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COMMENTS ON DUAL-MODE NUCLEAR SPACE POWER & PROPULSION SYSTEM CONCEPTS*

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I. INTRODUCTION

These comments are based on a rather intense period of work in The Aerospace Systems Laboratory at Princeton University around the early 1970s and some later efforts by the authors and others in the Techno-Systems Analysis Corporation and RCA Astro through the mid-1970s and into the 1980s. We have been convinced for many years that some form of Dual-Mode Nuclear Space Power & Propulsion System (D-MNSP&PS) will be essential to spacefaring throughout the Solar System and that such systems must evolve as mankind moves into outer space.

II. BACKGROUND

The earliest work on the dual-mode derived from a need to dispose of the nuclear rocket reactor afterheat which was used to generate auxiliary power for long durations and reduces the quantity of hydrogen required for cooldown and the duration of cooldown thrusting. John H. Beveridge of Aerojet Nuclear Systems Company presented this first paper in 1971.

Subsequent thinking led to the mathematical modeling of concepts wherein large amounts of thermal power would be taken continuously at appropriate temperatures for conversion to electrical power from a specially configured rocket reactor. Dual-mode operation provides relatively high-thrust accelerations from the direct thrust mode and low-thrust accelerations with higher effective jet velocities from electric thrusters. Detailed conceptual designs of D-MNSP&PS for specific missions should be undertaken and compared with other means for carrying out such missions in the context of an overall evolving space program.

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III. DUAL-MODE NUCLEAR SPACE POWER & PROPULSION SYSTEM CONCEPTS

It must be kept in mind that space power and propulsion systems will evolve from present systems according to the demands of an ongoing program of diverse elements. Chemical rockets will continue to be used for the indefinite future for a variety of missions. After nuclear space power and propulsion systems and electric rocket concepts are proven they may be used advantageously for many classes of space missions especially those requiring high energy and complex flight paths.

A. Direct Nuclear Rocket Thrust

Nuclear rockets of the Rover(aka NERVA) Program were the most highly developed of nuclear space propulsion devices. The Small Nuclear Rocket Engine (SNRE) design introduced at the very end of this program was well proven and could be an excellent starting point at around 375 MWt for re-initiation of development and test work. With "slush" hydrogen as the propellant contained in insulated tanks for unmanned heliocentric missions,especially round trips, from and to transport nodes in long-lived Earth orbits lived Earth orbits. Much study and analysis is needed to identify the optimum nuclear rocket systems, vehicle configurations and flight paths for comparison with other means for performing such a mission.

B. Nuclear Electric Rocket Thrust

Nuclear electric rockets for primary propulsion have been delayed in their development by the lack of suitable nuclear space power systems which were denied funding following the cancellation of space nuclear propulsion and power programs in 1973. High effective jet velocities of electric rockets require large power supplies to provide even the low thrust accelerations and long thrusting periods that are characteristic of this form of propulsion. Their primary applications are missions that have flight paths in heliocentric space away from massive bodies.

The Kaufman electron bombardment ion thruster was an excellent development effort at the NASA Lewis Research Center;while arcjets,magnetoplasmadynamic and other electric rocket thrusters with a variety of propellants have also been developed. However an electric rocket thruster with proper characteristics for cruising throughout the solar system has yet to make its appearance.

C. Combinations

Mission analyses have shown that optimum performance of advanced Solar System missions, especially manned missions, requires combinations of propulsion (and power) systems.

D. Proposed Dual-Mode Reference System Design Concepts

1. Overall System

The Initial D-MNPSP&P Reference System should be based on (a) present(1990) and (b) advanced(1995) technology for use on comparable missions in the 2000 and 2005 time period respectively. The technology bases must assume a continuity of research, technology and advanced development work during the period on all vehicle subsystems; although this does not appear to be likely in the present funding circumstances world-wide, and especially in the USA.

Modification of the LANL Rover reactor at 1500 MWt or SNRE with 375 MWt full rocket power could also provide continuous (87,600 h) thermal power at lower levels of 150 to 35 MWt respectively and at a constant temperature of 1500 K for use by an efficient closed cycle electrical power generation systems producing between 45 and 10 MWe. The waste heat rejection subsystems would make use of deployable heat pipe radiators.

The advanced systems should be based on proposed concepts that have been clearly defined and appear to be realizable before the end of the 20th century for missions in the second decade of the next century. The overall character of these systems should be represented by new materials, sophisticated concepts, higher powers and temperatures, very high reliability and operational safety. These advanced systems require systems and mission analyses that are parametric, probabilistic and detailed, but must also be basically realistic.

Very advanced systems need to be defined and analysed, but should be handled on a separate basis that emphasizes research and technology aspects of major components; e. g., type of second or third generation reactor. Sensitivity analyses need to be conducted, and parametric studies need over appropriate ranges to give an overall understanding of the systems characteristics.

2. Major Subsystems

Dual-Mode Nuclear Space Power & Propulsion Systems can conveniently be broken down into a number of subsystems as given below. Although various concepts may have other subsystems or lack some of those shown; for the present purposes these should suffice for the Reference System definition.

a. Nuclear Subsystem

The Nuclear Subsystem includes the energy source and controls for the release of thermal power at elevated temperatures. In the D-MNSP&PS the thermal power is removed for two purposes. The lower power is released over the entire lifetime of the system once it has attained a long lived Earth orbit, and the lower power components will be maintained at a constant operating temperature of 1500 K (or higher for advanced systems).

(1) Reactor Types

There are a number of reactor types that are capable of being configured for dual-mode use. The gas (hydrogen) cooled epithermal carbide core that is fueled with enriched uranium oxide is heart of the LANL Rover and SNRE reactors. Some fuel element development for long duration, multiple thrusting periods at maximum temperature will be required. The capability for operation for 10 y at lower temperature and power levels will also represent a development challenge. Dual-mode operation of these and other types of reactors is a very substantial challenge that must be met by conceptual design effort and research and technology work including systems and component analyses. Mission analysis must also be performed before the D-MNSP&PS can be defined and related to the reactor type.

(2) Nuclear Radiation Shields

The D-MNSP&PS require much more substantial shields than the "shadow" shields that are ordinarily provided because the reactor operates continuously albeit at lower than rocket power levels. Something between a 2 pi and 4 pi tailored shield with cooling provisions will need to incorporated;however, although the additional mass must be accounted the transport of this mass can be discounted by Lunar exploitation activity. Vehicle conceptual design will be conditioned by nuclear radiation sheilding considerations.

(3) Thermal Power Source Heat Exchanger

One of the major problems in realizing the D-MNSP&PS capabitity is the removal of thermal power from the core for the generation of electric power. Depending on the type of reactor this may be accomplished in several ways. A pumped loop may be placed in or near the core and connected to the electric generation system. Specially configured heat pipes may be placed in the core where they would serve to remove thermal power and also act as supports for the core. One of the difficulties is to arrange for these elements to operate at a prescribed lower temperature even during rocket thrusting,and they must operate for the life of the vehicle with minimum mass and very high reliability.

b. Power Conversion Subsystems

(1) Direct Thrust Nozzles

Direct thrust would be provided by hot hydrogen flowing through a conventional nozzle as in a Rover engine;however the reactor would be fastened to the vehicle structure. The expansion portion of the nozzle would be movable at the throat and control the vehicle in pitch and yaw. Roll control would make use of auxiliary jets. Some research,technology and development work will be required to realize this capability.

(2) Thermal to Electrical Conversion Systems

(a) Closed Cycle Brayton Systems

The electrical generation systems that meet the requirements for dual-mode operation with high efficiency and long lifetime are the Brayton cycle gas turbine power systems that have had much development attention for other applications. Recent developments that are important for space use include new high temperature materials and foil bearings. A considerable amount of analysis and development aimed at specific characteristics are needed before the Brayton systems can be unqualifiedly selected for dual-mode application.

(b) Other Systems

Before other power conversion systems can be considered seriously much analysis and some technology work is needed so comparisons and selections can be made.

(3) Electric Rocket Propulsion Systems

Electric rocket thrusters are discussed in Section III.B. above,but a propulsion system includes other elements such as:power conditioning units,thruster clustering and control,plume control and emi considerations. Propellant tankage and control also need attention. The primary problem remains to identify the kind of thrusters for the D-MNSP&PS and to proceed with development for test and use.

c. Waste Heat Rejection Subsystems

Primary heat rejection radiators for D-MNSP&PS have large areas and temperatures around 1000 K;and often need to be deployed and provided with meteoroid protection. Advanced developments with new materials and working fluids have been made in recent years,but more work is needed. Mission specific radiators need to be designed,developed and tested. A number of auxiliary waste heat sources are found throughout the system and the vehicle but they are generally of lower temperature and can be dealt with locally.

d. Control and Safety Subsystems

The problems of control and safety are unusually severe because the D-MNSPS&PS is a very complex system and must be controlled over a wide range; in fact it is not altogether clear how it can be controlled and made safe. Much analysis and testing is needed to begin to answer these questions.

3. System Disposal Concepts

Work has been in progress for a number of years on the disposal of nuclear power sources in outer space by the United Nations Scientific and Technology Subcommittee and others. I has been generally concluded that they can be safely operated and disposed of if careful provisions are made and carried out responsibly. It is the United States position that nuclear reactors should not be started below altitudes with orbital lifetimes sufficiently long for radioactive species to have effectively decayed. D-MNSP&PS must have provisions for deployment to remote orbits where collision with orbital objects is nil and orbital lifetime is infinite.

IV. POSSIBLE 21st CENTURY DUAL-MODE MISSION APPLICATIONS

Generic Missions of the early years of the 21st century can make excellent use of the D-MNSP&PS vehicles and in a few years they become essential as the space program of the period evolves. The Table presented below shows missions of the 2000 to 2020 period where use of the Dual-Mode System should be evaluated; it should be understood that both the D-M and the missions will be evolved substantially in the course of the period.

TABLE

Possible Early 21st Century Dual-Mode Mission Applications

Geo-centric Operations
- Nuclear Operational Station
- Cargo Operations in Earth Orbits

Cis-Lunar Missions
- Unmanned and Manned Lunar Shuttles

Lunar Exploitation
- Lunar Resources
- Lunar Bases
- Lunar Observatory

Helio-centric Missions
- Asteroids and Minor Bodies
  = Unmanned Exploration
  = Manned Exploration
  = Manned Exploitation

- Martian Missions
  - = Unmanned Round Trips
  - = Manned Expeditions
  - = Martian Bases

- Other Solar System Missions
  - = Outer Planet and Moons Orbiters and Landers
  - = Outer Planet Moons Explorers
  - = Outer Planet Round Trips
  - = Trans-Neptune Explorers

All D-MNSP&PS vehicles will depart from and return to a geo-centric operational station at an altitude that has an orbital lifetime of more than 300 years. This transport node will have an inclination that facilitates the nuclear vehicles that it will service.

It is anticipated that D-MNSP&PS vehicles will operate in cis-lunar space for training purposes with cargos of opportunity.

The first major dual-mode missions will probably consist of unmanned and manned asteroid explorations. Such missions could be of consequence for some period of time.

Martian missions will probably be carried out on a global basis with a very ambitious scenario that utilizes a wide variety of chemical and nuclear propulsion.

Other solar system and galactic missions will follow after the first two decades and will make maximum use of the power and propulsion technology that has been brought into being.