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INNOVATIVE NUCLEAR THERMAL PROPULSION TECHNOLOGY EVALUATION: RESULTS OF THE NASA/DOE TASK TEAM STUDY

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Abstract

In response to findings from two NASA/DOE nuclear propulsion workshops held in the summer of 1990, six task teams were formed to continue evaluation of various nuclear propulsion concepts. The Task Team on Nuclear Thermal Propulsion (NTP) created the Innovative Concepts Subpanel to evaluate thermal propulsion concepts which did not utilize solid fuel. The Subpanel endeavored to evaluate each of the concepts on a "level technological playing field," and to identify critical technologies, issues, and early proof-of-concept experiments. The concepts included the liquid core fission, the gas core fission, the fission foil reactors, explosively driven systems, fusion, and antimatter. The results of the studies by the panel will be provided.

I. Introduction

During the NASA/DOE NTP workshop in July 1990, the mission analysis panel identified several of the proposed concepts which could have significant mission benefit. Primarily, these technologies offered significantly higher specific impulses, I_{sp}, than the solid core concepts. Subsequently, a joint NASA/DOE Nuclear Thermal Propulsion (NTP) Task Team was convened and has examined prospective technologies in more detail by meeting regularly during FY 91. Because of the input from the astronaut corp and the Mission Analysis Task Team, the technologies that offered very fast transits to Mars gained increased emphasis. Consequently, a Subpanel to investigate advanced concepts was formed from the NTP Task Team to examine, compare, and prioritize those nuclear propulsion concepts classified as innovative, i.e. those concepts offering very high I_{sp} but with technology readiness levels of around 1.

The charter of the Innovative Concepts Subpanel was to attempt a comparison of the several concepts which did not involve the operation of solid core fuels. Thus, particle bed reactors and the Low Pressure Concept were not studied. The two exceptions, which were included, were the Foil Reactor and the direct Fission Product Drive concept. Although these concepts involved solid fuel forms, they were included due to the conceptual nature, non-equilibrium thermodynamics and high I_{sp} offered. In short, the following concepts were evaluated:

- Liquid Annular Core
- Gas Core:
  - Closed Cycle
  - Open Cycle
  - Electric Propulsion

  Note: ("Gas" core is used generally to cover droplet, vapor, gas, or plasma fuel form concepts).
- Foil Reactor
- Fission Product Drive
- Explosive driven - push or pull
- Fusion - Magnetic
  - ICF
- Antimatter - Direct Drive
  - ICF

The goal of the Subpanel was to compare each concept on a "level technological playing field", identify critical issues specific to each concept and identify early proof of concept (POC) experiments which could be performed within the next few years. In essence, a priority list for the concepts would be developed to "guide" the Nuclear Propulsion Program's support of research in this area.

Given the ideas involved, the panel quickly ascertained that the data base supporting the gas core reactor concept was qualitatively far ahead of the other proposed ideas. As a consequence, all of the other ideas were evaluated using a similar procedure as the NTR workshop, i.e., advocate presentations were made to the panel which then discussed issues, experiments, and technical feasibility. Alternatively, the gas core concept was evaluated by organizing a Gas Core Workshop in which a much broader scientific constituency was used to evaluate ideas and develop POC's.

II. Gas Core Workshop

The Los Alamos National Laboratory hosted the Gas Core Workshop in Boulder, Colorado, on April 2-4, 1991. The 33 attendees represented 11 universities, 11 industries, NASA centers, DOE laboratories, and DOE Headquarters. The first day entailed presentations of past research and short synopses of potential capabilities by the attendees. The second day consisted of four working subsessions in the areas of neutronics, radiation hydrodynamics, materials, and facilities. The output from the subsessions was summarized and submitted to the full NTP panel as recommendations for research.

Initially, the performance potential and mission benefits were presented at the workshop by one of the authors (Borowski). In order to develop the desired Earth/Mars transit times of a few months, specific impulses of several thousand seconds are required to deliver the required velocity change to the ship. Because of the constraints of material melting, solid core rockets cannot produce these exhaust velocities. However, by utilizing a gaseous or plasma fuel form, where the melting temperature of the cooled containment wall is the constraining factor, Isp's of up to 5000 s may be conceived.

The declassified version of a gaseous fuel reactor concept was first put forth by Kerrebrock and Meghreblin.[1] During the ROVER/NERVA program in the 1960's, significant work was performed on a variety of concepts. In essence, the concepts differed with regards to the method of containing the uranium fuel while allowing the hydrogen working fluid to exhaust.

A closed-cycle, physically contained uranium vortex concept was investigated by the United Technologies Corporation (UTC). Dubbed the Nuclear Light Bulb (NLB) (see Fig. 1), the idea relied on radiative coupling between the uranium fuel and the hydrogen propellant through a fused silica bubble which contained the fuel. Experimental work on radiation induced opacity, uranium vortex formation, and radiative coupling were performed in the early 1970's. During this time UT demonstrated a radio-frequency heated uranium plasma vortex in a cylindrical silica tube and performed radiation damage studies of the silica. Because of the fused silica presence in the core environment, however, this concept has a probable Isp range of between 1600 to 2000 s. The UT Division of Pratt Whitney has continued to be interested in pursing this concept.

The coaxial flow open-cycle concept (see Fig. 2) which relied on hydrodynamic containment was proposed by Weinstein and Ragsdale[2] in 1960. The concept relied on the hydrodynamic flow pattern of the hydrogen to contain the uranium plasma. Because no solid material was in the core, the potential I_{sp} could reach 5000 s. Containing the fuel, however, is a major obstacle. Although 100% containment will not be required, reducing the fuel leakage rate to acceptably low levels is a major requirement which has not yet been proven. Some experimental evidence for hydrogen to fuel mass-flow ratios of a few hundred has been inferred, however, from cold flow conditions of simulation gases in a spherical geometry. If a mass flow ratio of H_2 to U could be demonstrated at around 400, then the open cycle concept could be justifiable. In addition, researchers have recently reported working on the design, fluid dynamics, and neutronics models for a open-cycle gas core engine.[3,4]

In addition, because of recent work by the Innovative Nuclear Space Power Institute (INSPI),[5] the idea of using a gas core reactor

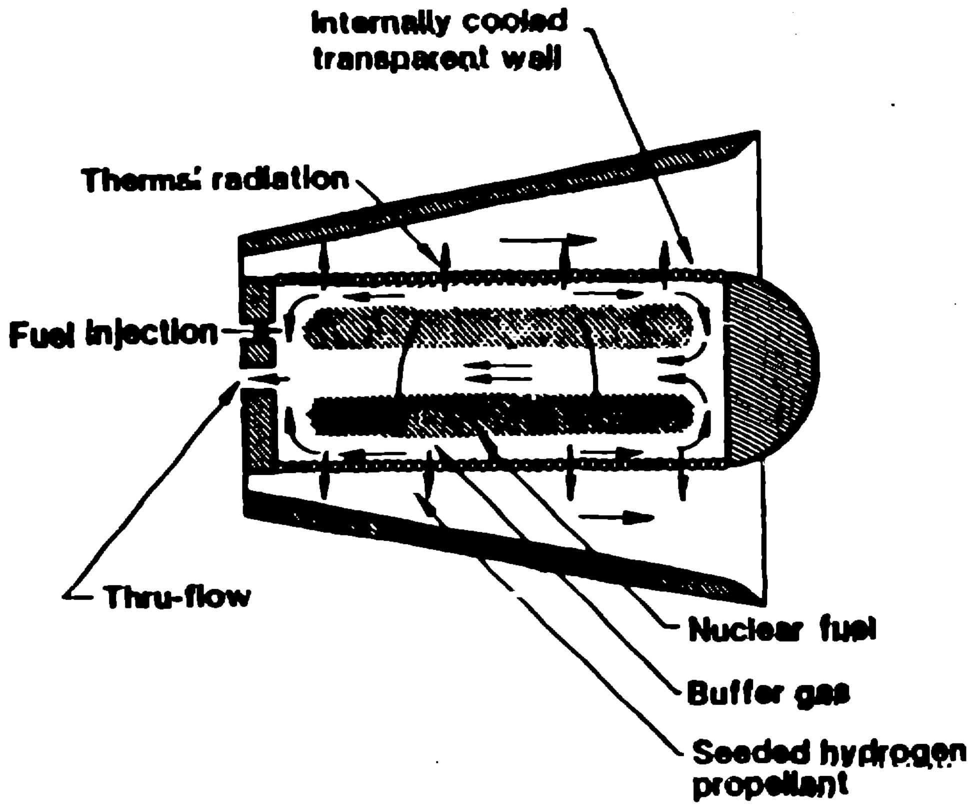

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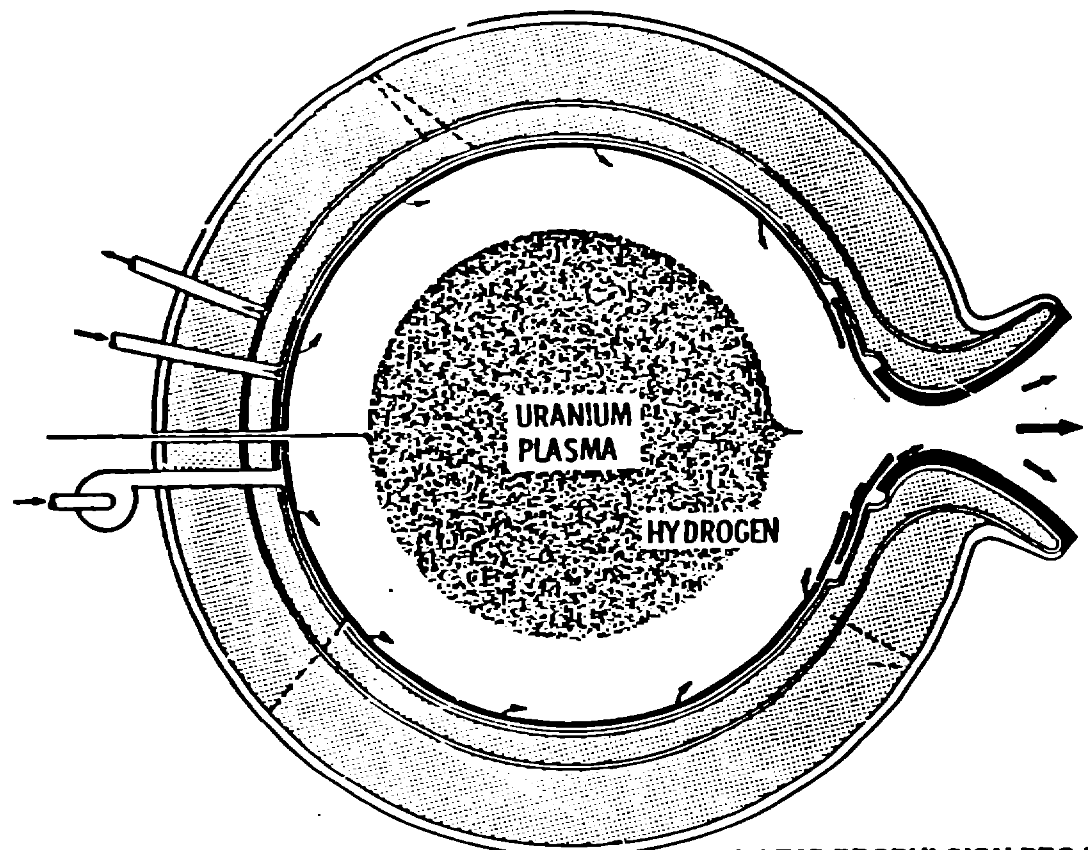
FIG. 1 - NLB schematic

OPEN CYCLE GAS CORE ENGINE - THE CONCEPT



coupled to a magneto-hydrodynamic (MHD) conversion system for NEP was also considered. The INSPI has investigated several droplet, vapor, and gas core concepts with the goal of designing high-power space-based electrical sources. As part of this effort, they have investigated the idea of enhancing the conductivity of the exhaust gas by neutronically coupling the uranium laced exhaust to the reactor and generating charged fission products while passing through the MHD convertors. Simulation POC experiments have been performed using the Godiva critical assembly at the Los Alamos National Laboratory to induce the $^3He(up)T$ reaction in a He gas flow. Significant increases of conductivity were observed indicating the potential for enhancing MHD conversion efficiency. The combination of a gas core engine and an MHD conversion system offers the possibility of developing a low specific mass, high power electric propulsion system for fast manned missions.

Subsession Results

Although several concepts exist which employ a wide variety of temperatures, pressures, and fuel forms the technological challenges were grouped into four broad categories: neutronics, radiation/fluid dynamics, materials, and facilities. A Subpanel was formed for each of these categories and chartered with the tasks of identifying critical issues in that category for all concepts, critical issues that were concept dependent, and critical proof-of-concept experiments.

A summary of the findings of the Subpanels is shown in Table 1. In essence, the primary driver for most of the groups was the required operating temperature. Because the chamber temperature will be significantly higher than the wall or moderator temperatures, new technological and computational capabilities are needed. Neutronically, the cold moderated neutrons which are reflected back into the core will be upscattered to the chamber temperature. This will tremendously affect power distributions and stability. In turn, the neutron coupled power distribution will impact the fluid dynamics of the gas, especially the mixing at any interface with injected, cool hydrogen. In addition, the extreme temperatures will demand new materials for walls, nozzles, and containment vessels which currently do not exist.

Although these issues and problems were envisioned as difficult, they were not perceived as insurmountable. Several nuclear test reactors currently exist in which to perform basic studies. In addition, numerous high power, high-mass, gas-flow test facilities could be used for the materials development effort. The facilities Subpanel did identify the need for a high power, high temperature clean gas-jet capability. Currently, two 250 kW RF coupled facilities exist, one at at the TAFA Corporation and the other at Los Alamos. The need for a higher power test stand was clearly identified in order to perform the high fidelity simulation experiments for several concepts. More specifically, the uranium/hydrogen interface, the plasma/materials interface, and the radiation transport in a seeded gas were all problems that could be addressed at such facilities.

Eventually, the gas core concept will have to be demonstrated as a coupled system but, perhaps, at subscale. The NLB concept is conducive to such a test and could be executed in the near term. The open cycle concepts , however, will probably require access to the Fuel Element Test Facility (FETF) which is being considered for the Nuclear Propulsion Program being formulated to support the Space Exploration Initiative. If possible, the Subpanel recommended that the FETF be designed to accommodate a large volume cavity containing a uranium gas to demonstrate feasibility once the basic concepts had been proved in the laboratory.

Overall the Gas Core Workshop was successful in that it identified issues and experiments pertinent to developing a gas core propulsion system. In addition, extensive computational and experimental capabilities were delineated at universities, industries, and government laboratories which can be utilized to support gas core rocket research. Following the workshop, many participants felt that the gas core concepts could become competitive with the solid core rocket within a few years if the identified proof of concept tests were successful.

Table I

SUMMARY OF SUBPANEL FINDINGS

Neutronics

- The treatment of neutron scattering in the resonance region needs to be examined closely.
- Scattering kernels for light molecules (e.g., BeO) need to be examined at near-thermal energies.
- Are envisioned computers capable of running fully coupled codes?
- Compare U^{235} vs. U^{233} as a fuel.
- Perform experiments to benchmark neutron upscattering.

Fluids/Radiation

- Theoretically investigate temperature and density gradient effects on hydrodynamically contained plasmas.
- Investigate potential for electro-magnetic enhancement of containment in high-density, partially ionized media.
- Perform RF heated experiments to examine plasma/H^2 interface, molecular seeding, and radiation transport.
- Perform cold flow tests to benchmark fluid codes.

Materials

- Examine nozzle material issues of H^2 embrittlement, transpiration cooling, fission product chemistry, radiation damage, and high melting point.
- Examine storage and handling of UF_6, UF_4, and uranium vapor/plasma.
- Perform opacity and erosion experiments on fused silica for varying radiation doses.

Facilities

- Design laboratory facilities to simulate the radiation environment or the thermal environment
- Examine scalability of tests to keep facility costs down.
- Perform in-core radiation damage tests at existing reactors.
- Design large, high-power RF heated test facility for nozzle testing and large scale verification.
- Perform critical assembly tests on subscale fuel "elements".

III. Alternative Concepts

The Innovative Concepts Subpanel convened immediately after the Gas Core Workshop to evaluate a set of alternative nuclear propulsion ideas. A summary presentation for each concept was made to the Subpanel by an "advocate." Critical issues pertinent to the concept were then discussed in much the same context as that of the Gas Core Workshop. Ultimately, the concepts were ranked in priority by the panel. The ranking was intended only as guideline for the innovative concepts path of the Nuclear Propulsion Program. The concepts and their advocates were:

1) Foil Reactor - Gary Polansky (SNL)
2) Fission Product Drive - Chet Motloch, INEL (for LLNL)
3) Liquid Annular Core - Chet Motloch INEL (for Hans Ludwig, BNL)
4) Explosive Driven Concepts: ORION and Medusa - John-Dale Solem, Los Alamos
5) Fusion - Stan Borowski (NASA LeRC)
6) Antimatter - Steve Howe (Los Alamos)

Foil Reactor

The Foil Reactor[6] is depicted schematically in Fig. 3 In essence, the concept relies on fission products escaping from thin foils of UO_2 into the hydrogen flow stream passing by each foil. Thus, the fission products heat the hydrogen directly producing a non-thermodynamic equilibrium. In this way the hydrogen temperature could be higher than the UO_2 melting point and produce an I_{sp} of perhaps 990 s.

Two primary issues concerned the panel. The first was the durability of having a very large reactor core full of very thin foils. The questions of surviving launch vibrations and long burn times were raised as major tests. Secondly, several panel members postulated that the hot hydrogen would indeed reach thermodynamic equilibrium with the downstream foils. Thus, the concept would be limited to UO_2 melting temperatures and result in a lower Isp.

FP Drive

The Fission Product Drive (FPD) was first proposed[7] in 1989. The concept relies on having a critical assembly produce fissions in a series of thin wires arrayed as the spokes of a bicycle wheel (see Fig. 4). The fission products escape the wires, are deflected and focused by an external magnetic field, and produce thrust directly. Based on the average energy of an escaping particle an I_{sp} of around 1.0×10^6 s would be possible at low thrust.

Several issues were raised for this concept. The mechanical behavior, survivability and lifetime of the thin wires was questioned. In addition, the presence of a strong magnetic field would require a heavy magnetic field generator. The mass and power requirements were a major issue due to the need for low-thrust systems to have a low specific mass, (kg/kW). Furthermore, an Isp of a million seconds is not necessary for intra-solar system missions. The panel questioned whether the overall system mass would actually be an improvement over potential high performance electric propulsion systems.

Liquid Annular Core

The Liquid Annular Core Concept[8] is shown in Fig. 5 A cylindrical shell of uranium is brought to criticality. As the uranium heats up, the inner surface liquifies and transfers heat to the hydrogen coolant passing down the axis. The liquid sheath is maintained by rapidly rotating the cylinder. Because the fuel is allowed to melt but not boil, higher exhaust temperatures can be reached to produce an I_{sp} of about 1600 s.

The major issues raised for this concept essentially involved fluid dynamics and thermodynamics. The immediate question was the rate of mass loss due to Kelvin-Helmholz instabilities at the hydrogen uranium interface. Secondarily, the acceleration of the ship will tend to "sag" the liquid sheath to the "rear" of the cylinder deforming the power distribution and, perhaps, leading to nonuniform melting. No avenue exists for liquid uranium recirculation. Finally, the question of the thermodynamic balance was raised. If the outer surface of the uranium is to remain solid but most of the heat is to be generated in the solid shell then some manner of cooling must be applied to the solid. The axial hydrogen flow does not appear sufficient to remove the heat. If some type of "transpiration cooling" is used, however, the mass loss of the liquid will increase due to bubbling.

Schematic of Direct Heating NTR

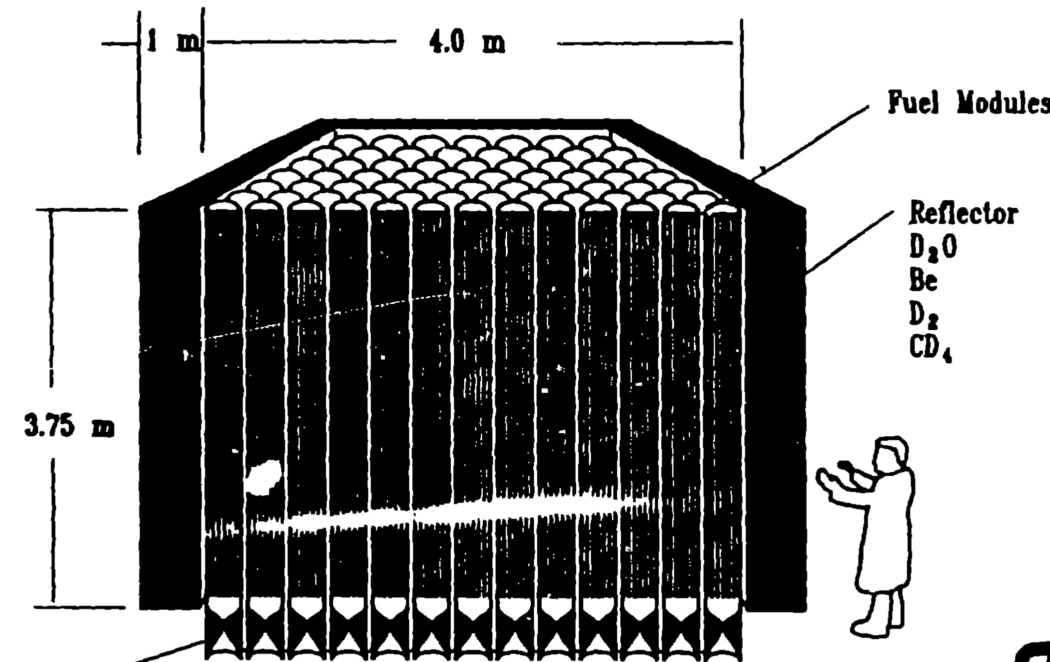


FIG. 3 FOIL REACTOR

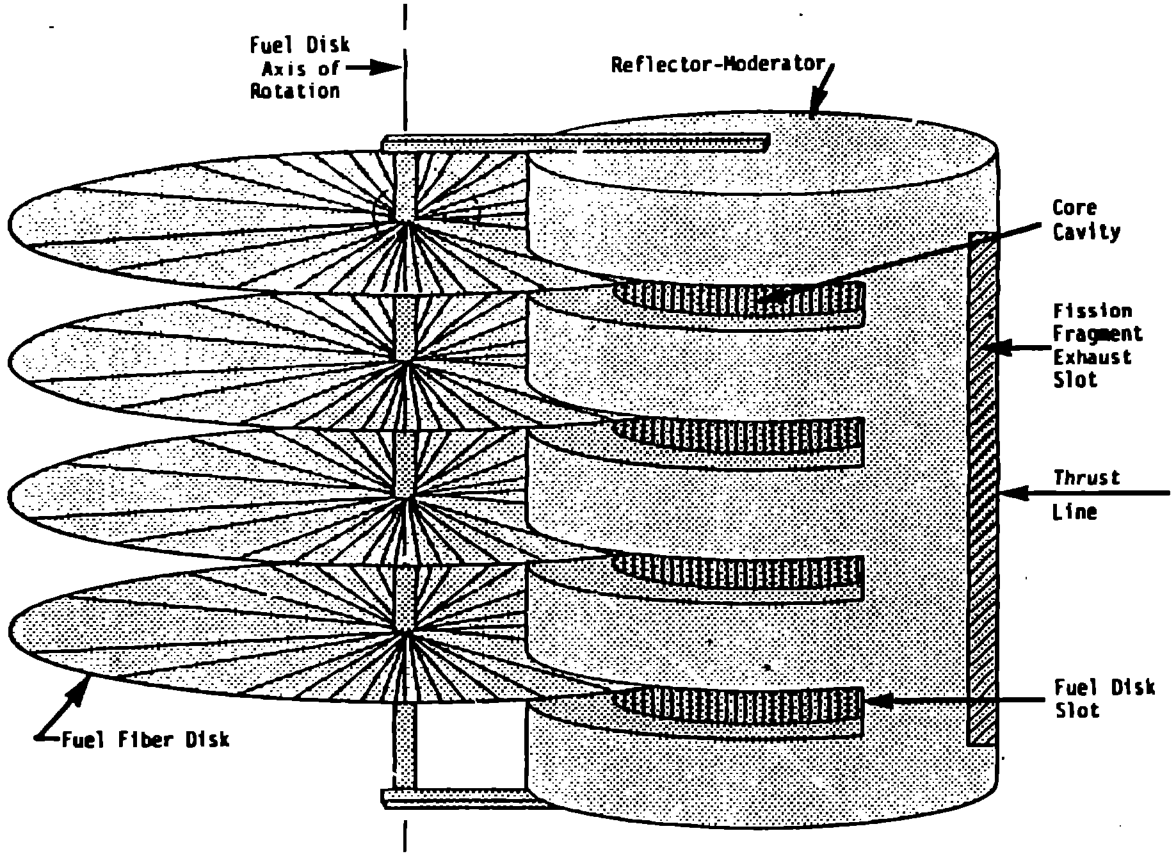


FIG. 4
~~Figure 1.~~ Potential fission fragment rocket engine configuration.

Because of the presence of liquid uranium and the possibility of exhausting droplets, this concept would also impact the design of any ground based test facility.

Explosive Drives

The idea of an explosive driven spaceship was first proposed in 1947 by Stan Ulam and Fred Reines. From 1961 to 1966, the concept was investigated under the Orion Project[9,10] at the Los Alamos Scientific Laboratory. Substantial amounts of neutronics transport, nuclear explosive device design, and radiation coupling calculations were performed which indicated the feasibility of the concept. In addition, experimental tests using small successive boosts from high explosives were performed.

In essence, the concept relies on a sequence of small nuclear explosions to produce high velocity pulses of mass. These "pressure waves" are then caught by the spaceship to transfer momentum. Depending on the distance between ship and detonation, surface ablation of the "catching" surface may also be used to enhance momentum transfer to the ship. Because the pulse width of the pressure wave is very narrow, however, some manner of "shock absorber" or "pulse stretcher" mechanism must be employed to spread the ship's acceleration out in time.

The original ORION concept envisioned a large ship with a massive pusher plate as shown in Fig. 6. The advantages of the concept were high Isp, and high thrust. The disadvantages were the storage and detonation of several thousand nuclear devices, radioactive exhaust, and large ship mass.

A more recent concept proposed to the panel, dubbed MEDUSA, is to utilize the explosion in a "pull" instead of "push" mode. In essence, the same basic principles apply except that a large, light weight sail is positioned out ahead of the ship. The explosion, then, occurs between the ship and the sail. By placing the sail far away from the explosion, the ejecta is cool by the time it reaches the sail surface so that no ablation occurs. The tethers of the sail then act as springs to stretch the acceleration pulse.

The primary obstacles perceived by the panel were radiation damage to the tethers and the sail, radiation exposure of the crew module, and simultaneous control of the several thousand, kilometer-long tethers. The presentation given the panel did include some analytic treatment of these concerns. Although the results of the initial analysis demonstrated no violation of any physics, the Panel recognized that severe engineering problems would be inherent in such a system.

Fusion

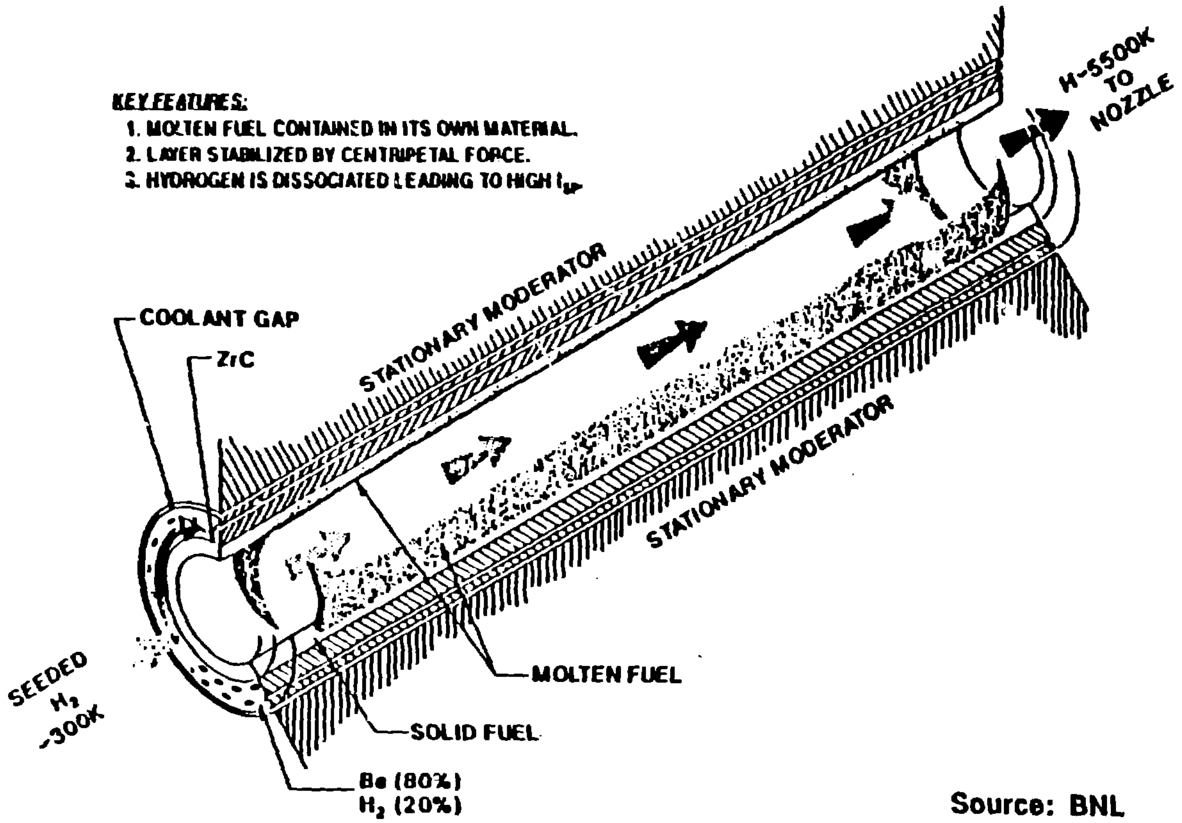
A brief summary of the major accomplishments of the U.S. fusion program was presented to the panel along with a number of fusion-based propulsion concepts. Several ideas of using fusion for propulsion have been investigated extensively for several years. Most of these concepts have incorporated variations in driving mechanisms (magnetic fields, lasers, particle beams, or muons), reactions (DT, DD, D^3He through $p^{11}B$), and coupling mechanisms (direct product escape, fluid coupling, radiative coupling, magnetic field redirection, and conversion to electricity) to produce thrust.

The major advantages are very high specific impulse, high specific energy (energy per unit mass of reactant), and non-radioactive exhaust for most concepts.

In brief, the major obstacle is achieving a sufficient burn of reactants to deliver significant thrust to the vehicle. To date, net energy gain has not been achieved by any non-weapon fusion device. Although an actual net energy gain is required for ground based fusion power, a propulsion system may be justifiable for an energy gain less than unity if a sufficient fraction of the driving energy is converted to useful jet power. Thus, several of the concepts, such as those involving aneutronic reactions, which have been examined during the fusion program may be attractive propulsion candidates even though their "ignition" temperatures are much higher (and therefore more difficult to burn) than the neutron-producing reactions.

A secondary obstacle pertinent to several fusion-based concepts is the difficulty in coupling the energy released to a propellant. In essence, until the time that extra-solar system missions are launched, the I_{sp} produced by "bare" fusion reactions is actually too high for efficient applicability to intra-solar system missions. Thus, a working fluid, probably hydrogen, must be introduced and heated by

LIQUID ANNULAR REACTOR SYSTEM



Source: BNL

FIG. 5 - LARS

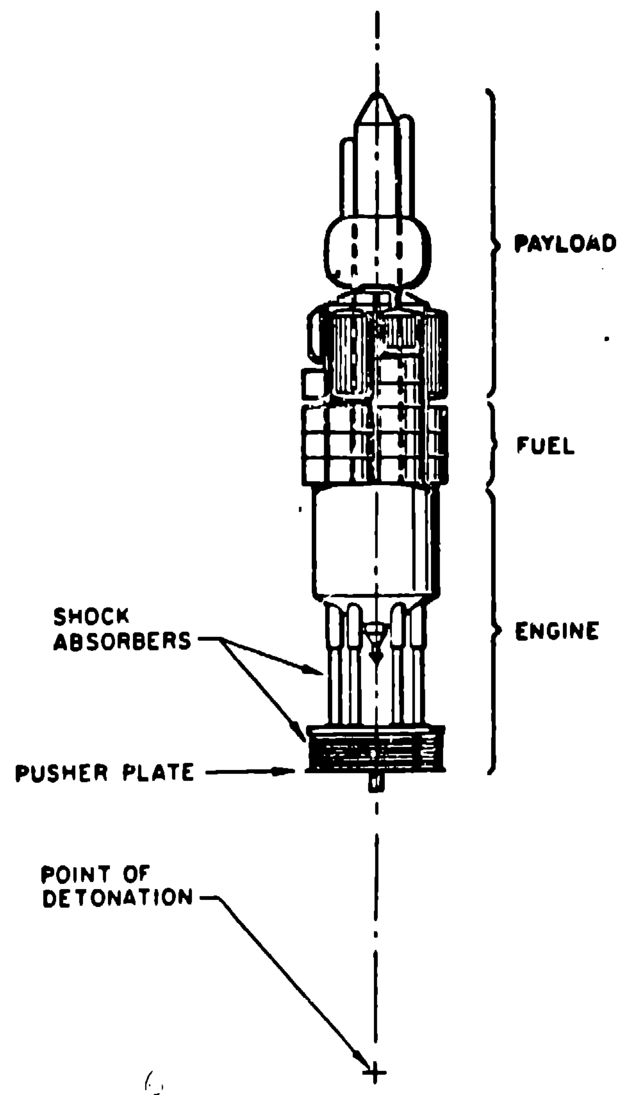


Fig. 1--Reference nuclear-pulse vehicle

the fusion reaction products. The working fluid, however, cannot be allowed to exist in the reaction region because it will dampen or suppress the conditions necessary to attain the fusion reactions. Therefore, coupling the reaction products to a working fluid is an issue for magnetic fusion concepts.

For Inertial Confinement Fusion (ICF) propulsion, however, the imploded targets can be coated with an inert material to reduce I_{sp} and increase thrust. Reduction of the average particle temperature, however, will affect the coupling of the expanding plasmoid to the magnetic cusp or nozzle. Thus, the temperature dependence of the "magnetic reflection" of a plasmoid is a serious issue for ICF. In addition, most of the techniques for producing the implosion, such as laser drivers, entail very massive, inefficient systems and large power supplies. Reducing the mass of an ICF propulsion system is a major issue.

Antiprotons

The concept of using antiprotons ($\bar{p}$) for propulsion was first proposed by Sanger[11] in 1953. Since then, several authors[12,13] have investigated a variety of propulsion concepts ranging from heating a solid tungsten core to allowing the relativistic pi mesons produced by the annihilation process to directly escape. Antiprotons are currently being produced in the world at the rate of about 10^{14} particles per year. Based on the past 30 years of production experience, antiproton production rates have increased by an order of magnitude every 2.5 years. If this trend continues, almost a mg/yr. (6×10^{20}) could be produced by the early 2000's. To accomplish this level of production significant progress needs to be made in accelerator technology.

Antiprotons are currently stored in large synchrotron rings. By lowering the particle energy, storage can be achieved in compact structures know as ion traps. Current experiments plan to decelerate and capture up to 10^{10} antiprotons in such a trap. The storage capability of ion traps is limited. However, these traps will provide a source of sub-thermal $\bar{p}$'s for development of better storage mechanisms suitable for propulsion. The application of antiprotons to propulsion requires the coupling of the energy released in the mass-conversion reaction to thrust producing mechanisms. In addition, there are recent proposals which would enhance the average energy released per $\bar{p}$ used. These proposals entail using the $\bar{p}$'s to produce inertial confinement fusion[7] or to produce negative muons which can catalyze fusion. By increasing the energy released per $\bar{p}$, the effective specific cost, (dollars/joule) can be reached.

The primary advantages offered by antiproton annihilation are (1) total conversion of reactant mass to energy (100% burnup), (2) specific energy (joules /kg) of greater than 100 times fusion and 1000 times fission, (3) large range of I_{sp}'s producible (1000 s to 10^7s), depending upon concept or operating condition of a given concept (i.e., variable I_{sp}), (4) the potential for direct coupling of the reaction products to the propellant, and (5) negligible production of neutrons (concept dependent).

The primary obstacles to the use of antiprotons are (1) expensive production costs, (2) long term storage of a material that interacts with all matter, and (3) coupling the very energetic reaction products to a working fluid to produce high thrust capability. Although antiprotons are currently produced at several accelerators around the world, the production cost is very dependent upon the production level, the accumulation efficiency, and ultimate energy required for storage. The development of a large demand for propulsion could substantially reduce the cost per antiproton to attractive levels.

If the antiproton storage issue can be resolved by future research, then such concepts offer the possibililty of a true high thrust, high Isp propulsion system.

IV. Conclusions and Discussion

After participating in the Gas Core Workshop and reviewing the other advanced concepts, the Subpanel attempted to reach some general conclusions regarding the various ideas. In general, the panel asserted that some level of support (probably 10% of the total budget for nuclear propulsion) should be focused on the advanced concepts. These ideas offer the potential of real breakthroughs in propulsion systems which could dramatically accelerate the exploration of space. By supporting proof of concept experiments in the laboratory setting, feasibility of these concepts could be determined.

The Panel also made an attempt to prioritize the concepts based on the presentations made to the panel, the presentations made at the NASA/DOE NTP and NEP workshops (summer 1990), and the experience bases of the members. An effort was made to incorporate such factors as performance potential, technological risk, testability, safety, crew impact, and current technological status. The following priority list shown in Table II was intended to be a guideline only for the funding of advanced concepts i.. the nuclear propulsion program. The Panel's assessment, however, showed a clear emphasis for the first four concepts and markedly reduced support for the last three ideas.

(2) perform open cycle hydrodynamic modeling and further develop fully coupled design codes,
(3) perform cold flow tests to benchmark fluid dynamic codes,

(4) perform radio-frequency heated gas jet studies of plasma/gas interfaces, radiation transport, gas seeding, and erosion,

(5) investigate behavior and material compatibility of UF6, UF4, and uranium vapor/plasma in simulated operation conditions,

(6) verify the idea of a magnetic cusp/nozzle using laboratory generated plasmoids,

TABLE II

GUIDELINE PRIORITY LIST

1. Gas Core Fission Systems - Open and Closed Cycle
2. Fusion - Emphasis on ICF
3. Antiproton - Direct Heating and ICF
4. Explosive-Driven Concepts
5. Foil Reactor
6. Liquid Annular Reactor
7. Fission Product Drive

In addition, the panel recognized that the Advanced Propulsion part of the program could be a major vehicle for the involvement of universities. Clearly, research laboratories and industry will pursue both the mainline program and advanced concepts, but university research efforts and experimental capabilities may be more compatible to supporting the future concepts.

In order to pursue some of the critical issues identified by the panel, a list of potential critical experiments was compiled. The experiments and the facilities to support the research varied widely from small laboratory scale tests to use of the Nuclear Fuel Element Test Facility planned for the solid core test program. Some of the experiments and studies that were considered necessary in the near term were:

(1) experimentally examine window opacity vs. radiation dose and window/fuel erosion for the NLB concept,

(7) perform fully coupled ICF calculations for antiproton driven implosions,

(8) pursue antiproton storage concepts and perform low energy annihilation cross section measurements, and

(9) development of transpiration-cooled, high-temperature materials.

Other potential experiments and studies are currently being solicited.

In summary, a small Subpanel of the Nuclear Thermal Propulsion Task Team has met and reviewed several nuclear based propulsion concepts. The concepts under consideration had to have the potential of producing thrust with a specific impulse of greater than 2000 s. Because of the past work on gas core fission systems, these concepts were rated the highest with regards to future support. More advanced concepts utilizing fusion reactions and antiproton reactions were also supported as high potential but long range possibilities. The panel concluded with the recommendation that support of Advanced Concepts was necessary for a comprehensive, integrated advanced technology nuclear propulsion program.

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