity, and will travel around the sun in the same orbit as the Earth, but at a position very far from it. A positive C3 will put the vehicle on an elliptical heliocentric orbit.

A Hohmann transfer represents the most energy efficient orbit transfer method. The orbit osculates the planetary orbits at both the initial point and the destination. This feature minimizes out-of-plane maneuvering at the destination. A Hohmann transfer is initiated by applying the desired impulse so the ΔV is in the same direction as the planet's orbit around the Sun for outbound legs, and antiparallel for inbound legs (outbound indicates away from the sun). The minimum Earth departure ΔV is 3.2-3.8 km/sec, and varies due to the eccentricity of Mars' orbit (on less favorable years, Mars is farther from the Sun, so the energy and consequently the velocity to reach a higher potential energy point is greater). Hohmann transfers to Mars typically have transit times of ~250 days.

A second impulse is required to enter a circular or elliptical orbit at Mars. A Hohmann transfer is energetically desirable because the transfer and planetary orbits are realigned and the orbital velocities match. Without this second impulse, the vehicle would continue in a ~550 day orbit back toward the Sun with a periapsis near the Earth's orbital trajectory and an apoapsis near Mars' orbit. The orbit insertion ΔV is determined in the reverse fashion of the departure ΔV, since the objective is to remove energy from the vehicle's transfer orbit in order to enter Martian orbit. The orbit insertion ΔV for a Hohmann transfer is ~1.0 km/sec.

"High energy" transits use considerably more ΔV at planetary departure. The greater ΔV can be used to put the vehicle on a non-Hohmann transfer, producing a shorter transit time. Figure 1 depicts the difference between low and high energy transfers. The high energy nature of these trajectories is evident in the C3 values. The minimum energy transit described above has a C3 of 6 - 9 km2/sec2. Doubling the minimum ΔV increases C3 to ~100 km2/sec2, and can reduce transit times to as little as 60 days. However, this increase in ΔV at planetary departure results in a substantial increase in the ΔV required for capture at the target planet, compounding the penalty for increasing the departure ΔV.

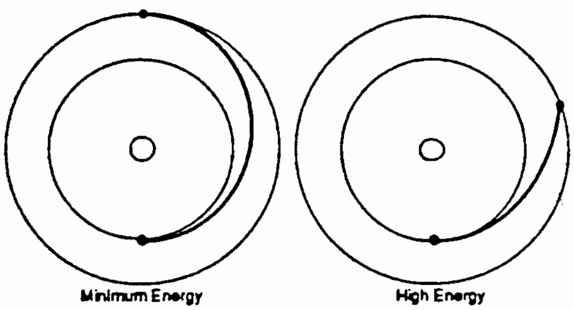

Fig. 1 - Low Energy vs High Energy Transits

An actual trajectory to Mars requires selecting trajectories that intersect the Mars orbit where the planet is at that time. Furthermore, the return trajectory must arrive at the Earth. This makes Mars-Earth positioning critical, and permits missions only when this positioning is nearly perfect. These mission "opportunities" fall into two categories, described below.

Opposition & Conjunction Missions

Potential missions to Mars fall into two categories, based on planetary positioning. Opposition class missions center about a Sun-Earth-Mars opposition, where the Sun and Mars appear on opposite sides of the Earth. Conjunction class missions center about a Sun-Earth-Mars conjunction, where the Sun and Mars appear on the same side of the earth.

Both classes of missions involve Mars arrival and departure at or near the opposition date, as illustrated in Figure 2. Opposition-class missions, since they are centered about the opposition, arrive and depart Mars during the same opposition. This limits the stay time at Mars to a few days or weeks, since longer stays move arrival and departure further from the opposition date, and end up requiring more energy. Conjunction-class missions perform Earth-Mars transit about one opposition, and perform Mars-Earth transit about the subsequent opposition. Since the synodic cycle, or time between oppositions, is about 26 months, conjunction-class missions have long stay times, on the order of 2 years.

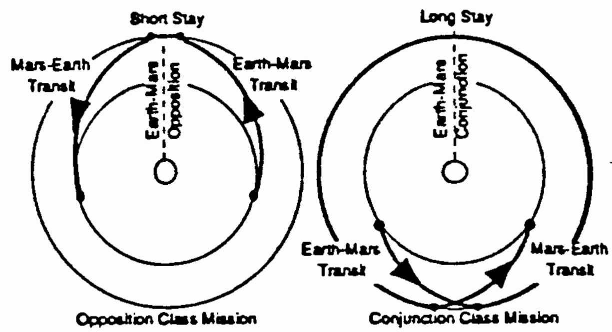

Fig. 2 - Opposition & Conjunction Class Missions

The NASA 90 day study and other studies have identified opposition-class missions as the most likely candidates for initial exploration of Mars, and conjunction class missions as likely candidates for permanent colonization/base support. This philosophy is adhered to in this report, and the benefits offered by high T/W to all mission opportunities are demonstrated.

"Easy" vs "Difficult" Opportunities

The Martian orbit is fairly elliptical with an eccentricity of 9.3%, while the Earth's orbit is nearly perfectly circular. This results in substantial energy differences required for transfer orbits, since the Martian aphelion is 1.2 times its perihelion. Transfers occurring near Mars aphelion require significantly greater energy.

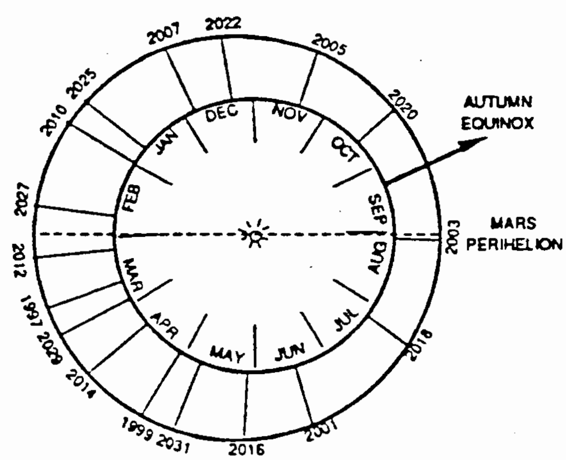

Fig. 3 - Mars-Earth Oppositions 2001 - 2031

It is apparent from Figure 3 that some years are more favorable for missions than others. The NASA 90 Day Study acknowledges this, and plans its architecture for the easier 2016 - 2022 opportunities. This does not address the issue of the difficult opportunities, and indicates the limitations of chemical propulsion.

Study Ground rules

The ground rules for our analysis are based on the 90 Day Study, modified by subsequent published work and the results of previous in-house work. As noted, a "split/sprint" mission was utilized. The split/sprint mission seeks to minimize both crew transit time and IMLEO by delivering cargoes not needed before Mars orbit to Mars on an unmanned vehicle along a minimum energy trajectory. Since this cargo vehicle is unmanned, the concerns about crew welfare do not apply. Cargoes delivered on this Mars Cargo Vehicle (MCV) include the lander and ascent stage, all surface equipment, satellites for Mars orbit, and the Earth return stage. The crew travels to Mars on a Mars Transfer Vehicle (MTV) along a high energy trajectory, and docks with the MCV in Mars orbit. The habitat is then attached to the Earth return stage, and the mission proceeds.

The 90 Day study identified the year 2016 for the first manned exploration mission. It further identified this mission as opposition class with a 30 day stay. This mission does not require an overly ambitious schedule, has a suitable stay time for a first trip, and occurs during a moderately easy opportunity which is followed by several easier opportunities, making a multi-mission effort simpler. Our analysis kept these ground rules for its "reference mission."

A conjunction-class mission was also considered. The mission opportunity about the years 2018-2020 were selected for the conjunction mission, so that the opposition mission could precede a long stay on Mars.

Initial studies found that fast all-propulsive missions were possible, so aerocapture and Apollo-type crew return were not considered. Elimination of these two design features not only eliminates two very costly and risky development programs (and single-point failure modes), but also lifts maximum-speed restrictions at Mars and Earth capture imposed by physical and technology limits. This enables faster transits. Table 1 summarizes the ground rules used in the analysis.

The PBR propulsion system is projected to yield 1000 seconds of Isp at a thrust-to-weight ratio of 20-40. A thrust value of 75,000 lbf was chosen to be compatible with other NTP work, and is reasonable for a PBR-based system. However, a T/W of 20-40 does not include man-rating requirements, which include a radiation shield to protect the crew. The mass of this shield is dependent on a number of factors, so a neutronic analysis was performed on the reference configuration to determine what *shielded* T/W was realistic. Shielding to attenuate the radiation dose to the crew to 10 rem/mission, coupled with other man-rating improvements, reduced the engine T/W to 12-14. A value of 10 was chosen for added margin.

Orbits:	
Earth Departure: 407 Km Circular	
Mars: 250 x 33840 Km (1 Sol)	
Earth Capture: 407 Km x 34500 Km	
Payloads:	
Habitat	25 t
Truss (Per Vehicle)	2t
Lander & Cargo (Opposition)	75 t
Lander & Cargo (Conjunction)	250 t
Crew Size	6
Reserves/Other:	
ΔV Reserve	2 %
Performance Reserve (Isp)	2 %
Trapped Propellant	1 %
Cooldown Propellant	Calculated
50% impulse credit taken.	
Gravity Losses	Calculated
3 Burn Earth Departures	
RCS:	
Isp = 320 Sec	
20 M/Sec for each transit leg.	
50 M/Sec on-orbit.	
Consumables in transit:	4 Kg/Man/Day

Table 1 - Mission Ground Rules and Parameters

Figure 4 illustrates the crew vehicle configuration developed for this study. Two of these vehicles are required per mission. One delivers the crew to Mars orbit (the MTV). The other is brought to Mars orbit (without the habitat) by the cargo vehicle, and is used to return the crew to Earth (the ETV). The ETV utilizes more heavily insulated propellant tanks than the MTV, since the tanks must sit idle for a longer period of time. The MCV is essentially similar, although the long truss is not required, since the vehicle is unmanned.

Rather than using one or two large tanks, the advantages of staging are realized by using 7 tanks per vehicle. 4 tanks are emptied two at a time for planetary departure, and 3 tanks are used for planetary capture. The tanks are filled with slush hydrogen to alleviate the boiloff problem, and tank insulation is used in sufficient quantity to preclude boiloff throughout the missions, with the exception of the ETV in the conjunction mission, which loses some propellant to boiloff.

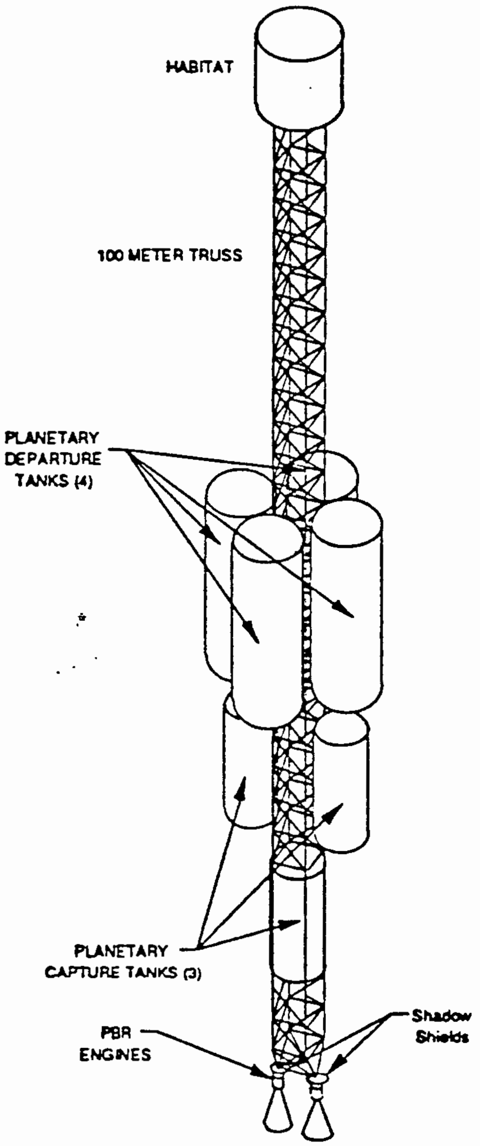

Fig. 4 - MTV/ETV Vehicle Configuration

The tank construction consists of a filament-wound graphite-epoxy (or similar composite material) shell, insulated with foam and multi-layer insulation (MLI), with an aluminum-lithium micrometeoroid shield. The planetary capture tanks are 15 ft in diameter, and the planetary departure tanks are 20 ft in diameter. Tank length is optimized for each vehicle, and allowances are made for plumbing and support structure. Tank placement was made with consideration for both center-of-gravity and engine radiation, and the engine shadow shields were designed to protect all the propellant tanks. The planetary capture tank mounted on the centerline provides a significant amount of radiation attenuation, and is emptied last.

An important assumption used throughout the analysis is an allowance for mission success with one engine out on each vehicle. The PBR's compact size makes this possible with a reasonable IMLEO penalty, which will be discussed later. "Mission success with one engine out" means that loss of an engine on any stage will not impact the completion of all mission objectives, nor will it cause any changes to the mission schedule. This assumption was incorporated by carrying the dead weight of a "spare" engine in all analyses.

III. Results of Analysis

Trajectory & Vehicle Analysis

The ground rules and assumptions detailed above are the result of an on-going analysis effort that grew out of simple rocket-equation calculations to the much greater level of detail employed in this study. The initial goal of the study was to determine IMLEO reductions offered by the PBR when applied to the NASA 90 Day Study reference mission. The realization of the hazards of prolonged crew exposure to deep space shifted the focus away from IMLEO to short transit times. However, "short" is a relative term, and some guideline was needed to avoid developing an absurd design. Cost was the most obvious choice, and a simple measure of cost in this case is IMLEO. An upper limit to IMLEO would serve as a good fence for limiting the efforts to shorten the trip. An upper limit of 1000 t was chosen for the total IMLEO (MTV+MCV+cargoes, etc.) for the opposition class mission, since this value appears in many studies and articles. A 1000 t IMLEO would require 4-7 launches of a typical heavy-lift launch vehicle planned for the Space Exploration Initiative. The much higher cargo requirements of the conjunction-class mission overrides this cap, so the IMLEO cap was set to 1200 t.

With this upper limit established, a minimum transit time could be determined. The MULIMP interplanetary trajectory optimization program utilized by NASA (Ref. 5) was used in conjunction with an in-house vehicle sizing code to develop opposition and conjunction-class missions that minimized transit time while meeting IMLEO criteria. A 270 day opposition-class mission was developed for the 2016 opportunity that met the criteria and ground rules established herein. This mission had crew transit times of 80 days Earth-to-Mars and 160 days Mars-to-Earth, with an IMLEO of 986 t. In addition to the various ground rules, the mission incorporated a 10 day launch window at Earth, and flexibility on the Mars departure date. The MCV departs 870 days prior to the MTV launch window opening, during the previous opposition, permitting check-out of the lander and return stage prior to crew departure.

A conjunction-class mission was developed for the 2018-2020 opportunity. The mission developed has crew transit times of 60 days Earth-Mars and 80 days Mars-Earth, with a 710 day stay time at Mars. IMLEO for this mission is 1178 t. Table 2 summarizes the opposition and conjunction-class mission analysis results.

	2016 Opposition	2018-2020 Conjunction
ΔV's (km/sec):		
Cargo TMI	3.6	3.5
Cargo MOC*	2.7	3.0
Crew TMI	7.7	8.0
Crew MOC	7.4	7.5
Crew TEI	7.3	5.7
Crew EOC	6.9	3.9
	35.6	31.6
Durations (days):		
Cargo E-M	294	275
Crew E-M	80	60
Crew Stay	30	710
Crew M-E	160	80
Total Crew Transit Time	240	140
Masses (tonnes):		
MTV	281	300
MCV**	453	741
ETV	252	137
IMLEO	986	1178

* Includes 1.5 km/sec for rendezvous.
** Value excludes mass of ETV, which is part of its payload.

Table 2 - Results of Mission Analysis

The opposition-class mission schedules crew departure for 21 April 2016, with a 10 day launch window. The conjunction-class mission schedules crew departure for 30 June 2018, also with a 10 day launch window. The cargo vehicles arrive in Mars orbit well before crew departure.

These two missions are subsequently referred to as the "reference" missions.

Engine Operating Requirements

Developing preliminary mission profiles for Mars or other missions only requires identifying engine thrust, weight, and specific impulse. However, several other parameters must be considered when planning actual architectures and development programs. These parameters, including engine operating time, number of restarts, throttling requirements, and the like, can become design drivers if the desired values for best performance (or minimum IMLEO) exceed what is reasonably achievable.

Table 3 identifies the operating parameters for the PBR propulsion system in the reference mission.

Unit Thrust	75,000	Lbf
Unit T/W (Shielded)	10	
Specific Impulse	1000	Sec
Operating Temperature	3200	K
Nozzle Expansion Ratio	150:1	
Max Required Life*	6800	Sec
Max Number of Starts	6	
Total Number of Engines/Mission:		
Opposition	8	
Conjunction	8	
Max Vehicle Acceleration**	1.7	G

* One Engine Out ** No Engine Out

Table 3 - PBR Engine Operating Requirements

The values in Table 3 represent first-order design parameters, and optimizations and trade studies may dictate that other values are more appropriate. For example, sensitivity studies indicate that a lower unit engine thrust helps reduce IMLEO, but increases operating time and number of engines per mission. It may be found that the indicated thrust-to-weight can be achieved with a nozzle larger than 150:1, permitting an increase in Isp or reduction of the estimated 3200 K operating temperature. The reference missions were sized at full throttle, but maximum acceleration can be reduced if lower loads will reduce weight. This, of course, increases engine operating time.

Only a full development program can confirm or deny the validity of the engine operating parameters, but the values identified are not unreasonable, especially given the time available to develop a PBR engine and the substantial rewards it offers.

IV. Sensitivities to Design Parameters

Sensitivity analyses provide invaluable insight into the relative risks and rewards of technologies that lead to the design parameters selected for a mission. The impact of variations in values for Isp, engine T/W, engine size, engine life, habitat mass, consumables, tank design, and other design parameters on IMLEO or mission duration is assessed for the opposition reference mission. Since this mission has a higher impulse requirement in a more difficult opportunity, it is more taxing, and its results can be applied to the conjunction mission.

Since the NERVA program represents the most mature design currently available for SEI, it is used as a point of comparison. NERVA parameters of 75,000 lbf thrust, 925 sec Isp, and 2.3:1 shielded T/W are used (Ref. 6).

Mission Duration vs IMLEO

The IMLEO cap of 1000 t determined the opposition mission duration of 270 days. As SEI progresses and HLLV designs evolve, a better estimate of what IMLEO is feasible will develop. Figure 5 depicts a trade between IMLEO and mission duration for the opposition reference mission.

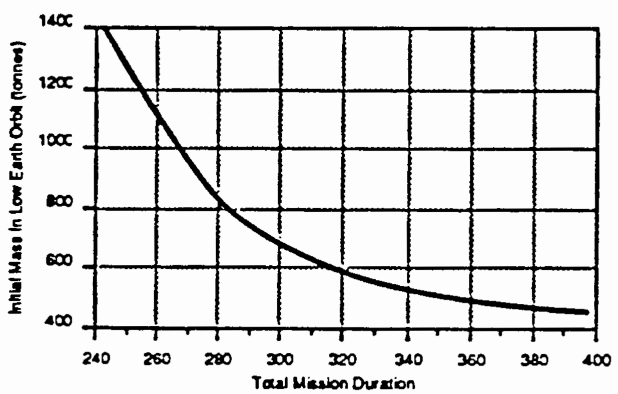

Fig. 5 - IMLEO Sensitivity to Mission Duration

The reference mission is on a relatively steep portion of the curve, indicating that adding a few days to the mission duration can offer a significant reduction in IMLEO. This feature of the reference mission makes achieving a lower IMLEO relatively painless i.e. extending mission duration 10 days reduces IMLEO 100 t.

Engine Isp and T/W Sensitivity

Figure 6 illustrates the sensitivity of the opposition reference mission IMLEO to Isp and engine T/W (shielded). Figure 7 depicts the sensitivity of mission duration to these parameters. The IMLEO curves indicate a strong sensitivity to Isp, as would be expected, but also indicate the effect of low T/W. T/W's below 6 start driving IMLEO upward quickly, and offer little design robustness and higher technical risk, in that small changes in engine T/W result in large changes in IMLEO. Lower Isp coupled with lower T/W only compounds the problem. The gains for higher Isp are significant, but those for T/W's greater than 10 become smaller and smaller, as the engine's mass starts to become less significant.

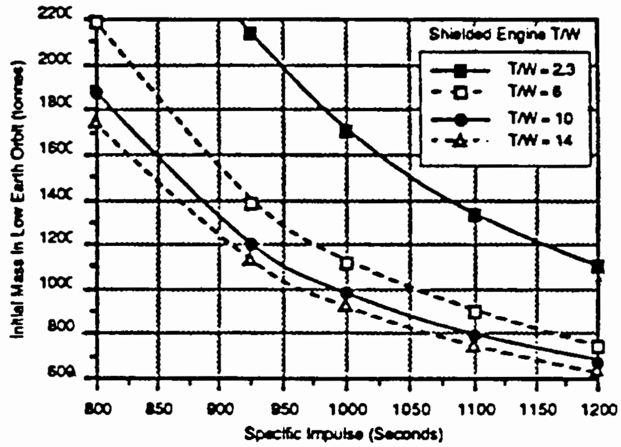

Fig. 6 - IMLEO Sensitivity to Isp & T/W

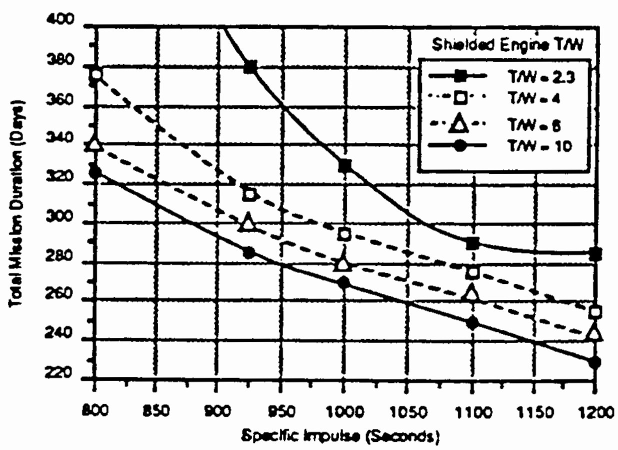

Fig. 7 - Mission Duration Sensitivity to Isp & T/W

An alternative to increasing IMLEO is extending the mission's duration. Figure 7 illustrates information similar to that in Figure 6, notably that low T/W lengthens the mission and increases the duration sensitivity. T/W's above 10 do not noticeably shorten the mission, and were omitted from the figure for clarity. Any gain in Isp will provide significant benefits.

Engine Size & Operating Life Sensitivity

The 75,000 lbf thrust level selected for the reference mission engine was rather arbitrary. The one engine out requirement makes smaller engines advantageous, but decreasing engine size increases the number of engines per mission and the maximum operating time. The vehicle sizing code optimizes the number of engines per vehicle for minimum IMLEO, subject to a maximum engine life and maximum number of engines per vehicle. The latter is held to 7 by geometrical considerations. Figure 8 illustrates the sensitivity of IMLEO to engine size and maximum life.

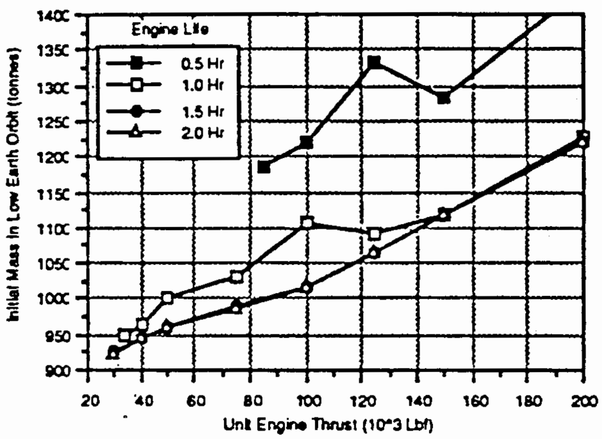

Fig. 8 - IMLEO Sensitivity to Engine Size & Life

Figure 8 indicates that more small engines are desirable, as would be expected, given the engine out condition. However, the data, generated with a fixed engine T/W, does not reflect the mass penalty for multiple small engines. A greater number of small engines would also increase manufacturing cost and vehicle complexity, and may negate the IMLEO reduction.

Habitat Mass Sensitivity

One of the potential advantages of a short mission is a reduction in the size of the crew habitat. The 25 t habitat mass used in the reference mission was derived in part from the 30.5 t value quoted in the NASA 90 day study. The 90 day study habitat has design features not needed in the reference missions, and was downsized accordingly. These features included: attachment provisions for an ECCV and an aerobrake, the requirement to withstand aerobraking structural and thermal loads, and storage requirements for up to 2 years worth of consumables.

Figure 9 depicts the sensitivity of IMLEO to habitat mass for a PBR-based system and for an equivalent NERVA-based architecture. One tonne of habitat mass is equivalent to 22 t of IMLEO for the reference opposition mission, and is equivalent to 37 t for the NERVA-based mission. This disparity further indicates the robustness of the PBR system in comparison to lower T/W NTR's.

Sensitivity to Consumables

One of the key technologies targeted by the Stafford Synthesis Group for SEI is closed cycle crew life support. A closed cycle system can reduce the crew consumables requirement an order of magnitude. The value of 4 kg/man-day used in the reference missions represents a good degree of recycling, but values down to 2 kg/man-day or less may be possible for a fully closed system. IMLEO shows a linear sensitivity to rate of consumables, with a 1 kg/man-day change in consumables corresponding to a 7.5 t change in IMLEO for the reference opposition mission. Small changes in consumables appear negligible for this first-order sizing assessment, but an open system with a longer transit time will show a significant IMLEO penalty for consumables.

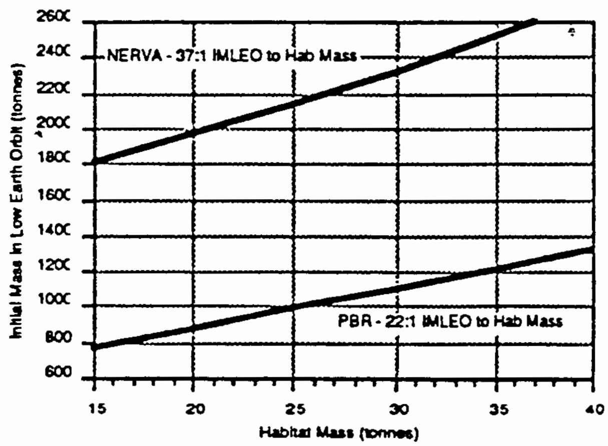

Fig. 9 - IMLEO Sensitivity to Habitat Mass

Tank Design Sensitivity

The reference mission assumes graphite-epoxy tanks with MLI and an aluminum-lithium micrometeoroid shield. The 15 ft diameter tanks have a tank wall thickness of 0.10 in, and the 20 ft diameter tanks have a wall thickness of 0.12 in. A lower technology alternative is using aluminum-lithium for the tank pressure vessel. A 0.157 in thickness has been quoted for this design. Using this tank design would add 150 t of IMLEO, or would add 10-15 days to the mission for the same IMLEO. Current and near-term efforts, including the National Aerospace Plane (NASP), are working towards lightweight tank designs. There is a performance payoff to lightweight tanks, and it is expected that such technology will be available in the Mars exploration time frame. In addition, lightweight tank technology would be beneficial to virtually all space and earth-to-orbit vehicles, making it a high payoff technology.

One Engine Out Feature

The one engine out design feature offers large benefits in terms of mission safety and reliability, but imposes penalties on IMLEO and engine life. Eliminating the requirement can reduce the opposition reference mission IMLEO by 91 t, and reduce the number of engines per mission to 5 from 8. Alternatively, the maximum required engine life can be halved to under 1 hour. However, one engine out enables a large number of abort options, and the penalty for its incorporation must be judged with respect to mission safety and reliability.

V. Applicability to Other Opportunities

The performance offered by the PBR propulsion system expands the architecture options available for SEI. The reference mission is designed around the 2016 mission opportunity. Since some other opportunities are more difficult and some are easier in terms of ΔV requirements, the impact of other opportunities on mission duration was assessed. Figure 10 illustrates opposition mission durations in a range of near term opportunities , and Figure 11 illustrates conjunction mission transit times. Stay times are excluded from the conjunction mission figure for clarity. IMLEO is limited to the same caps used for the reference missions (1000 t opposition-class and 1200 t conjunction-class).

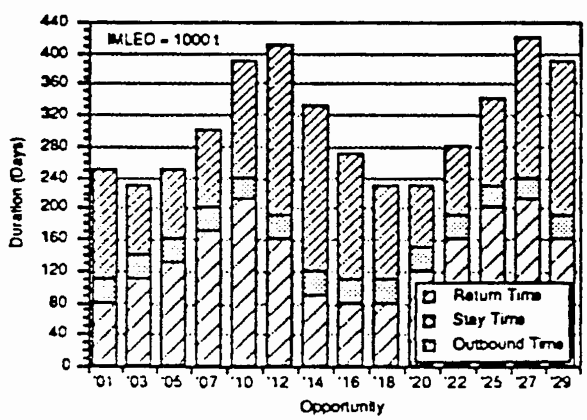

Fig. 10 - Opposition Missions

The impact of Mars' elliptical orbit is evident, but fast missions are still feasible, and an architecture incorporating a mission every opportunity would benefit from the PBR propulsion system. Faster missions in the most difficult opportunities can be accomplished by adding IMLEO

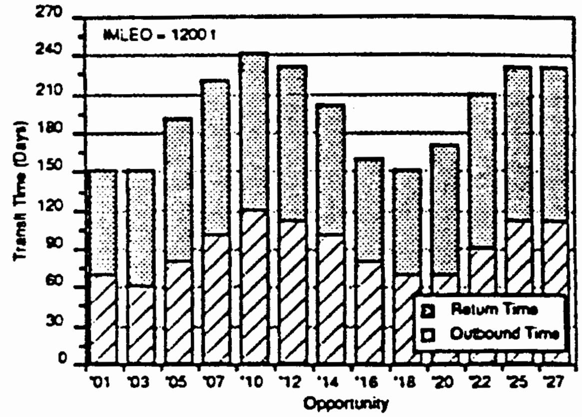

Fig. 11 - Conjunction Missions

VI. Conclusions

The compact design of the PBR propulsion system offers major advantages over other nuclear thermal rocket designs, especially when incorporated into a high energy mission architecture. The PBR's small size not only reduces its weight, but permits a smaller and lighter radiation shadow shield. This leads to a significantly higher engine thrust-to-weight than other NTR's, and makes high energy missions much easier to develop and implement.

The opposition-class mission described in this study benefits enormously from the PBR. The same mission equipped with a lower T/W engine with the same Isp would either have twice the IMLEO or would be 60 days longer. Conjunction missions benefit similarly.

The PBR also offers more design practicality to fast, high energy missions. Its required operating time per mission is half that of low T/W systems, its thermal mass is lower, reducing the quantity of cooldown propellant required, and the impact of a shortfall in achieving a 10:1 thrust-to-weight value is minor.

The ability to generate large ΔV changes with a PBR-equipped Mars vehicle makes performing "difficult" missions and non-optimum architecture requirements much simpler, adding flexibility to the exploration program. The PBR system also allows simplification of the mission architecture through elimination of the need for other new technologies. Spin-off uses of the PBR include a broad range of high energy space exploration missions. The advantages offered by the PBR are numerous and significant, and a PBR propulsion system will be a powerful tool in Man's continued exploration of space.

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A NUCLEAR THERMAL ROCKET ENGINE DESIGN BASED ON THE PARTICLE BED REACTOR SUITABLE FOR A MARS MISSION*

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Abstract

A mission to Mars will be characterized primarily by relatively long run times and the requirement to achieve a high specific impulse and a high thrust/weight ratio. The particle bed reactor (PBR) concept is inherently flexible, in that with minor changes, it can be designed to satisfy many missions. This flexibility results from the fact that most of the reactor operates at modest temperatures and only a very small volume of the core operates at the outlet temperature. In view of the two requirements two types of PBR will be considered in this paper. The first will attempt to maximize the specific impulse, while the second will attempt to maximize the thrust/weight ratio.

It can be concluded from this study that the inherent flexibility implicit in the PBR design makes it a logical choice to achieve an optimized compromise between specific impulse and thrust/weight ratio.

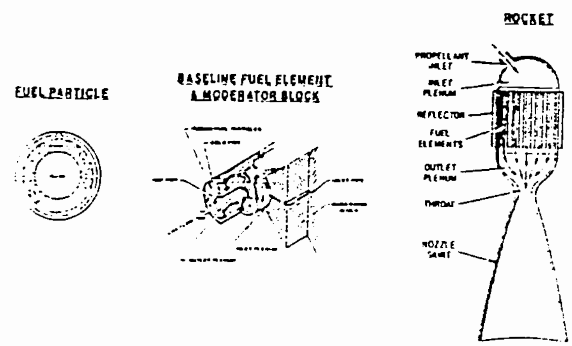
INTRODUCTION

The Space Exploration Initiative (SEI) with its Lunar and Mars missions has emphasized the need for nuclear power. This need covers both the generation of long-term power to support a base but also to supply power to propel spacecraft to either the Moon or Mars. The propulsion based reactors fall into two categories. First, those which operate for long times and are used to generate electric power which is used to power ion thrusters. Second, those which act as a heat source to heat a propellant (generally hydrogen) which is expanded in a nozzle to generate thrust. The latter propulsion devices generate a high thrust and thus the reactors need only operate for a comparatively short time. The latter class of reactors can be based either on solid (such as NERVA/Rover), liquid or gaseous core concepts. In this paper a concept based on a solid core will be described. These concepts are generally considered technologically more mature, and thus would probably be among the first to be used in the initial stages of an SEI starting in the beginning of the next century.

Specifically, the concept to be considered here is based on the Particle Bed Reactor (PBR). Briefly, this concept consists of fuel elements made up of particulate fuel, on the order of 500 microns in diameter contained between coaxial frits (porous tubes) which in turn are placed in a hexagonal pattern and surrounded by moderating material. This concept is illustrated schematically on Figure 1 which shows the fuel particle, a single element and the resulting rocket engine based on the PBR. The design of this PBR will be based on the requirements of a mission to Mars. This mission will be characterized by several relatively long runs (total time approximately 100 min.) and a specific impulse (I_{sp}) of ~1000 s. This implies that the materials be radiation resistant and compatible with each other in the presence of the propellant. These goals can potentially be met by using a beryllium moderator, graphite uranium carbide/zirconium carbide fuel particles and a carbon-carbon/zirconium carbide hot frit.

In the following sections a design philosophy will be outlined, results of the analysis will be detailed and conclusions of the study will be drawn.

SCHEMATIC REPRESENTATION OF A PARTICLE BED REACTOR BASED ROCKET CONCEPT



*Research carried out under the auspices of the U.S. Department of Energy under Contract No. DE-AC02-76CH00016.

Design Philosophy

In designing a nuclear thermal rocket (NTR) one would like to simultaneously maximize the specific impulse and the thrust/weight ratio. A high specific impulse implies efficient utilization of propellant. A high thrust/weight ratio implies a light weight engine and this attribute could enable the use of a cluster of engines to enhance reliability, or could be used to maximize the payload. It was found that no practical design can currently be configured to simultaneously maximize both specific impulse and thrust to weight ratio. A high specific impulse implies maximizing the mixed mean outlet temperature and minimizing the molecular weight of the exhaust gas. A high thrust/weight ratio implies maximizing the power density, which requires a high operating pressure and high propellant flow rate.

In view of the above divergent requirements two reactor designs were developed. The first, which maximizes the thrust/weight ratio will operate at a high average bed power density, high propellant pressure and result in a small low mass reactor and nozzle. The second design will maximize the specific impulse, will operate at ultra high temperatures (close to the material maximum), low pressures (partially dissociated exhaust gas), low power density and will result in a large high mass reactor and nozzle. The parameters for these two designs are shown on Table 1.

Table 1 Range of engine parameters examined

	High Thrust Weight	High Specific Impulse
Power (MW)	1000-10,000	500-1000
Average Bed Power Density (MW/l)	20-80	2.5-5
Chamber Temperature (K)	2500-3200	3200-3500
Chamber Pressure (MPa)	7-14	0.5
Nozzle Expansion Ratio	50-100	50-100
Specific Impulse (s)	800-1100	1100-1200
Thrust (N)	1.8(5)-1.8(6)	7.0(4)-1.4(5)

Results of Analysis

The two PBR reactor concepts outlined on Table 1 have been studied. Physics, fluid dynamics heat transfer and shielding analyses were carried out for selected sizes. Table 2 shows results for two reactor concepts based on the two design philosophies outlined above. Both reactors generate 1000 MW, however, their respective thrust/weight ratios are quite different. In addition to the unshielded reactor a shield mass was estimated for a shield which only covers the reactor i.e. shield diameter pressure vessel ID. Several shield types were considered and the results will be discussed below. The shield assumed in Table 2 is a lithium hydride/tungsten combination with an overall thickness of 40 cm. A reduction of approximately 25% in the thrust/weight ratio results from this addition. The physics analysis of these reactors was carried out using the MCNP Monte Carlo code. This code makes it possible to explicitly represent all geometric details necessary to make an accurate determination of the multiplication factor. In these analyses the heterogeneous nature of the PBR, as illustrated in Figure 1 is preserved and all the leakage paths are explicitly represented. Neutron spectral shifts which occurs between the moderator and fuel bed are accurately accounted for, since the MCNP code use a point cross section library.

Uncertainties associated with group average cross section libraries are avoided in this analysis. From these analyses it is seen that both reactors have a sufficiently large margin in multiplication factor (k_e) to allow for any reduction implicit in an in-depth mechanical design. Furthermore, it is seen that both reactors are high leakage devices, particularly regarding photons. Finally, the coolant worth is higher by an order of magnitude for the high thrust/weight ratio case. This is due to the comparatively hard spectrum in this case.

Table 2 Calculated parameters

	High Thrust/ Weight	High Specific Impulse
Power Level, MW	1000.0	1000.0
Total Engine Mass (w/o shield (kg))	968	3565.0
Shield Mass (kg)*	336	1190
Thrust/Weight (w/shield)	13.9	3.0
Multiplication Factor (k)	1.154	1.199
Neutron Leakage	0.34	0.30
Photon Leakage	0.75	0.62
Total Coolant Worth (ΔK)	0.047	0.0046

*Shield diameter = Pressure vessel I.D.

In addition to carry out detailed analyses of various systems an overall estimate of engine thrust/weight ratio was made for a variety of engine thrusts. This study confined itself to the high thrust/weight designs. In carrying out the engine weight estimate the following components were included:

a) Reactor
b) Pressure vessel,
c) Nozzle (expansion ratio 100:1),
d) Two turbo pump assemblies,
e) Two propellant management systems,
f) Instrumentation and controls, and
g) In the cases were shielding is included the shield diameter = pressure vessel ID.

Results of this study are shown in Figure 2. These results were determined for three reactor concepts i.e. nominal, conservative and aggressive. In addition the results are shown for shielded and unshielded reactors. It is seen that average thrust/weight values for the three reactor concepts are approximately 26, 19, and 15 for the aggressive, nominal and conservative respectively. Addition of shielding reduces the value of thrust/weight by approximately 25%. It is seen that all the systems have thrust/weight ratio above 10. Since, for a mission to Mars the sensitivity of IMLEO (Initial mass in low earth orbit) as a function of T/W (Thrust/weight) is very low above values of T/W of approximately 5 any of these systems would be acceptable. For values of T/W below 5 the value of IMLEO rises sharply and costly less optimal systems result.

A 75000 lb_f thrust engine has been deemed optimal for a Mars mission. In view of this the 2000 MW (80,000 lb_f) reactor was considered in more detail. Figures 3-6 summarizes these results. Figure 3 shows the variation of multiplication factor(k_e) with fuel element pitch/diameter (P/D). It is seen that for two moderator volume fraction (.8 and .98) the value of k_e increases with P/D, peaking at approximately 1.8. Figure 4 shows the variation of k_e with moderator volume fraction for P/D=1.7. This is a monotonically increasing function. Moderator porosity is required to allow for moderator coolant channels and secondarily to reduce the moderator mass. The variation of T/W with P/D for the 80,000 lb_f engine is shown on Figure 5 for unshielded reactors. This variation decreases monotonically with increasing P/D. Finally, for a P/D=1.7 the variation of T/W with moderator volume fraction is shown on Figure 6. It is seen that this variation is not a very strong function. Although it would seem that in order to maximize T/W the value of P/D should be minimized. However, the variation of k_e with P/D (Figure 3) shows that for sufficient margin in k_e requires that $1.7 \leq P/D \leq 2.0$. Finally, the effect of P/D variation on feedback coefficients needs to be investigated before the final choice of P/D is made.

A preliminary analysis of reactor shield performance was carried out. Three shield designs were considered, all with a thickness of 40 cm. and with a diameter equal to that of the pressure vessel. It is seen that the two shields containing hydrogen are the most efficient at stopping neutrons. The high Z (number of electrons/unit volume) shield is most efficient at stopping gamma rays. However, to optimize the shield design details of the components being shielding need to be determined. An additional requirement of the shield is to prevent propellant boil off during operation. It is clear that a lithium hydride/tungsten shield warrants further optimization.

Conclusions

The following conclusions can be drawn from this study.

- The PBR has several unique attributes which make it attractive as a propulsion reactor.
  - High heat transfer area enables reactor to operate at high bed power densities.
  - For a given total power, the high power density results in a small and thus low mass reactor - useful if redundant engines are desired.
  - Direct cooling of particles results in the highest possible gas temperature for any particle design - desirable for maximizing specific impulse.
  - Coolant flow path ensures that the moderator controls (internal or external) and most structural components operate at coolant inlet temperatures - assures a wide selection of moderators, ensures reliable operation of control rods and structural components.
- These attributes will result in a reactor design which should approach the practically achievable limits of specific impulse and thrust/weight ratio for a solid core reactor design.

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Particle Bed Reactor Engine Technology

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PARTICLE BED REACTOR ENGINE TECHNOLOGY

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Abstract

This paper discusses the Particle Bed Reactor (PBR) based propulsion system being developed under the Space Nuclear Thermal Propulsion (SNTP) program. A PBR engine is a light weight, compact propulsion system which offers significant improvement over current technology systems. Current performance goals are a system thrust of 75,000 pounds at an Isp of 1000 sec. A target thrust to weight ratio (T/W) of 30 has been established for an unshielded engine.

The functionality of the PBR, its pertinent technology issues and the systems required to make up a propulsion system are described herein. Accomplishments to date which include hardware development and tests for the PBR engine are also discussed. This paper is intended to provide information on and describe the current state-of-the-art of PBR technology.

I. Introduction

Particle Bed Reactor engine technology offers significant improvement over existing propulsion systems in both performance and mission capability. One propulsion system figure of merit is Specific Impulse (Isp) which is about 480 sec for the best chemical engine with a thrust to weight ratio (T/W) of 50 or more. In contrast, a PBR engine could be capable of an Isp on the order of 1000 sec at a T/W comparable to that of a chemical system. The established performance goals would offer enhanced capabilities for missions such as planetary exploration, manned missions and orbital transfer vehicle applications. Manned missions would benefit since transit time can be significantly reduced, minimizing the adverse affects of zero-gravity and cosmic radiation.

The PBR concept originally conceived by Brookhaven National Laboratory is a nuclear thermal device which makes use of nuclear heating to directly heat a cryogenic propellent and expel it through a nozzle to produce thrust. The engine nozzle can be gimbaled to provide thrust vectoring and thereby vehicle control. Hydrogen is the propellent (coolant) of choice due to its high heat capacity and low molecular weight. Other cryogenic propellents such as ammonia or carbon dioxide would be suitable but would be significantly less efficient.

II. Reactor Description

The core of a PBR for use in a propulsion reactor is comprised of a hexagonal array of fuel elements. Each element is surrounded by a moderator which slows down neutrons produced by fissions. Neutrons which are slowed down are reduced in energy and have a greater likelihood of producing another fission. The entire core can be encased in a reflector which improves the efficiency of the reactor by reflecting neutrons back into the core. Each element within the core assembly is made up of two concentric porous cylinders or (frits) and the fuel bed. Cold H_2 gas enters the outer (cold frit) via an inlet plenum which is formed by the cold frit and moderator.The H_2 gas then flows radially through the fuel bed where it is heated to about 3000 Kelvin. This is illustrated in Figure-1.

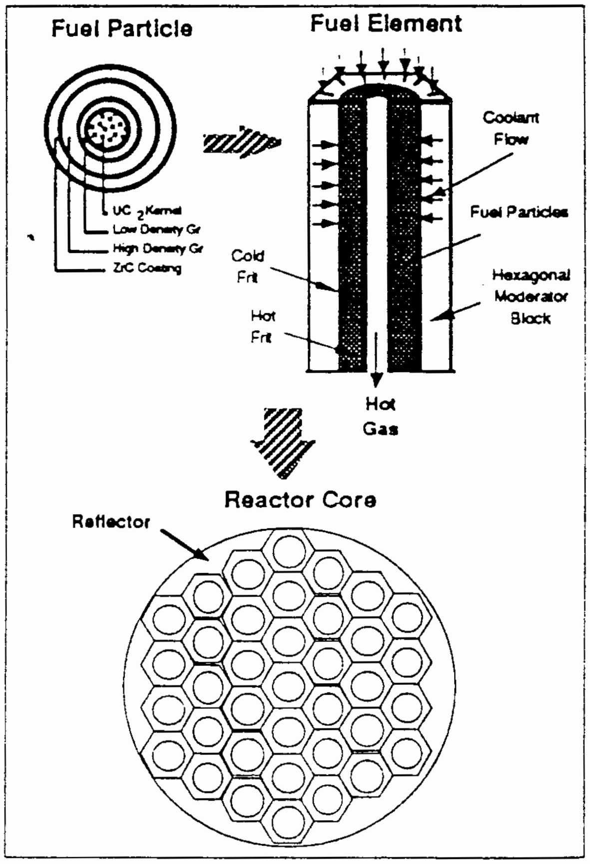


Figure - 1 PBR Build-Up

The heated gas is then channeled through the inner (hot frit) and collected in a chamber to be

* Member AIAA

exhausted through a nozzle to produce thrust. Propellent must flow through the reactor during and after operation. The cold frit is used as a flow control device in order to match the flowrate to the local power profile within the bed. Flow control is achieved by tailoring the pressure drop of the cold frit.

What makes the PBR an attractive heat source is its high surface area to volume ratio produced by the particle bed geometry, this results in a lightweight compact reactor. The fuel itself is a 500 micron sphere containing a fuel kernel of UC_2, layers of pyrolytic graphite for containment of fission products and a zirconium carbide outer layer for erosion protection.

Although power decays exponentiallyafter shutdown, the core still produces energy which must be removed. If a flow to power match is maintained the temperature of the outlet gas can remain constant and some performance can be recovered. Post operational flow (cooldown flow) must continue until the decay power generated by the core is in equilibrium with the heat radiated to the environment.

Reactor Control System

Control of the reaction is accomplished by using neutron absorbent material such as cadmium or gadolinium which act as poisons. Mechanisms for control vary the exposure or view factors of the poisons.

Control mechanisms must operate in a severe radiation environment. Drive motors or actuators of mechanical control elements must be cooled or remotely located to avoid problems associated with nuclear heating.

Reactor Technology Issues

The power generated within the particles of each element varies axially as well as radially. In addition, the total power generated in each element within the core is not constant. Due to this variable power distribution, a propellent flowrate which is matched to local power is required to avoid excessive temperatures in the particle bed. Power to flow matching is of particular importance during startup.

Since the flow passages within the element are small, local high particle temperatures could occur from a blockage in the cold frit, hot frit or bed itself. A blockage can be caused by the break-up of particles producing debris which can plug the hot frit or bed. The cold frit is of lesser concern since any debris from the particles would be carried toward the hot frit since this is an open system. In addition the flow passages of the hot frit are relatively large compared to the bed, therfore it is not likely to plug.

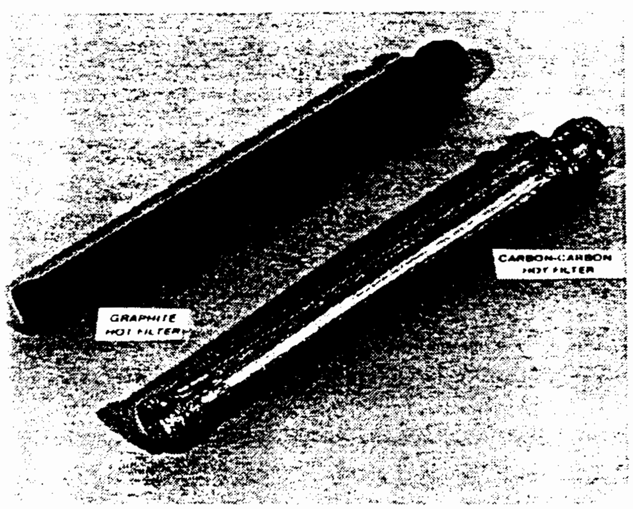
Depending upon the application, a fast start requirement (rapid rise to full power) results in significant thermal stresses. Both the bed and hot frit will undergo a thermal transient from cryogenic temperature (≈25 K) to operating temperature (≈3000 K) in the desired time frame. Expansion of the bed must be considered in the design of the fuel element.

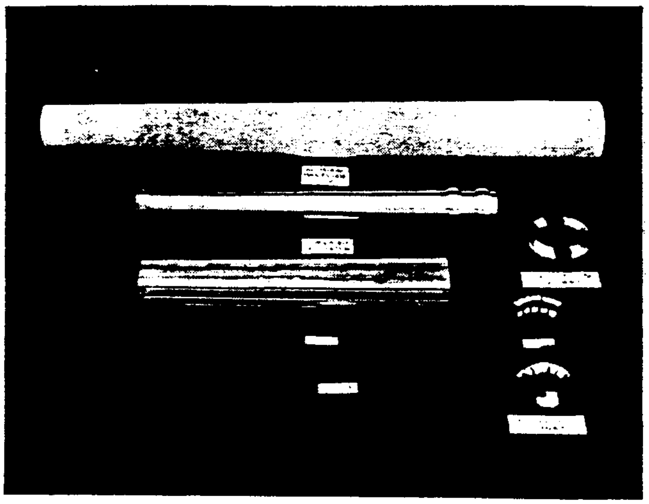
A key technology issue is the protection of materials from high temperature and erosion. High temperature coatings are required to protect the particles and hot frit. Particle coatings are designed to be erosion resistant and neutronically benign as well as resistant to cracking and spalling.

Due to the nature of cryogenic propellents bi-phase flow within the reactor and or the propulsion system is a concern. Liquid H_2, for example, can contribute to the reaction within the core and thus is not desirable. In addition bi-phase flow within the ducting of the propellent feed system can cause flow oscillations and choking.

III. Development Hardware and Test

Development hardware efforts to date include the fabrication of fuel particles, hot and cold frits as well as test apparatus and test specimens. Fuel particle coatings to minimize erosion of the particles in hot hydrogen, and a high-temperature turbine development program to fabricate a turbine capable of 2750K are also in development. The following photographs depict a sample of the constructed test hardware.





The most advanced test to date of a complete fuel element occurred in the Pulsed Irradiation of a Particle Bed Reactor Fuel Element (PIPE) test which was conducted in an existing reactor. Hydrogen gas was heated to temperatures near 2500 K in this test. This test was very useful for the development process. The next major test of a complete fuel element will be run in a test called NET (Nuclear Element Test) which will be run toward the end of FY-92.

IV. Propulsion System Description

Figure-2 schematically illustrates how the reactor core is integrated into a pressure vessel and nozzle assembly to produce an engine. The nozzle as depicted in Figure-2 is not regeneratively cooled and is assumed here to made of Carbon-Carbon.

Buildup to a propulsion system from the basic engine shown in Figure-2 requires the integration of several additional systems. These systems provide for: startup, propellent feed, engine control and engine cooldown.

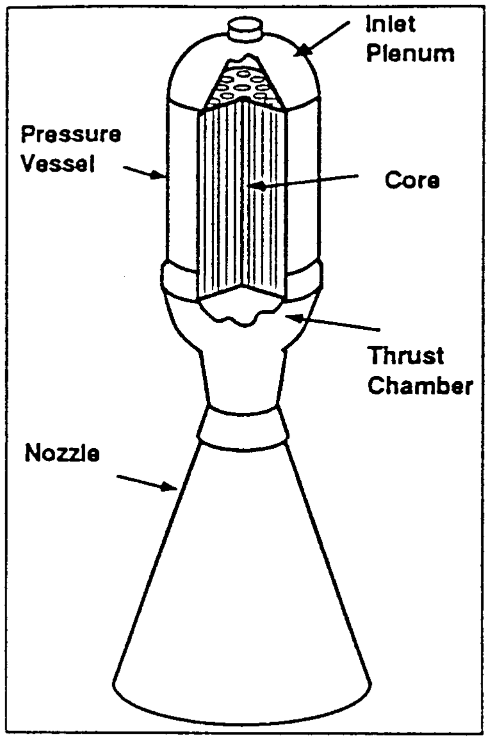


Figure - 2 Engine Schematic

Start System

System startup can be achieved through the use of a pressurized or hot gas which is fed to the turbopump to begin a bootstrap start if fast starts are required. An alternative is to bootstrap using the thermal mass of the system to gasify the H_2 and tank head to produce turbine rotation. However this alternative is slow and bi-phase flow becomes a significant problem. In addition a large tank head requirement will result in a heavy propellent tank.

Propellent Feed System

Propellent is delivered to the reactor from a turbopump which is powered by heated Propellent. Depending on the type of cycle used, the energy to drive the turbine is supplied as follows:

In a *bleed cycle* a small portion of hot gas is tapped from the thrust chamber and depending on the temperature limits of the turbine may be mixed with cold flow to achieve the desired temperature. A turbine rotor and housing made of Carbon-Carbon with a suitable high temperature coating would not require mixing. Exhaust from the turbine can be passed through a nozzle to recover some performance (Figure - 3).

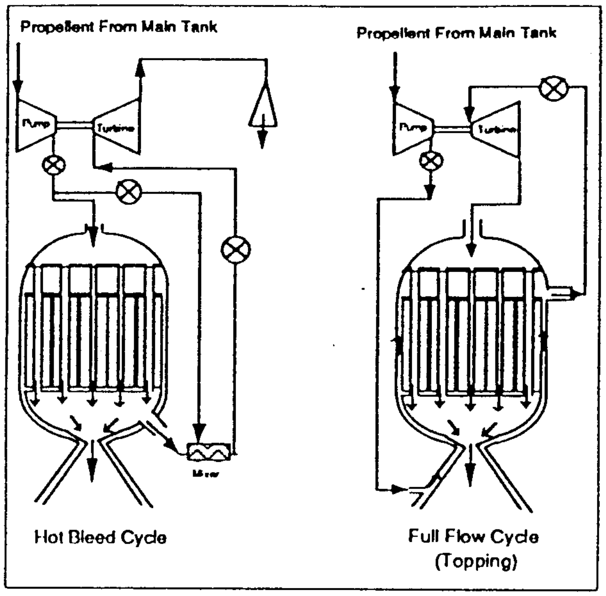


Figure - 3 Cycle Schematics

In the case of a *full flow cycle*, the full propellent flow passes through a regeneratively cooled nozzle as well as the reactor pressure vessel and then enters the turbine where work is extracted. The turbine exhaust then feeds the reactor core. Since the full massflow passes through the turbine the required temperature rise is low compared to the bleed cycle. The core receives full flow which drives up overall system performance but the weight penalty associated with a full flow turbine and ducting must be traded. Weight penalties can be minimized with a *split flow cycle* which delivers only a portion of the full flow to the turbine after being heated by the regen and reactor vessel. The turbine exhaust in this case is introduced into the remaining flow into the reactor. In Man Rated applications the reactor shielding must be cooled and would also be a source of heat for the turbine. The cycles in figure-3 are shown without shielding and in both cases would require some flow for cooling equipment.

Engine Control System

Control of the engine involves matching the power and flow along with monitoring engine parameters. Flowrate is controlled by varying the speed of the turbine. A control valve located on the inlet line to the turbine regulates the flow into the turbine and thereby its speed. In addition a control valve as shown in Figure-3 (bleed cycle) regulates the cold flow to the mixer in order to maintain a desired turbine inlet temperature. Power and flowrate can be measured to achieve a power-flow match. Reactivity control involves the use of neutron poisons such as cadmium. In the event of a safety shutdown or SCRAM a mechanism capable of delivering a sufficient amount of neutron absorber or poison must be available.

To maintain a constant desired outlet temperature, changes in power must result in changes in flowrate. The question of flow response should be addressed to determine the time required for the flow out of the pump to reach the core. Depending on the thermal inertia of the system a sufficient lag in flow response time can result in an unacceptable temperature rise within the core in the event of a power anomaly.

Shutdown System (Decay Heat Removal)

Reactor power decay is a function of power level and engine run time. Decay is exponential but the energy generated over a period of time is considerable. The volume of propellent which must be carried for decay heat removal is mission dependent, a long period of coast would require a significant volume of propellant to be carried. Depending on the specified exit gas temperature the total volume of propellent required can be as high as 10% of the tank capacity. A high exit temperature is desired to maximize efficiency and minimize propellent volume. However, erosion due to high temperature exposure of components over a long period of time is a problem. Thrust produced during cooldown can result in usable impulse.

Delivery of propellent to the core during the decay heat removal period can be accomplished by using a dedicated system or use of the main propellent tank. Figure - 4 is a conceptual design of a PBR engine system which uses the main tank for cooldown flow. Tank head is maintained using a gaseous helium source to provide sufficient pressure for hydrogen blowdown. Maximizing cooldown performance requires matching flowrate to decay power but a minimum flowrate may exist to ensure proper flow distribution through the core.

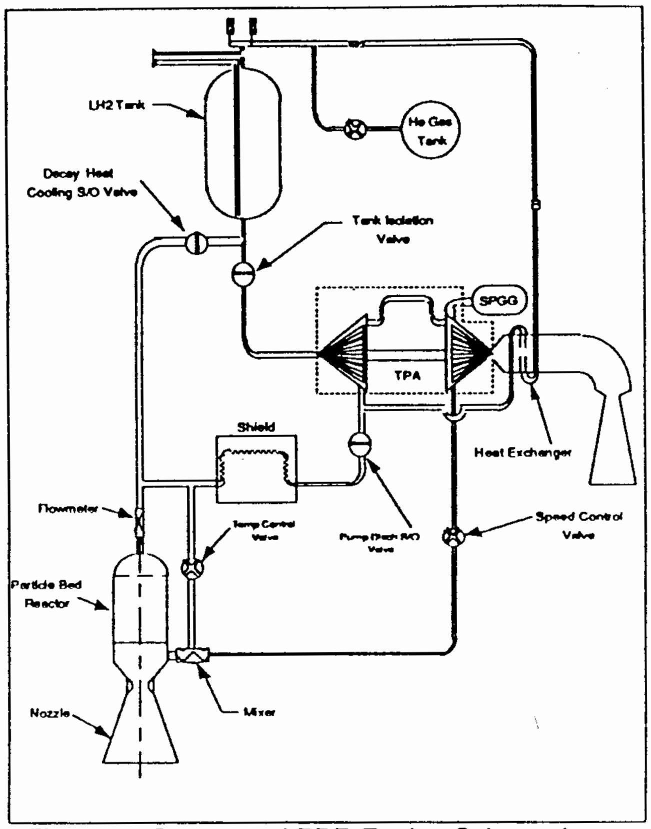


Figure - 4 Conceptual PBR Engine Schematic

The conceptual design in figure - 4 uses a solid propellent gas generator (SPGG) or starter cartridge. The SPGG provides power to the turbine during startup. Reactor power must come on line before the cartridge is exhausted, and at this point bleed gas from the chamber can be phased in to begin bootstrap. Note this design provides reactor shielding. Shield cooling in this case is provided by the full pump flow. Operational tank pressurization is provided using the turbine exhaust to heat a predetermined flow which is tapped from the main propellent feed line

Mass estimates for the conceptual engine shown above for a 75,000 lbf thrust level are shown on Figure - 5. Masses are approximate and represent an engine system without shielding.

Core Assembly......................	1390
Reactor controls....................	170
Pressure Vessel/ Nozzle Assembly..................	540
Propellent Feed Sys. (inc. TPA,Lines,Valves)..........	330
Instrumentation.....................	100
Total Mass Estimate (lbm)	2530

Figure - 5 Estimated Mass Breakdown

V. Performance Benefits

The benefits of high Isp include the capability to put more payload into orbit and allow for high ΔV missions. High ΔV missions enable a vehicle to reduce transit time by achieving a greater velocity or to enable a vehicle to travel further in space. Figure - 6 illustrates the improvement in payload capability of a PBR at 1000 sec of Isp compared to the best chemical engine at an Isp of 480 sec. A dramatic increase in payload at a given ΔV and useful payload capability at higher ΔV are realized with increasing Isp. For interplanetary missions high Isp provides a larger payload capability.

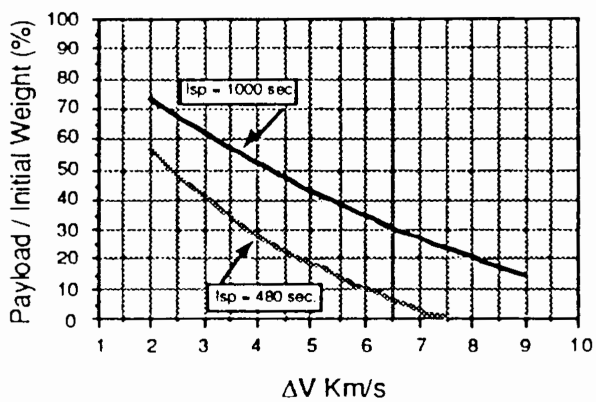


Figure - 6 Benefit of High Isp

Advantages of High Thrust - to Weight

The high thrust-to-weight ratio of the PBR engine offers it a significant advantage over other, low thrust-to-weight nuclear thermal rockets. A PBR engine generating 75,000 lbf thrust would weigh approximately 2500 lbs, whereas a NTR with an engine T/W of 4 would weigh 18750 lbs at the same thrust level. The PBR would permit an additional 16,250 lbs of payload for the same mission, and enables missions with much smaller initial masses in Low Earth Orbit (LEO). For example, the Titan IV launch vehicle can deliver approximately 50,000 lbs to LEO. If a high velocity mission to one of the outer planets was desired, a vehicle equipped with the PBR engine could be delivered to LEO with only one Titan launch, whereas a vehicle equipped with a low engine T/W system would require two or more launches. With the cost of delivering payload to orbit at several thousand dollars per pound, the PBR enables enormous reductions in launch costs, and also eliminates the risks associated with on-orbit assembly and multiple launches.

VI. Conclusions

PBR engine technology will provide a propulsion system offering major advantages over current technology as well as other nuclear thermal designs. Its compact size and weight yield a very high engine T/W providing greater application capabilities.

Manned missions would benefit from reduced transit time and reduced exposure to cosmic radiation. As an upper stage, a PBR engine will significantly reduce launch costs. The system is an important element in the Space Exploration Initiative (SEI) and will serve our nation in becoming leaders in space.

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THE PARTICLE BED REACTOR NUCLEAR WASTE CONVERSION OPTION

Radioactivity is a naturally occurring phenomenon that, even though most of us may not realize it, is a part of our every-day life.

There are many examples of natural and artificial radioactivity that we live with and depend upon on a daily basis. Examples of naturally occurring radiation are the cosmic rays that penetrate our earth's atmosphere from outer space, radioactivity from elements in the earth's crust, and yes, even from small amounts of radioactive elements in each and every one of us. We depend upon radioactivity to help us stay healthy. Radioactivity is nature's phenomenon that allows doctors and dentists to use X-rays to determine if you have a broken bone or a cavity in your teeth. Radioactivity is used to power heart pacemakers, as well as NASA's interplanetary satellites such as Voyager and Galileo.

Thus, we see that radioactivity can enhance our lives when it is handled with knowledge and treated with respect. As with most of nature's benefits, if radioactivity is handled in an indiscriminate manner it will become a detriment to mankind. We have all benefited from electricity generated from environmentally-clean nuclear power stations. Our country's nuclear weapons program preserved the world's peace during the tensions of the cold war, until its recent end. However, both the commercial nuclear power industry and our country's nuclear weapons program have produced, as a byproduct, a large amount of radioactive nuclear waste. The United States has now put a high priority on the safe disposal of the nuclear waste it has stockpiled over the past forty years.

Nuclear waste is classified as either "low-level" or "high-level." Low-level nuclear waste is material that remains radioactive for a limited amount of time; that is, seconds to a few hundred years. Low-level waste can be effectively stored and maintained in burial sites until it is no longer a threat to the environment. High-level nuclear waste, on the other hand, can remain radioactive and a threat to the environment for thousands of years. Many experts believe that we can safely bury the high-level waste in geologically stable storage caverns, but many believe that we do not have the right to burden our future generations with our high-level waste.

As an alternative to storing the high-level nuclear waste, we can convert it to low-level waste in an intense field of low-energy neutrons. One very promising concept for producing this intense field of low-energy neutrons necessary for a nuclear waste conversion system is the Particle Bed Reactor (PBR). The PBR is a nuclear reactor concept that was first introduced by scientists at Brookhaven National Laboratory. It is now being developed for military applications and space exploration by an industrial team lead by Grumman, working in coordination with National Laboratories. Due to the intense neutron field it produces, the PBR Nuclear Waste Converter System converts the high-level waste to low-level waste in a short amount of time and with a small in-reactor inventory of radioactive material.

As with much of the technology that we benefit from today, the PBR's origin was for military application. The Grumman industrial team and National Laboratories are investigating the use of this technology to solve an environmental concern for the benefit of all mankind.

PARTICLE BED REACTOR
NUCLEAR ROCKET CONCEPT

Hans Ludewig
Brookhaven National Laboratory

It is gratifying to see that we are not the only ones talking about the particle bed reactor anymore (Refer to concept just presented by J. Ramsthaler).

The concept (see Figure 1) consists of fuel particles, in this case (U,Zr)C with an outer coat of zirconium carbide. These particles are packed in an annular bed surrounded by two frits (porous tubes) forming a fuel element; the outer one being a cold frit, the inner one being a hot frit. The fuel elements are cooled by hydrogen passing in through the moderator. These elements are assembled in a reactor assembly in a hexagonal pattern. The reactor can be either reflected or not, depending on the design, and either 19 or 37 elements, are used. Propellant enters in the top, passes through the moderator fuel element and out through the nozzle.

Beryllium is used for the moderator in this particular design to withstand the high radiation exposure implied by the long run times.

As far as design philosophy is concerned, I would like to introduce another parameter (Figure 2). Stan Gunn talked about the importance of specific impulse. I would like to talk about the added importance of thrust-to-weight ratio as well. Mission analyses indicate that the thrust-to-weight ration should be above 4.0.

We looked at two reactor designs; one that tried to maximize the thrust-to-weight and one tried to maximize the specific impulse (Figure 3). To maximize the thrust-to-weight requires a high power density, high pressure, and high temperature. These requirements result in a small, high thrust reactor.

The high specific impulse design operates at reduced pressure to introduce some dissociation of the hydrogen and thus increase the specific impulse. A low power density is implied by operating at a low pressure. Because of the lower density of the gas, the engine becomes bigger, heavier, and the thrust is lower.

These are the parameters which were considered (See Figure 3). The engines range from 1,000 megawatts to 5,000 megawatts, in the high thrust-to-weight cases and 500 to 2,000 megawatts in the specific impulse case.

Power densities in the bed were also varied. This is not average power density of the core, but in the bed. The chamber temperatures range over 2,500K to 3,500 K and in the low pressure case we increased the temperature beyond from 3,000 K to 3,750 K.

The pressures range considered was 7 MPa - 14 MPa, depending on power density. At the higher bed power density, higher pressures are required. The low pressure case operated at a much lower pressure; 0.5 MPA.

We did full up analyses of these cores. These reactors were all found to be critical and coolable. We took into account pressure drops and heat transfer in the fluid dynamics analyses.

An important point I want to make here is that thrust to weight ratio drops (Figure 4) when comparing the two reactor design philosophies. These are unshielded and still within the limits of the baseline. However, as soon as one adds on a shield, and again this shield is a fairly cavalier design, one notices that the low pressure design drops way down and is below the baseline requirement.

Technology status (see Figure 5) is divided into analysis, proof of principle experiments and prototype experiments. As far as analysis is concerned, we use the Monte Carlo code (MCNP) that is standard in the industry.

In the case of fluid dynamics, we did have to generate our own codes. One cannot use an off-the-shelf fluid dynamics code and modify it. We made a 1-D survey code and transient code to study start-up. These were reported on at the Albuquerque meetings in 1987.
We use the standard Ergun correlation for pressure drop in the bed. There has been additional work by Achenbach that essentially confirms this work and that was reported in 1982 in Munich.

As far as the materials work is concerned, we have done various tests and the most significant had to do with the compatibility of zirconium carbides and hydrogen. Again, this was reported in 1985 in Albuquerque.

As far as the electrically heated tests are concerned, we built full diameter, half length fuel elements, and demonstrated that we can extract ten megawatts per liter from the bed.

In the case of fuel development, many people have looked at zirconium carbide coated fuel particles. I just refered to an ORNL report here, but work has gone on in this country. The Germans have looked at it, and so have the Soviets and Japanese. As for the UC/ZrC kernel, there is a reference that goes back to 1963 that reported manufacturing these. So I would put the technology readiness of this concept at around four.

The other item we were asked to address was the potential for new technology and safety requirements (see Figure 6). I think that for our concept, coatings are important. The mixed carbide coatings which have a melting point of about 4,000 K would really help.

Finally, enhanced light weight structures are important. Particularly if one can make them out of low Z materials in an effort to reduce the radiation heating, particularly if high power densities are required to maximize the thrust-to-weight. The platelet technology which Aerojet worked on for some time for reentry vehicles would be very useful in our moderators.

Safety issues are generic for most concepts (see Figure 7). Fuel element test reactor safety is uppermost in our work. The ETR (Element Test Reactor) will be used to develop the fuel element for the full scale reactor.

Ground test facilities are required to test several engines, to develop a reliable system. I would like to see a space craft with at least three engines on it, and that's where the high thrust-to-weight ratio requirements comes in. If one can design an engine that has a high thrust-to-weight ratio, one can afford to put several of them on the vehicle and still meet the thrust-to-weight goal.

Launch criticality and Earth reentry; these are standard accident scenarios that we all have to analyze.

Several energy release scenarios exist. Those associated with hydrogen deflagrations/detonations will probably be more important than those from nuclear events. I think we all know what is required there.

We think that we can propose multiple engines with our concept (see Figure 8). If we select a high thrust-to-weight ratio, small shields are implied. These would be smaller since they don't have to be shadow shields and they would also be easier to decouple, assuming that's a requirement.

The fuel particles are small and most particles in the bed are relatively cool. The only ones that are hot are the ones that are closest to the hot frit. Three-quarters of them will be cooler and thus failure and fission product release is expected to be low.

We have tried to make our designs using light weight materials with low Z to reduce the radiation heating effects. The thermal gradients are fairly moderate across most components, implying low thermal stress.

As far as key technology issues are concerned for high temperature particles, the erosion resistance is certainly important (see Figure 9). I would like to point out at this stage that the velocity of the coolant through the bed is of the order of 50 to 100 meters per second. Tests should be done on particles in hydrogen at about 7 MPa, at operating temperatures of about 3,000 K at that velocity.

Again, the same comments hold for the frit. The velocities are again the same since the coolant flows radially through the frit. The cold frit has to be manufactured, as was pointed out earlier, to have variable porosity to shape the flow.

We have a large selection of moderators at our disposal. In the current design, we use beryllium. However, various materials can be used, since the moderator operates at inlet temperature. Thus, we can use it to maximize whatever parameter we want to maximize.

It is important to carry out an integrated element test (see Figure 10). This should be done in a test reactor. We would test for cyclability, and also demonstrate that we don't have any auto catalytic failure modes.

As far as the rest of the engine is concerned, I think a radiatively cooled carbon/carbon nozzle should be developed. It has to be nuclear-radiation resistant, erosion resistant, and joined with the pressure vessel.

The key technology for the turbo pump, would be development of carbon/carbon rotors in order to reduce the heating and operate at reactor outlet temperature.

The schedule and costs have been divided into four major tasks before the year 2006: design analysis, technology development, engine test reactor system, and then the GTE, which would be the ground test system (see Figure 11).

The first task is a design analysis which continues through the CDR (Critical Design Review) for the flight test engine. Technology development would include tests, primarily on fuel, coating, and frit materials. The element test reactor would be used to carry out the integrated test on the fuel element.

We estimate that the entire program would cost one and a half billion dollars. Approximately a billion dollars would be required for the program to advance through to the ground test.

In the first year we will develop an engine design compatible with the mission (see Figures 12 and 13). In carrying out this task, we need to follow these philosophies: maximizing the thrust-to-weight or the specific impulse, depending on the system analysis; developing a plan to carry out the proof of principle test; and then of course starting the experimental work.

In phase one, the engine work will be continued. We will demonstrate high temperature particles to meet the mission, demonstrate that we can build hot and cold frits that would meet the mission cyclability, and operate full-scale elements in the test reactor. We would have to carry out a critical experiment. Nobody mentioned a critical experiment yet, but that's a physics test to make sure the physics methods are validated.

In order to develop the fuel element design, one would first carry out electrically heated tests and then eventually nuclear heated tests. Design of the ETR, which is the element test reactor, would be a major effort. There would have to be some work on the carbon/carbon nozzle. Finally the demonstration of carbon-carbon turbine rotors and mixer will be required.

For phase two, we have to select the site for the element test reactor and satisfy all safety requirements (Figure 14). We would prepare the site and then construct and carry out the test. I am sure that there are many other tasks in there, but that's approximately five years away.

As far as major facilities are concerned, critical experiments could be carried out at the available facilities; Los Alamos, or ANL (see Figure 15).

We would have to have a fluid dynamics test facility to check the two phase flow problems involved in start up. A large amount of hydrogen will be required and probably some of the NASA labs would be good candidates for these tests.

An ETR site would have to be selected. It is not clear where one would construct it. ~~It might be concept-specific.~~ I am sure that the test cavity in the middle of the reactor to test concepts would be different depending on the concept. Again, the site for the GTE would have to be selected. Of course, the GTE would be concept-specific, as well.

Finally the GTE might have to have an altitude chamber to simulate start up, particularly if one is going to have a regeneratively cooled nozzle, since the pressure drop must be simulated, implying a sufficiently large nozzle.

In conclusion, we feel that the PBR has several advantages for this mission (Figure 16). High heat transfer allows it to operate at very high power densities for a given total power. Thus we can design a very high-thrust, light-weight reactor. This would be useful if one wants to use redundant engines. Direct cooling of the particles enables one to operate as close as possible to the material limits of the coating. The coolant flow path ensures that all internal components of the reactor, moderator, control rods and so forth operate at inlet temperatures. This ensures reliable operations. And finally we feel that for solid core rockets, this concept would get the closest to the achievable limits, whether one wants to maximize thrust-to-weight or specific impulse.

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SCHEMATIC REPRESENTATION OF A PARTICLE BED REACTOR BASED ROCKET CONCEPT

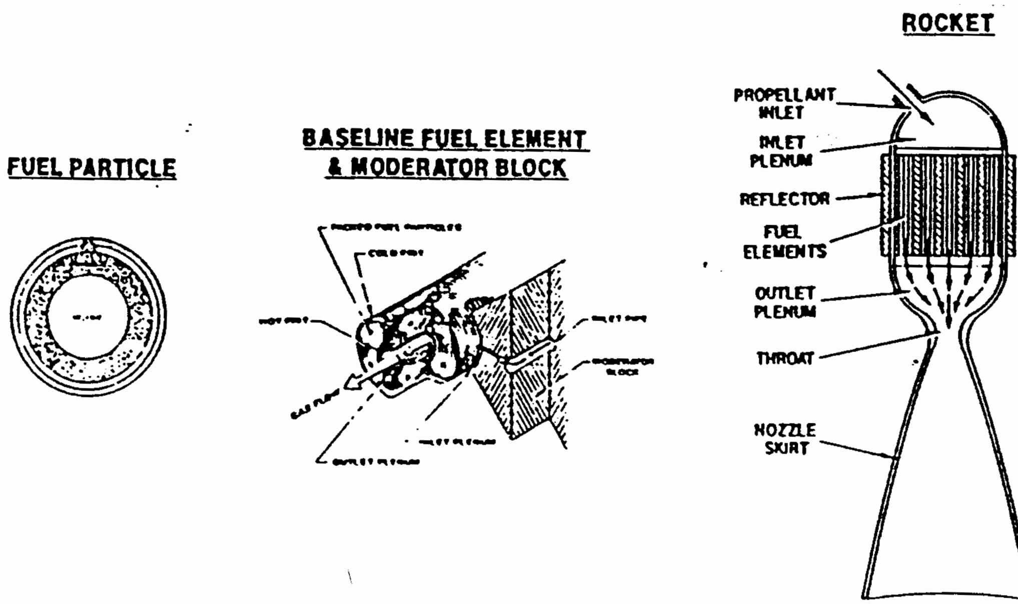

Figure 1

DESIGN PHILOSOPHY

- MAXIMIZE THRUST/WEIGHT
  - HIGH POWER DENSITY
  - HIGH PRESSURE
  - HIGH TEMPERATURE
  - SMALL SIZE
  - HIGH THRUST

- MAXIMIZE SPECIFIC IMPULSE
  - LOW POWER DENSITY
  - LOW PRESSURE
  - ULTRA HIGH TEMPERATURE
  - LARGE SIZE
  - LOW THRUST

Figure 2

ENGINE PARAMETERS

	HIGH THRUST/WEIGHT	HIGH SPECIFIC IMPULSE
POWER (MW)	1000 - 5000	500 - 2000
AVERAGE BED POWER DENSITY (MW/L)	20 - 80	5
CHAMBER TEMPERATURE (K°)	2500 - 3500	3000 - 3750
CHAMBER PRESSURE (MPA)	7.0 - 14.0	0.5
SPECIFIC IMPULSE (S)	850 - 1060	1000 - 1300
THRUST (N)	2.0 (5) - 1.0 (6)	6.0 (4) - 2.0 (5)

Figure 3

CALCULATED PARAMETERS

	HIGH THRUST/WEIGHT	HIGH SPECIFIC IMPULSE
TOTAL ENGINE MASS (W/O SHIELD (kg)	650 - 5500	2800 - 6000
THRUST/WEIGHT (W/O SHIELD)	20 - 35	4.0 - 7.5
SHIELD MASS (kg)	1300 - 6400	3700 - 7900
THRUST/WEIGHT (W/SHIELD)	8.6 - 14	2.0 - 3.2
MAXIMUM FUEL TEMPERATURE (K°)	2500 - 3650	3200 - 3900

Figure 4

STATUS OF TECHNOLOGY DEVELOPMENT

(BASED ON WORK CARRIED OUT FOR OTV AND MMW PROGRAMS)

	PHYSICS	FLUID DYNAMICS	HEAT TRANSFER	MATERIALS
ANALYSIS	EXPLICIT MONTE CARLO ANALYSIS - MCNP (LA-7396-M) (1986)	1-D SURVEY CODE 1-D TRANSIENT CODE (4TH SYM. ON S.N.P., ALB., NM) (1987)		--
PROOF OF PRINCIPLE EXPERIMENTS	--	PRESSURE DROP CORRELATION ERGUN (CHEM. ENG. PROG. 48:89-97) (1952)	HEAT TRANSFER CORRELATION ACHENBACH' (INT. HEAT TRANS. CONF. MUNICH) (1982)	COMPATIBILITY OF ZrC WITH H_2 (2ND SYM. ON S.N.P., ALB., NM) (1985)
PROTOTYPE EXPERIMENTS	--	ELECTRICALLY HEATED BLOWDOWN EXPERIMENTS (6TH SYM. ON S.N.P., ALB., NM) (1989)		ZrC COATED FUEL PARTICLES (HOMAN AND KANIA, ORNL/TM-9085, JAN. 1985), (UZr)-C FUEL PARTICLES (SYM. ON CARBIDES IN NUCL. ENG., HARWELL) (1963)

Figure 5

POTENTIAL NEW TECHNOLOGY AND SAFETY REGULATORY IMPACT

- HIGH TEMPERATURE COATING TECHNOLOGY FOR FRITS AND FUEL

- FIBER ENHANCED LIGHT WEIGHT STRUCTURAL MATERIALS
  - LOW Z TO MINIMIZE RADIATION HEATING

- PLATELET CONSTRUCTION OF COMPONENTS TO FACILITATE FLOW CONTROL AND COOLING.

Figure 6

SAFETY ISSUES TO BE ADDRESSED BY ALL NTR CONCEPTS

- **FUEL ELEMENT TEST REACTOR SAFETY**
- **GROUND TEST FACILITY SAFETY FOR AN OPEN CYCLE REACTOR**
- **RELIABILITY/REDUNDANCY FOR SYSTEM MAN-RATING**
- **LAUNCH CRITICALITY ACCIDENTS**
- **EARTH RE-ENTRY ACCIDENTS**
- **ENERGY RELEASE OF POSSIBLE FAILURE SCENARIOS**
- **EXTENSIVE SAFETY REVIEW AND DOCUMENTATION EFFORT REQUIRED**

Figure 7

POTENTIAL SAFETY ADVANTAGES OF CONCEPT

- COMPACT SIZE AND WEIGHT
  - MULTIPLE ENGINE REDUNDANCY POSSIBLE
  - EASIER TO SHIELD
  - EASIER TO NEUTRONICALLY DECOUPLE MULTIPLE ENGINES
- CONTAINMENT/CONFINEMENT CAPABILITY OF FUEL PARTICLES
  - REDUNDANCY
  - MOST PARTICLES ARE RELATIVELY COOL
- MOST CORE MATERIALS ARE COOL
- USE OF LIGHT-WEIGHT STRUCTURAL MATERIALS MINIMIZES RADIATION HEATING
- THERMAL GRADIENTS ACROSS MOST INDIVIDUAL COMPONENTS ARE SMALL

Figure 8

KEY TECHNOLOGY ISSUES

- HIGH TEMPERATURE PARTICLE/COATING
  - EROSION RESISTANT
  - NEUTRONICALLY BENIGN
  - COMPATIBLE WITH HOT FRIT

- HOT FRIT/COATING
  - EROSION RESISTANT
  - COMPATIBLE WITH PARTICLES
  - ACCEPTABLE MECHANICAL PROPERTIES

- COLD FRIT
  - MANUFACTURABLE WITH VARIABLE POROSITY
  - NEUTRONICALLY BENIGN

- MODERATOR
  - LARGE SELECTION OF MODERATOR POSSIBLE WITH PBR
  - SELECT MODERATOR WHICH WILL BE COMPATIBLE WITH MISSION PROFILE

Figure 9

KEY TECHNOLOGY ISSUES (cont'd)

INTEGRATED FUEL ELEMENT TEST

- DEMONSTRATE ABILITY OF FUEL ELEMENT AND THUS REACTOR TO REPEATEDLY CYCLE IN POWER FROM ZERO TO FULL POWER
- DEMONSTRATE MAXIMUM LIMIT IN ACHIEVABLE BED POWER DENSITY AND HOT CHANNEL FACTORS
- DEMONSTRATE STABLE OPERATION OF ELEMENT, NO AUTOCATALYTIC TEMPERATURE OR FUEL FAILURE MECHANISMS

- CARBON/CARBON NOZZLE - RADIATIVELY COOLED OPTION
  - EROSION RESISTANT
  - JOINT WITH PRESSURE VESSEL

- TURBO PUMP ASSEMBLY
  - CARBON/CARBON ROTORS FOR TURBINE

Figure 10

SCHEDULE AND COSTS

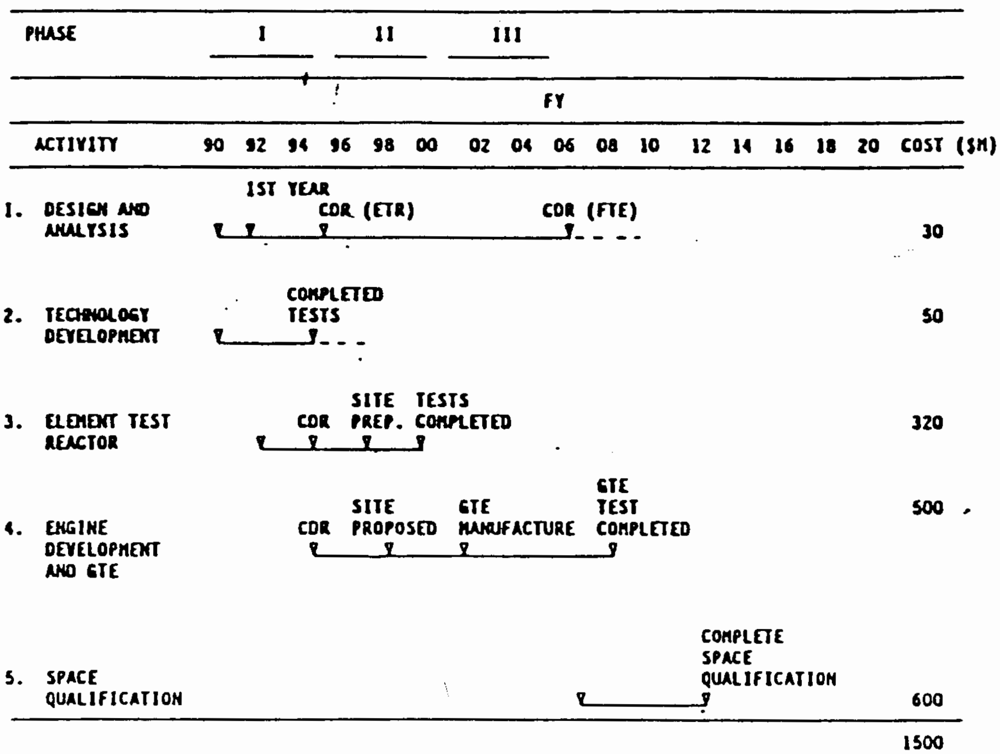

Figure 11

CRITICAL TESTS/ACTIVITIES

- FIRST YEAR
  - DEVELOP ENGINE DESIGN COMPATIBLE WITH MISSION ANALYSIS
  - DEVELOP A PLAN FOR COMPONENT PROOF OF PRINCIPLE AND PROTOTYPIC EXPERIMENTS BASED ON ABOVE DESIGN
  - START EXPERIMENTAL WORK

Figure 12

CRITICAL TESTS/ACTIVITIES (cont'd)

- CRITICAL TEST - PHASE I
  - CONTINUE ENGINE DESIGN AND DEVELOPMENT
  - DEMONSTRATE A HIGH TEMPERATURE PARTICLE TO MEET MISSION NEEDS
  - DEMONSTRATE BOTH HOT AND COLD FRITS TO MEET DESIGN GOALS
  - OPERATE A FULL SIZE FUEL ELEMENT IN A TEST REACTOR (TREAT, ACRR)
  - CARRY OUT A CRITICAL EXPERIMENT
  - CARRY OUT PROTOTYPIC ELECTRICALLY HEATED FUEL ELEMENT FLOW EXPERIMENT TO DEMONSTRATE REPEATABLE, STABLE OPERATION AT MAXIMUM POWER DENSITY
  - DESIGN ELEMENT TEST REACTOR (ETR)
  - DEMONSTRATE CARBON/CARBON NOZZLE
  - DEMONSTRATE CARBON/CARBON TURBINE ROTORS
  - DEMONSTRATE MIXER FOR TURBINE FEED

Figure 13

CRITICAL TESTS/ACTIVITIES (cont'd)

- CRITICAL TESTS - PHASE II AND III
  - SELECT SITE FOR ELEMENT TEST REACTOR AND SATISFY ALL NECESSARY REGULATORY AND SAFETY AGENCY AND REQUIREMENTS
  - PREPARE TEST SITE FOR ETR AND GROUND TEST ENGINE (GTE)
  - CONSTRUCT AND CARRY OUT FUEL ELEMENT TESTS
  - DESIGN GROUND TEST ENGINE (GTE)
  - CONSTRUCT AND CARRY OUT GTE TEST PROGRAM

Figure 14

MAJOR FACILITIES REQUIREMENTS

- CRITICAL EXPERIMENTS (LANL, ANL (WEST AND EAST))
- FLUID DYNAMICS FLOW FACILITY TO VERIFY TWO-PHASE FLOW AND FLOW INDUCED VIBRATIONS EFFECTS DURING START-UP AND RUNNING
  - MUST HANDLE LARGE QUANTITIES OF HYDROGEN (NASA LABS)
- SITE FOR ETR - NEW
- ETR - NEW MAY BE CONCEPT SPECIFIC
- SITE FOR GTE (SAME AS FOR ETR (?))
- GTE - CONCEPT SPECIFIC
- GTE - ALTITUDE CHAMBER TO TEST START UP

Figure 15

CONCLUSION

- THE PBR HAS SEVERAL UNIQUE ATTRIBUTES WHICH MAKE IT ATTRACTIVE AS A PROPULSION REACTOR
  - HIGH HEAT TRANSFER AREA ENABLES REACTOR TO OPERATE AT HIGH BED POWER DENSITIES
  - FOR A GIVEN TOTAL POWER, THE HIGH POWER DENSITY RESULTS IN A SMALL AND THUS LOW MASS REACTOR - USEFUL IF REDUNDANT ENGINES ARE DESIRED
  - DIRECT COOLING OF PARTICLES RESULTS IN THE HIGHEST POSSIBLE GAS TEMPERATURE FOR ANY PARTICLE DESIGN - DESIRABLE FOR MAXIMIZING SPECIFIC IMPULSE
  - COOLANT FLOW PATH ENSURES THAT THE MODERATOR CONTROLS (INTERNAL OR EXTERNAL) AND MOST STRUCTURAL COMPONENTS OPERATE AT COOLANT INLET TEMPERATURES - ASSURES A WIDE SELECTION OF MODERATORS, ENSURES RELIABLE OPERATION OF CONTROL RODS AND STRUCTURAL COMPONENTS
- THESE ATTRIBUTES WILL RESULT IN A REACTOR DESIGN WHICH SHOULD APPROACH THE PRACTICALLY ACHIEVABLE LIMITS OF SPECIFIC IMPULSE AND THRUST/WEIGHT RATIO FOR A SOLID CORE REACTOR DESIGN

Figure 16