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A BIMODAL SPACECRAFT BUS BASED ON A CERMET FUELED HEAT PIPE REACTOR

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Abstract

Bimodal space reactor systems provide both thermal propulsion for the spacecraft orbital transfer and electrical power to the spacecraft bus once it is on station. These systems have the potential to increase both the available payload in high energy orbits and the available power to that payload. These increased mass and power capabilities can be used to either reduce mission cost by permitting the use of smaller launch vehicles or to provide increased mission performance from the current launch vehicle. A major barrier to the deployment of these bimodal systems has been the cost associated with their development. This paper describes a bimodal spacecraft bus with performance potential to permit more than 70% of the instrumented payload of the Titan IV/Centaur to be launched from the Atlas IIAS. The development cost is minimized by basing the design on existing component technologies.

Introduction

The concept of using a single space reactor to produce both direct thermal propulsion and spacecraft electric power has been studied for some time. More than twenty years ago, the Rover/NERVA program recognized the potential benefits of such a system (Koenig, 1986) and studied modifying their basic propulsion reactor design to accommodate electric power

generation. More recent studies within the Air Force Phillips Laboratory have illustrated the value of these bimodal reactor systems for missions of military interest (Kennedy and Vanek, 1994) and quantified the necessary system performance for such systems to be attractive over existing technologies (Kennedy and Jacox, 1995).

Based on these recent studies, the Phillips Laboratory and the Department of Energy's Office of Nuclear Energy have cooperated in developing bimodal bus designs to meet an initial set of performance requirements. This paper describes the results of one of those design efforts. The principal elements of a nuclear bimodal engine are the reactor core, radiation shield, power conversion and heat rejection system, and the propulsion system hardware. The reactor core of the current design draws heavily on the cermet fuel technology and propulsion system development that took place during the period of 1962 to 1968. A good overview of the cermet development program is given by Kruger (1990). Refractory metal cermet fuel, primarily based on UO_2 fuel encased in tungsten and tungsten-rhenium alloys, received extensive development for space power, space thermal propulsion, and aircraft nuclear propulsion applications. The current design employs a fuel element of similar design and dimensions to that proposed in the cermet propulsion system development.

The current bimodal system design employs liquid metal heat pipes for both energy transport from the reactor fuel to the energy conversion system and for the distribution of waste heat from the energy conversion to the radiator. Liquid metal heat pipes have been studied extensively

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for space applications and characterized both as to their performance (Merrigan, 1986) and lifetime (Lundberg, 1987). Although the current reactor system design is compatible with a variety of power conversion techniques, the baseline design employs conductively coupled multicouple thermoelectric devices based on the performance levels demonstrated in the SP-100 technology development program (Mondt, et al., 1994).

The use of hydrogen propellant for the orbital transfer is ideal in terms of providing the maximum specific impulse, but provides special challenges when integrating bimodal systems into existing launch vehicles. As the density of liquid hydrogen is very low (~ 70 kg/m³), a large propellant volume is required and consequently, there is insufficient volume available in most existing payload fairings. In most cases, the practical use of these bimodal systems requires that the payload fairings be lengthened, increased in diameter, or a combination of both. This type of modification raises a number of potential issues regarding launch vehicle limitations and the costs associated with both the launch vehicle and supporting facility modifications. These issues are discussed in more detail in the section on system integration.

The Bimodal Engine

The design of a bimodal engine presents several challenges. A single reactor must be designed to operate at two very different sets of conditions between the power mode and propulsion mode and to perform significantly different functions in each mode. The system must be highly reliable and have a long lifetime. The engine must include the hardware for power conversion and heat rejection, as well as that associated with propulsion operation, and the total engine mass must be as low as possible. It is also desirable to minimize dependence on active safety features in the reactor system design. In the power mode, the present system design produces 10 kW of electric power for a 10-year lifetime. In the propulsion mode, the system produces 2200 N of thrust with a specific impulse of 825 s. The total engine mass, which includes the reactor, power conversion and heat rejection system, power conditioning and battery, and the associated propulsion hardware, is estimated to be 1410 kg.

Reactor Core Description

The primary building blocks of the reactor core are cermet fuel elements and finned heat pipes. The fuel elements are nine-sided blocks, roughly triangular in shape, with 52 axial propellant channels as shown in Figure 1. The cermet blocks consists of 59.5% by volume UO₂ and 40.5% W. A thin cladding (74% W and 26% Re) is applied to the outside of the fuel element and the inside of each propellant channel. The fuel enrichment is 93% and all materials are assumed at 95% theoretical density.

The heat pipes provide energy transport from the reactor fuel to the power conversion system. The baseline design uses molybdenum as the heat pipe material and sodium as the working fluid. This combination has been tested for more than five years of life at 1400 K with significant

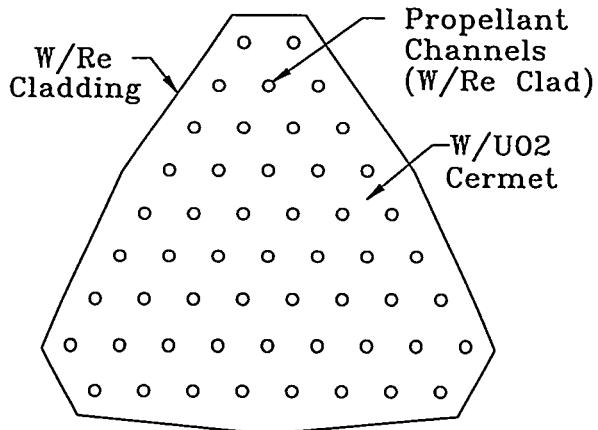


FIGURE 1 - CROSS-SECTIONAL VIEW OF CERMET FUEL ELEMENT.

heat fluxes (Lundberg, 1987). Arteries are employed to improve the performance of the heat pipe in the current design. The heat pipes also serve as the primary structural members in the core, serving a similar function to the "tie-tubes" of the Rover/NERVA design (Koenig, 1986). Each heat pipe has six fins and six propellant channels, as illustrated in Figure 2. A small gap is maintained between the fuel elements and the heat pipes such that the primary energy transfer between the fuel elements and the heat pipes occurs by thermal radiation. The fins on the heat pipes serve to enhance radiant heat transfer and maintain fuel temperatures at acceptable levels during power mode operation.

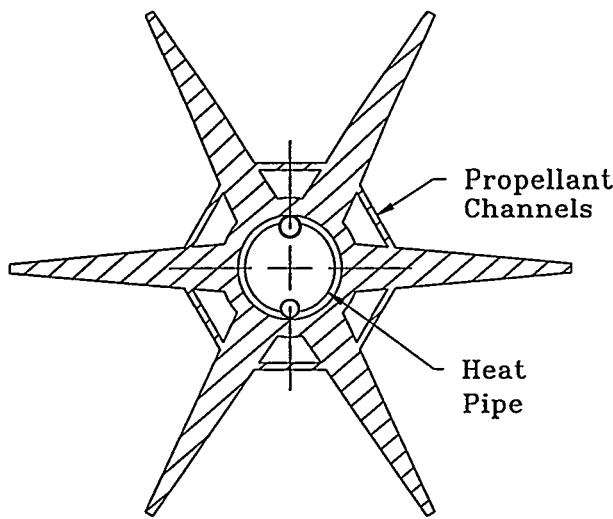


FIGURE 2 - CROSS-SECTIONAL VIEW OF HEAT PIPE ASSEMBLY.

The propellant channels are employed to cool the heat pipes during propulsion mode operation. After cooling the nozzle, reactor vessel, and other reactor components, the hydrogen propellant enters the plenum at the top of the reactor and flows down three of the channels in the heat pipe. The propellant turns around at the bottom of the heat pipe and flows up the other three channels before entering the second plenum where it is directed into the cermet fuel elements. The primary heating of the propellant occurs in the single pass through the cermet fuel elements; it is then expanded through a single nozzle to produce thrust. Although the hydrogen cooling is necessary to protect the heat pipes in propulsion mode, it does cause potential concerns as the hydrogen will permeate into the heat pipe during propulsion operation and could block the condenser section or affect artery priming. The baseline heat pipe design has been selected to minimize hydrogen sensitivity. In addition, methods to minimize the permeation of hydrogen into the heat pipe have been identified and are under evaluation.

The heat pipes are arranged on a triangular pitch with the fuel elements in the space in between to form the reactor core as shown in the radial cross section in Figure 3. The reactor vessel is made of stainless steel, 2 mm thick, and regeneratively cooled. The reactor core is separated from the vessel by a 1-mm-thick region that contains multifoil insulation to reduce the

vessel temperature in the power mode. Outside the reactor vessel are the beryllium radial reflector and control drums. The control drums are not illustrated in the figure, but 12 rotating drums with poison segments are utilized. An axial cross section of the reactor is shown in Figure 4. In this view, the plenums that supply the hydrogen propellant to the heat pipes and cermet fuel elements as well as the nozzle are illustrated. The current design employs an integrated beryllium oxide axial reflector on the cold end of the fuel element, similar to the design of the cermet propulsion program.

The reactor core design has been analyzed extensively in order to verify the feasibility of the system. The analysis has included nuclear analysis, structural analysis, thermal analysis, and thermal hydraulic analysis. The nuclear analysis is based on a highly detailed core model and has been used to verify the basic criticality of

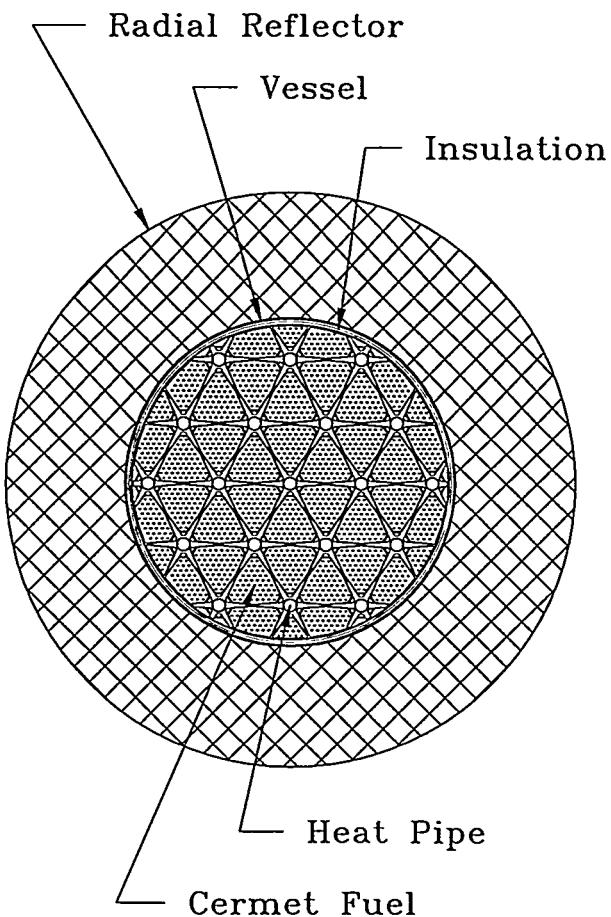


FIGURE 3 - RADIAL CROSS SECTION OF BIMODAL REACTOR SYSTEM.

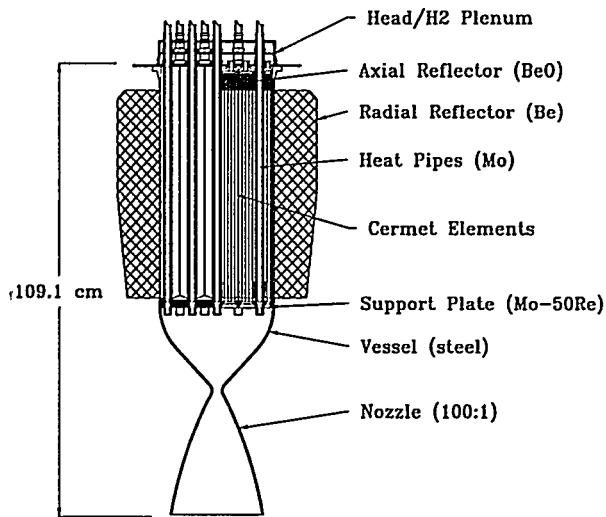


FIGURE 4 - LONGITUDINAL CROSS SECTION OF THE BIMODAL REACTOR SYSTEM.

the system as well as many other factors. These factors include the effectiveness of the control drums, the effect of fuel burnup, the reactor temperature coefficient, the effect of the hydrogen propellant on system reactivity, and behavior of the system on water immersion. The nuclear analysis also provided detailed power distributions within the fuel and quantified nuclear heating rates on key reactor components to support the thermal analysis. The radiation shield has not been designed in detail, but sufficient analysis was performed to quantify the effect of routing the reactor heat pipes around the shield and to permit a good estimate of the shield mass to be developed.

Structural analysis was performed to verify the ability of the primary reactor core to withstand launch loads and to determine the thermal stresses during the different operating modes. A thermal analysis was performed to verify the system performance in the power mode both for normal operation and the case of a single failed heat pipe. An extensive thermal hydraulic analysis of the reactor system was performed to quantify the propulsion mode performance. This propulsion mode analysis proved highly challenging because of the strong three-dimensional character of the heat transfer in the core that results from the regenerative cooling of the heat pipes.

Power Conversion and Heat Rejection

The ability of thermoelectric power conversion to provide reliable power in space for a long period has been demonstrated in the Radioisotope Thermoelectric Generator (RTG) program. Deep-space missions such as Voyager and Galileo have employed RTG systems based on radiatively coupled unicouple thermoelectric devices that have operated up to 18 years, far beyond their original design goal (Schock, 1994). These same unicouple devices were initially considered for the bimodal system but did not have sufficient performance to satisfy the mission requirements at the 10-kW electric power level. The SP-100 program made significant progress in increasing the performance of thermoelectric power conversion (Mondt, et al., 1994). Most of the performance improvement resulted from reducing temperature drops not associated with power conversion by conductively coupling the devices and increasing power density through the multicell design (England and Ewell, 1994). The SP-100 conductively coupled multicouple was selected as the baseline power conversion device for the bimodal system.

In the bimodal system, sodium heat pipes transfer the energy from the reactor core to the power conversion system at 1375 K. The power conversion system occurs in the conductively coupled multicouple thermoelectric devices placed on four sides of the sodium heat pipe. Potassium heat pipes on the back side of the thermoelectric devices distribute the waste heat to the radiator, which rejects the heat to space at 680 K. A cross section of this arrangement is shown in Figure 5. Figure 6 illustrates an outside view of the power conversion module. Note that the energy conversion modules form a very compact arrangement less than 25 cm in length. Figure 7 shows an overall view of the reactor system, shield, power conversion, and heat rejection system.

Based on the hot and cold side temperatures of the current design and performance levels demonstrated in the SP-100 program, the overall system efficiency is estimated to be 5.25% at end of life. Therefore, a thermal power level of 191 kW is required to produce the 10-kW electric output. The maximum fuel temperature for the power mode operation has been determined to

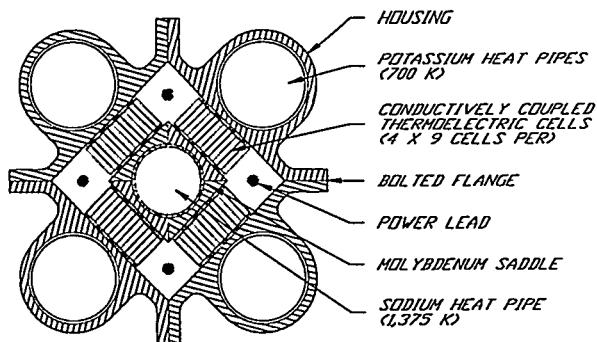


FIGURE 5 - CROSS-SECTIONAL VIEW OF THE POWER CONVERSION MODULE ARRANGEMENT.

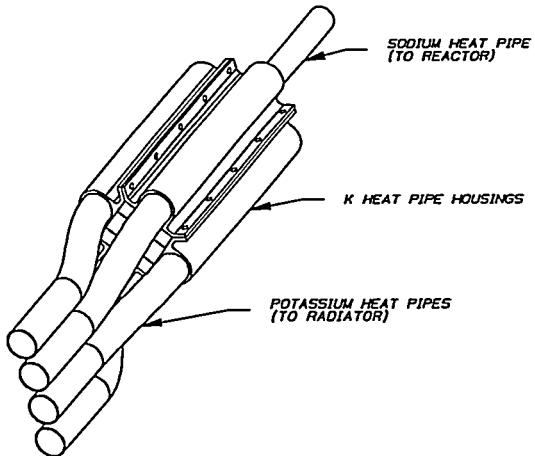


FIGURE 6 - AN OUTSIDE VIEW OF THE POWER CONVERSION MODULE.

be well within the acceptable range for the fuel form and the expected burnup. The fuel elements were also analyzed for thermal stress during the power mode operation, and the maximum stress value was also determined to be acceptable. One potential advantage of heat pipe energy transport is that redundancy is provided in the case of a single heat pipe failure. This case has also been analyzed and the maximum fuel temperature increased by 50 K. While the increase in maximum fuel temperature reduces the design margin, it should still be acceptable for long-term operation.

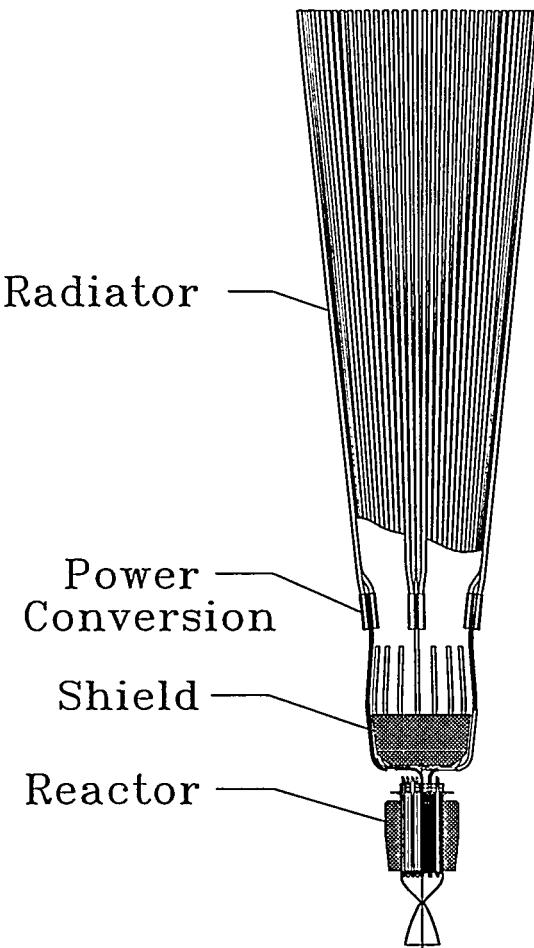


FIGURE 7 - OVERALL VIEW OF BIMODAL ENGINE SYSTEM. PART OF THE RADIATOR AND POWER SYSTEM ARE CUT AWAY TO BETTER SHOW THE POWER CONVERSION SYSTEM DETAILS.

Propulsion Mode Operation

In the propulsion mode, the reactor core operates at a thermal power level of 10.5 MW. Hydrogen propellant is delivered from the turbopump at approximately 80 K and is used to cool several external reactor components, including the nozzle, the reactor vessel, the shield, and the radial reflector and control drum assembly. During the cooling of these external components, the hydrogen temperature increases approximately 170 K. The propellant then enters the reactor plenum and performs the two-pass regenerative cooling of the core heat pipes, increasing in temperature to approximately 1000 K. This propellant is then used to drive the turbopump in an expander cycle. A number of

arrangements of the propellant flow for cooling the external components of the reactor are possible, and extensive engine cycle analysis has been performed for various configurations of the propulsion mode operation of this bimodal engine. In all cases the power available to drive the turbopump was more than adequate so many options can be considered in the final design.

After exiting the turbopump, the propellant returns to the reactor and flows through the cermet fuel elements. It is here that the primary heating of the propellant occurs, increasing in temperature to over 2500 K. The propellant then expands through a regeneratively cooled nozzle with an expansion ratio of 100:1. The engine produces a moderate thrust of 2200 N and a specific impulse, including the effects of finite expansion and the regenerative cooling of the nozzle, of 825 s. Thermal hydraulic analysis has shown that the peak propulsion mode fuel temperature is well below the limits normally associated with the cermet fuel. Propulsion mode stress analysis has determined the maximum stress in the fuel to be acceptable.

Although the moderate thrust level of the current bimodal concept is adequate to deliver payloads from low Earth orbit to geosynchronous orbit in reasonable time periods, a relatively large gravity loss (~20%) is associated with performing this maneuver in a single burn. This loss term can be reduced by performing multiple burns around the apogee and perigee of the orbit. For payload masses in the current range of interest, using a total of 17 burns to perform the geosynchronous orbit transfer can reduce this loss term to less than 1%. Total transfer time remains less than two days. As the thermal cycling behavior of the cermet fuel has been demonstrated to a far greater number of cycles, the multiple burn approach is baselined in all performance calculations.

Safety

A number of safety issues must be addressed in the potential application of a space reactor system. Most of these issues are very dependent on the specifics of the proposed mission and are difficult to analyze in general. However, experience has shown that one particular issue, the potential for the reactor to achieve criticality under conditions of water immersion and flooding, is a generic concern to all space reactor systems.

Experience has also shown that, in systems where water immersion causes a criticality concern, there may be no simple solutions to the problem without significantly modifying the reactor design. Therefore, in the design of the present bimodal system, the judicious selection of reactor core materials and a strong effort to minimize the void within the reactor, resulted in a design that gives passive safety on water immersion and flooding. It is not anticipated that any engineered safety features would be required to address the issue in the current design.

Mission Performance

Comparing the performance of a bimodal power and propulsion system to the conventional approach of an upper stage and separate spacecraft power system is not straightforward. In the current approach, an upper stage transfers the payload from low Earth orbit to the operational orbit and separates. In the bimodal approach, the bimodal bus performs the same orbital transfer but then remains as a part of the spacecraft to provide power and other functions. Therefore, the conventional definition of payload as that mass delivered to the operational orbit is not appropriate. For bimodal systems it is more appropriate to use instrumented payload, defined as the mass of those spacecraft systems not functionally replaced by the bimodal bus, to compare performance with conventional systems.

Another challenge in determining the performance of bimodal systems is that the use of hydrogen as the propellant implies a large propellant volume. Consequently, the performance of bimodal systems on most launch vehicles is limited by launch vehicle fairing volume and not by launch vehicle throw weight. Estimating the performance of these volume limited systems requires significant effort as the bimodal bus and payload integration must be studied in some detail. In addition, the performance goals of the current design effort can only be achieved by increasing the payload volume of the launch vehicle by increasing fairing length, diameter, or a combination of both. These modifications raise additional questions concerning the impacts on the launch vehicle and associated infrastructure. Additional issues associated with nuclear bimodal stage integration are discussed in the following section.

One method of characterizing the performance of the bimodal systems is to consider generic payloads with different payload densities. A number of different operational systems were examined and most payloads were found to fall within the range of 60 to 90 kg/m³. The Atlas IIAS launch vehicle performance to geosynchronous orbit was then calculated for the range of payload densities and a range of length extensions of the payload fairing. In this analysis, an external tank configuration is assumed, where the payload fairing is eliminated over the propellant tank and the propellant tank outer diameter is the same as the original fairing outer diameter. In this configuration a short nose fairing covers the payload portion during ascent.

Figure 8 shows the predicted payload performance of the Atlas IIAS system with the bimodal bus. The performance goal of 70% of the Titan IV payload is included for reference. The fairing length of 9.5 m corresponds to the existing payload fairing. The performance goal is not achieved at any of the payload volumes considered for this fairing. With a 1-m fairing extension, the 90-kg/m³ payload density just exceeds the performance goal, and with a 2-m extension, the performance goal is achieved or exceeded for all payload densities. A payload fairing extension of 1 m is currently in the planned Atlas evolution (Huber, 1994), and a fairing extension of 2 m is believed to be feasible for the current Atlas IIAS configuration.

System Integration

Although the generic payload studies of the previous section provide significant insights into the potential performance of a bimodal spacecraft, the volume limited nature of these systems requires that the integration issues be studied in more detail. In these detailed studies, a number of configuration drivers must be considered. These include:

1. Launch vehicle fairing envelopes and center of gravity limits for the long, bulky bimodal spacecraft systems.
2. Large propellant tanks that must serve as a pressure vessel to contain the liquid hydrogen and provide a link in the overall spacecraft load path.
3. An extendable boom that must be employed to separate the reactor from the spacecraft bus in order to reduce the radiation dose to acceptable levels. It must also provide adequate stiffness for spacecraft attitude control.
4. The nuclear engine length, including the radiator and stowed boom, that must be minimized to provide adequate payload volume.
5. An efficient load path joining the engine, tankage, and equipment structure that must be provided and joined to the launch vehicle through a suitable adapter and separation system.

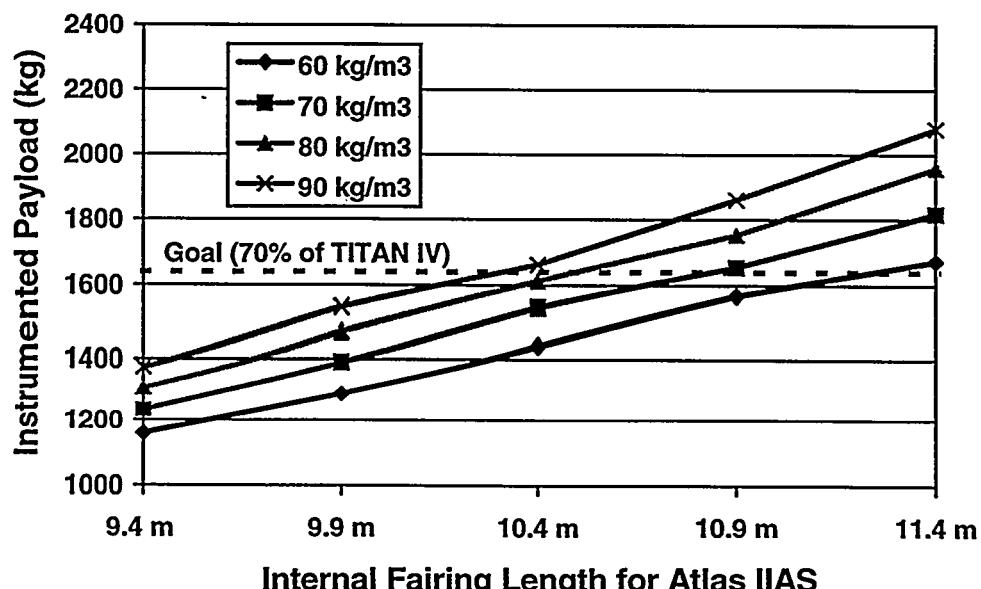


FIGURE 8 - PREDICTED PAYLOAD PERFORMANCE OF THE ATLAS IIAS LAUNCH VEHICLE AND NUCLEAR BIMODAL POWER AND PROPULSION SYSTEM TO GEOSYNCHRONOUS ORBIT.

6. The system weight that must be controlled to meet launch vehicle capabilities and payload mass requirements.

A point design has been examined for the Atlas IIAS launch vehicle with a 2.1-m payload fairing extension. The bimodal power and propulsion system, as described in this report, is used with a deployable boom to give a 15-m separation of the reactor from the payload. The external tank configuration, described in the previous section, is baselined in this analysis. The payload is considered to be a generic geostationary Earth observing satellite.

The launch configuration for this spacecraft is illustrated in Figure 9. The bimodal engine and boom are stowed in the forward section of the fairing and attached to the propellant tank forward skirt. The tank has a capacity of 3600 kg of liquid hydrogen, and provides space for 5 cm of insulation. The nose fairing is shown attached to the tank forward extension. The radiator panels are stowed outward, approximately 10 degrees from their operational position, to accommodate additional propellant. The bus and payload modules, with a total volume of 17.7 m³, are shown between the propellant tank and the launch vehicle adapter. This payload volume should be adequate for missions with compact payloads. This volume could be increased by adding additional length, diameter, or both to the payload fairing, although serious issues must be addressed regarding the launch vehicle and associated infrastructure impacts.

The orbital configuration for this bimodal spacecraft is illustrated in Figure 10. The ammonia arcjet thrusters provide orbital control and are located at the center of gravity of the orbital configuration. The satellite is shown in an Earth pointing configuration, characteristic of an environmental sensing or observation mission. A sensor cooler is illustrated pointing south, although in this type of mission it would be rotated seasonally (north or south) to position the cooler shade away from the sun. The bimodal spacecraft bus is suitable for a wide variety of missions in high orbits as the orientation of the spacecraft is virtually unrestricted. In lower orbits the gravity gradient effects on attitude control must be considered in selecting the orientation.

Conclusions

Bimodal space reactor power and propulsion systems have the potential to dramatically increase the available payload in high energy orbits and the available power to that payload. A bimodal engine design has been proposed that leverages the technology development effort of previous space reactor programs and possesses a potential performance that would be attractive for a variety of space missions. Important questions concerning the impact of payload fairing extensions remain and need to be resolved in future design efforts.

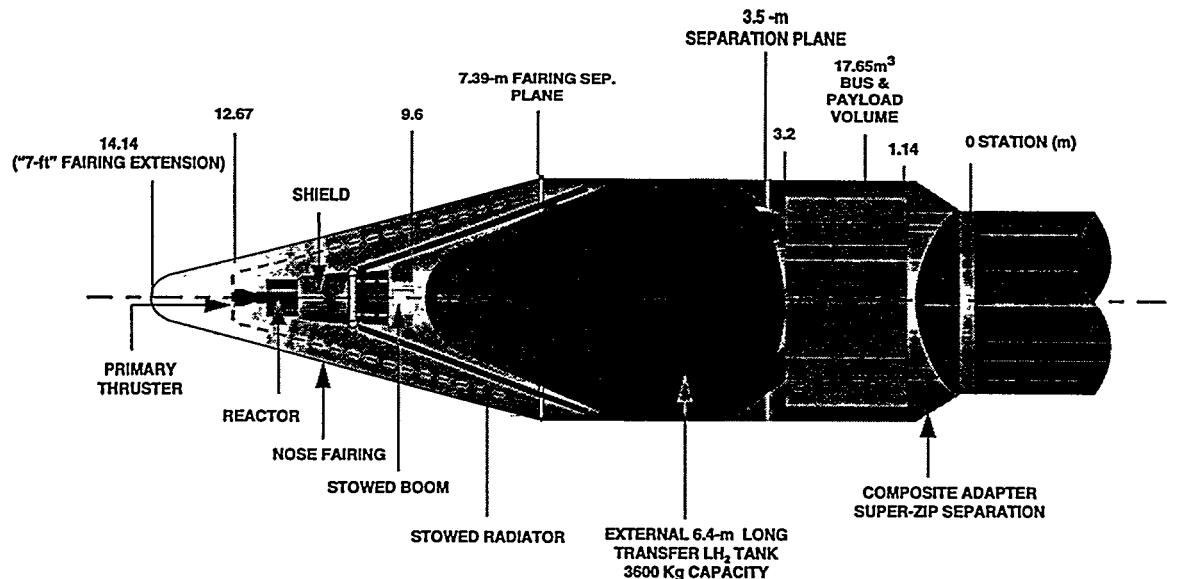


FIGURE 9 - BIMODAL SPACECRAFT LAUNCH CONFIGURATION FOR ATLAS IIAS.

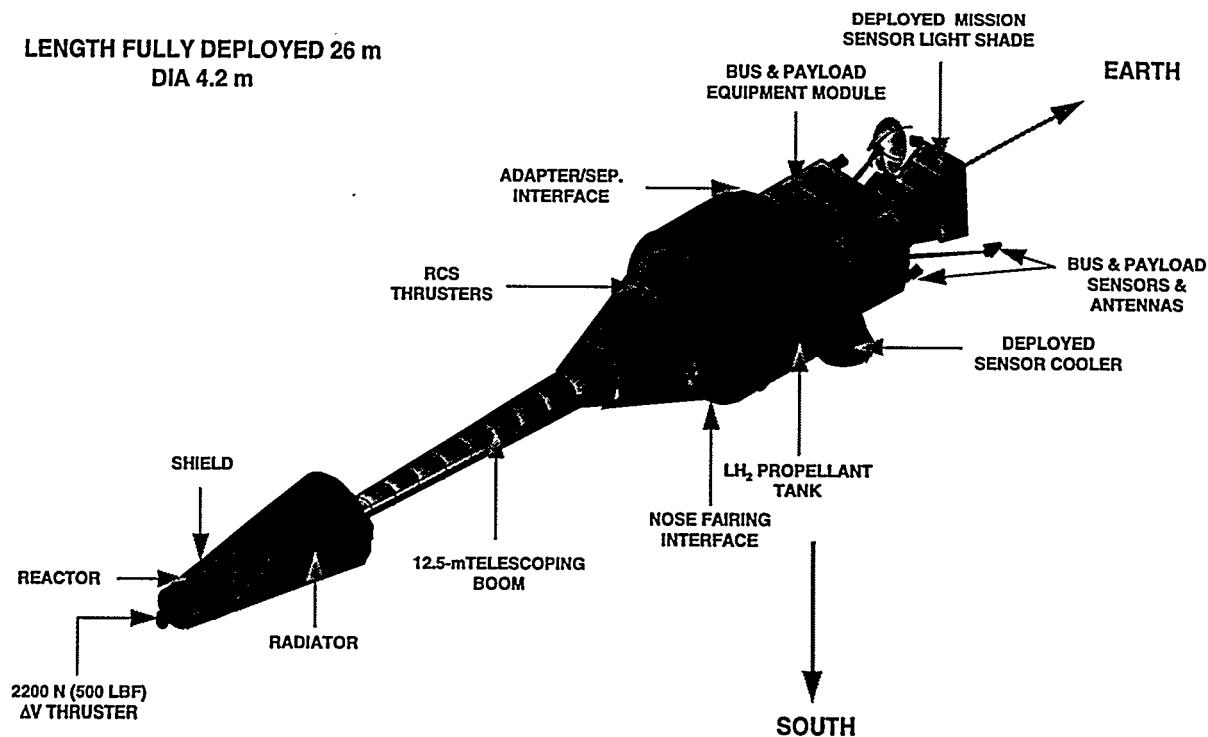


FIGURE 10 - BIMODAL SPACECRAFT ORBITAL CONFIGURATION.

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