NUCLEAR-POWERED SATELLITE STUDIES

FINAL REPORT

for the Period October 1, 1978 - March 31, 1980

MASTER

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ABSTRACT

Progress achieved during the period October 1, 1978 to March 31, 1980, on U.S. D.O.E. Contract No. DE-AC02-76ET 33013.M003 is reported. Discussions of several pertinent aspects are included, e.g., schedule, personnel, and technology developments. The reporting period represents the final 18 months of activities of a project which was designed to provide continuing support in the area of nuclear space power technology. Important results have been obtained and communicated to the scientific community via publications and presentations. Project personnel have participated in point design efforts, a NASA Space Power Committee, and periodically provided support to Department of Energy activities as the need arose. This final report is intended to summarize activities over the life of the project.

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1.0 INTRODUCTION

1.1 Summary of Progress

The then U.S. Energy Research and Development Administration awarded The Pennsylvania State University Contract No. EY-76-S-02-4045.*000 on July 1, 1976. This took the form of a special research support agreement which was conducted under the guidance of the Advance Systems and Materials Production Division of the U.S. Department of Energy. The project emphasis has been on nuclear powered satellite technology and applications. Activities have been established such that continuing support of the Space Applications activity within the Department of Energy has been provided while related new technologies were pursued. Contract work was completed under contract No. DE-AC02-76ET33013.M003.

During the first year of work some time was spent in part establishing task assignments and locating personnel to staff the project. A variety of activities were identified in order to fulfill project objectives and provide real time support to the Space Applications team. Contacts in industry and government were established for continued interaction throughout the project tenure. Many presentations were made to potential users of nuclear power supplies and project staff participated in design reviews and other related briefings as the occasions arose. The technical basis of this project was the development of tools and inputs to be used in evaluating applications of nuclear power to satellites. Considerations included new constraints of the Space Transportation System, projected missions through the 1990's, and technology advances in nuclear power supplies.

Communication of ideas and developments is a key factor in any research project, but it was particularly important here. The principal investigator continually interacted with industry and government agencies in order to

maintain a liaison with as many interested parties as was practical. New developments were documented and presented to the scientific community in a timely manner. During the five years of this project several publications have been generated. A number of presentations have been made at technical conferences. Spacecraft designers, NASA, and users have been the audiences. In-house briefings have also been conducted at user and contractor facilities. A number of areas of technology development have been addressed. These include a comprehensive simulation and computation capability, design aspects of nuclear powered synchronous satellites and orbit transfer vehicles, structural analysis of spacecraft elements (e.g., radiator, heat source, assembly, etc.), orbital decay of spacecraft, reentry dynamics of isotope heat sources, attitude control of dynamic isotope powered spacecraft, reactor power station design aspects, and transfer vehicles for nuclear waste disposal.

1.2 Major Results

Although details of technical developments are left for section 4 and the appendices, major results are summarized here. A comprehensive computer capability has been established within the Astronautics Research Laboratory. The three input/output terminals and an interactive graphics plotter have permitted the development of an extensive array of project-related software, including a general purpose attitude dynamics simulation, structural and thermal analysis during reentry, and orbit raising and decay simulations. A preliminary design of a nuclear powered communications satellite was developed to satisfy projected requirements of INTELSAT in the 1980's, the results of which appeared in the Journal of Spacecraft and Rockets. A nuclear/electric orbit transfer vehicle has been conceived and results were presented to NASA as an alternative to the payload limited IUS. This work

was presented at the 14th International Electric Propulsion Conference, Princeton, October 1979. This appears in Appendix B. A unique capability exists here to simulate orbital decay and attitude motion simultaneously. We have done this for Skylab and the General Purpose Heat Source (GPHS). This technology can be applied to any spacecraft or component of a satellite. Another nuclear/electric transfer vehicle was conceived for nuclear waste disposal. The results are to be presented at the 15th International Electric Propulsion Conference in April 1981. Appendix C contains this paper.

2.0 SCHEDULE AND PERSONNEL

A milestone chart was used to periodically summarize activities and plans. Of course, such a chart can only estimate the timing and extent of any given task. Details are left for later sections of this report.

Since the beginning of this project staffing has fluctuated in size and talents. Both personnel and assignments have changed during the years. However, appropriate adjustments were made in order to fulfill primary contract objectives. Figure 2-1 shows the organization chart used during the final 18 months of activities. Faculty participants included Dr. M. H. Kaplan, the principal investigator, who devoted 40-50 percent of his time, on the average, since the beginning of the project. Dr. Kaplan was responsible for the budget, schedule, and presentations. This is in addition to the technical responsibilities related to spacecraft design and mission analysis. He received the 1978 Award for Outstanding Achievement in Research in the College of Engineering of the Pennsylvania State University. In December 1978, his new book, Space Shuttle: America's Wings to the Future, was released by AERO Publishers. Dr. Kaplan is a Professor of Aerospace Engineering and Director of the Astronautics Research Laboratory. Dr. James C. Wambold, Associate Professor of Mechanical Engineering, guided the development of the structural and thermal analysis software for our reentry studies. He spent 10 percent of his time on this project and advising one of the graduate students. Stephen G. Alexander was a Senior Research Technologies and is now with the Martin Company. Mr. Alexander worked full-time on this project until receiving his Master of Science degree and was responsible for overseeing computer facility operation, orbital decay

Figure 2-1. Organization Chart

programs, and simulation software. Mr. Lin-Shu Yang worked on a half-time basis to develop stress and thermal analysis models of nuclear satellite components. Mr. R. M. Trn, Mr. E. F. Rutkowski, and Mr. R. M. Fredo were graduate assistants working half-time on the project. All three have completed Masters degrees. Occasionally, undergraduates assisted with a variety of support tasks while working on senior theses.

3.0 LIAISON ACTIVITIES

3.1 Presentations

A number of relevant presentations have been made over the past five years by the research team. For example, presentations were given at General Electric and Fairchild Industries on nuclear space power as part of a systems engineering course during the fall of 1977. Other presentations have been made at industrial facilities while a number of radio and television interviews have been aired. Furthermore, the principal investigator presented several papers dealing with the use of nuclear power supplies and related technology. One of these was given at the Seventh AIAA Communications Satellite Systems Conference, San Diego, April 24-27, 1978, entitled "A Nuclear Powered Communications Satellite for the 1980's." This was published in the July-August 1979 issue of the Journal of Spacecraft and Rockets. A paper was presented at the Tenth AIAA/IES/ASTM Space Simulation Conference on orbital decay of Skylab, in October 1978. This was published in the November-December 1979 issue of the Journal of Guidance and Control.

3.2 Publications

Several publications have been generated since the project began. Articles, papers, and reports relevant to this work are listed below.

1. M. H. Kaplan, "Nuclear Powered Satellite Design for Shuttle Launches," AIAA Preprint 77-508, St. Louis, March 1-3, 1977.
2. M. H. Kaplan, "Isotope Powered Satellites for Shuttle Launches," AIAA Journal of Spacecraft and Rockets, Vol. 14, No. 11, November 1977, pp. 703-704.
3. M. H. Kaplan, "Space Nuclear Power Supply Design in the Shuttle Era," Proc. of the 12th IECEC, Washington, D.C., August 28-September 2, 1977, pp. 1323-1328.

4. M. H. Kaplan, D. J. Cwynar, and J. J. Bednarz, "A Nuclear Powered Communications Satellite for the 1980's," Proc. of the AIAA 7th Communications Satellite Systems Conference, San Diego, April 24-27, 1978, pp. 655-659.
5. M. H. Kaplan, D. J. Cwynar, and S. G. Alexander, "Anticipated Attitude Motion of Skylab for a 1979 Revisit Mission," Journal of Spacecraft and Rockets, July/August, 1978, pp. 219-223.
6. M. H. Kaplan, D. J. Cwynar, and S. G. Alexander, "Simulation of Skylab Orbit Decay and Attitude Dynamics," AIAA Paper 78-1626, presented at the 10th AIAA/IES/ASTM Space Simulation Conference, October 1978.
7. -----, "A Life Cycle Cost Comparison for an Operational Seasat Mission Using Nuclear and Solar Power Supplies," ECON, Inc. Report 78-292, November 7, 1978.
8. M. H. Kaplan and S. G. Alexander, "Skylab Orbit Decay Update and the Eleventh Hour Contingency Plan," AAS Paper 79-032, presented at the AAS Rocky Mountain Guidance and Control Conference, February 1979.
9. M. H. Kaplan, D. J. Cwynar, and J. J. Bednarz, "A Nuclear Powered Communications Satellite for the 1980's," Journal of Spacecraft and Rockets, July-August 1979, pp. 268-272.
10. M. H. Kaplan, D. J. Cwynar, and S. G. Alexander, "Simulation of Skylab Orbit Decay and Attitude Dynamics," Journal of Guidance and Control, November-December 1979, pp. 511-516.
11. M. H. Kaplan, R. M. Trn, and D. Buden, "A Nuclear/Electric Orbital Transfer Vehicle for the Shuttle Era," AIAA Paper 79-2109 presented at the AIAA/DGLR 14th International Electric Propulsion Conference, October 30-November 1, 1979, Princeton, N. J.
12. E. F. Rutkowski and M. H. Kaplan, "A Nuclear-Electric Transfer Mission for Nuclear Waste Disposal," AIAA Paper 81-0706, presented at the AIAA/JSASS/DGLR 15th International Electric Propulsion Conference, April 20-22, 1981, Las Vegas, Nev.

A number of student reports and theses have also been completed.

Master of Science Theses

D. J. Cwynar, "An Automatic Attitude Control System for a Dynamic Isotope Powered Satellite," (also appears as P.S.U. Astronautics Research Report No. 78-1) May 1978.

S. G. Alexander, "Simulation of Orbital Decay for Satellite and Components," August 1979.

R. M. Trn, "Design Considerations for the Geosynchronous, Low-Thrust Orbital Transfer Mission," March 1980.

Undergraduate Project Theses

A. Y. Harrison, "Increasing the Output Power of the Brayton Isotope Power System," February 1978.

J. Trivisonno and C. Morgret, "Spacecraft Motion Simulation Using Digital Graphics," February 1978.

M. Hill, "Heat Transfer Analysis of a Rotating Thin-Walled Cylindrical Radiator and Heat Pipe Assembly for Possible Application as a Waste Heat Rejection Unit for a Spacecraft Powerplant," February 1978.

J. Ipoletta and M. Goodson, "Skylab Orbital Decay Projections," February 1978.

A. Muffoletto, "Thermal and Structural Design for GPHS," May 1979.

3.3 Point Design Activities with Government and Industry

The principal investigator and other project staff members had been involved in preliminary evaluations of nuclear power applications to DOD and NASA missions from time to time. Limited interaction with Fairchild Industries on GPS, GPSCS, and SSS took place during the project tenure. Funds left over from GFY 77 were used to initiate work by ECON, Inc., on a future NASA program, COASTSAT. Lockheed carried out a preliminary design effort on both a solar and a dynamic isotope powered version of such a satellite. ECON completed economic comparisons of these designs and issued a final report on November 7, 1978.

The principal investigator has made a number of trips to NASA, DOE, and contractors. For example, he visited the Los Alamos Scientific Lab a number of times to discuss studies related to General Purpose Heat Source reentry into the Earth's atmosphere and applications of nuclear reactors in the 1980's. Of course, visits have been made to the DOE offices in Germantown, Maryland.

The principal investigator was asked in 1978 to join the Ad Hoc Advisory Subcommittee on Power Technology for Future Synchronous Satellites and Platforms of the NASA Advisory Council, Space Systems and Technology Advisory Committee. As part of this activity, a preliminary design of a nuclear/electric orbital transfer vehicle was formulated. A presentation on this was made to this subcommittee on May 2, 1979, by Penn State and LASL (D. Buden). As a result, the nuclear option was included in the official recommendations to the NASA Advisory Council in June 1979.

4.0 TECHNOLOGY DEVELOPMENTS

This chapter is intended to provide summaries of each technology area developed over the past year. Detailed descriptions of analyses and simulations are presented when appropriate in appendices. Several tasks have led to separate publications which have been cited in section 3.2

4.1 Satellite Simulation Software

Many programs have been developed to simulate satellite motion under a variety of conditions. These are briefly presented here.

The Aerodynamic Coefficient Program determines drag, lift and moment coefficients on bodies of any geometry in the free molecular flow regime. For most orbiting bodies, this regime is above 80 miles altitude. The program uses a simplified flow model based on classical free molecular flow theory. Work on determining the aerodynamic force coefficients on a body in hypersonic continuum flow is continuing.

The Orbit Decay Routine uses a discrete orbital energy dissipation technique to simulate the decay of an orbiting body. The idea is that the kinetic energy dissipated due to aerodynamic drag, over a set time increment, is subtracted from the orbit energy to determine a new value of orbit energy. From this new value of energy, a corrected orbit radius can be computed. This procedure is iterated with an appropriate time step to obtain the orbital decay trajectory. Calculation of the aerodynamic drag force involves a predetermined drag coefficient, reference area, and value of local atmospheric density. This local density is computed from the Jacchia (1970) atmosphere model, which accounts for density variations due to altitude, position

(longitude and latitude), solar activity and geomagnetic effects. Actual and future predictions of solar activity data are continually obtained from NASA and NOAA.

The orbit decay routine has been exercised for computing the decay trajectory for the GPHS fuel module, Skylab and Cosmos 954. The routine can be used for any orbiting body whose drag coefficient is available and whose orbit is circular.

The Orbit Simulation Algorithm can accurately predict the motion of an orbiting body in any type of orbit. It can be used for simulating orbital transfers and orbital decay problems. For example, it can accurately predict the path of the GPHS fuel module during the last few orbits of reentry. The routine involves the numerical integration of three differential equations of motion over a specified time increment. Included in the equations are the forces (aerodynamic, solar pressure, engine thrust, etc.) acting on the orbiting body.

In the Attitude Dynamics Routine, the equations of attitude motion are numerically integrated to determine the motion of a rigid body over a specified period. The routine simulates attitude motion for all body geometries, and it handles aerodynamic, gravity gradient and control torques. This routine has been used to simulate attitude motion for Skylab and the GPHS fuel module.

The attitude dynamics routine and the orbital simulation program have been merged to simultaneously simulate attitude and orbital motion of a rigid body. This program has been used extensively for simulating the motion of Skylab.

4.2 GPHS Reentry Stability

The determination of the GPHS module reentry equilibrium orientation is important because of its influence on the aerodynamic heating of the module. The possible orientations of stability can be found through an analysis of the aerodynamic loading (pressure distribution) on the module. Once the pressures on the module have been computed, the relationship between the aerodynamic moments and orientation angle can be made. From this, statically stable orientations can be found (see Appendix A).

Using the reference system in Figure 4-1, if angular motion of the module is about the z-axis, then the module is statically stable at 74° and 106° as diagrammed in Figure 4-2. If motion is about the y-axis, then the module is statically stable at 45° , also shown in Figure 4-2. The results for motion about the x-axis are very similar, because of the module geometry, to the results for the z-axis.

A shift in the module's center of gravity was considered in order to obtain a more favorable position of static stability. From the many shifts considered for motion about the z-axis, the shift most desirable was that of 5 mm in the y-direction. From the moment plot, there are statically stable positions at 66° , 115° and 270° as diagrammed in Figure 4-3. But, the angular position of 270° is much more stable than the other positions. This means that for damped rotation about the z-axis, the module will very often stabilize at 270° or "face-on."

These results depend on the accuracy of the two-dimensional flow field pressure distributions for motion about each axis. Uncoupling the three-dimensional motion of the module into separate rotations about each axis

Figure 4-1. GPHS Module Reference System

Figure 4-2. GPHS Module Static Stability Orientations

Figure 4-3. GPHS Module Static Stability Orientations for Z-axis Motion with C. G. Shift ($\Delta Y = 5.0$ mm)

and analyzing the two-dimensional flow field can only be considered a rough approximation to the actual conditions. Attempting to propose stable orientations for the general case of three-dimensional random angular motion would be unjustified without computing the three-dimensional flow field.

4.3 Early Reactor Mission, Preliminary Design

The need for larger, high power payloads in Geosynchronous Earth Orbit (GEO) initiated the preliminary design of a nuclear/electric orbit-to-orbit transfer vehicle. The proposed vehicle would be taken to low Earth orbit by the NASA Space Shuttle and then work its way to GEO using ion thrusters powered by a nuclear reactor power system. Safety considerations specified that the initial altitude at which the vehicle would begin transfer, must produce a "safe" orbital decay time. The mission then involved an orbital transfer in the form of an ever-widening spiral from the "safe" initial altitude to GEO taking several months to complete.

A major part of the preliminary design study was centered around the selection of a thruster subsystem. The type and number of thrusters used directly influences the amount of payload that can be placed into GEO in a given mission timespan. Choice of a particular thruster subsystem was influenced by Shuttle payload and size constraints and the maximum output of the particular power plant.

Results of this study were put into the form of mission design charts which depict payload ratio as a function of initial vehicle mass and mission time.

4.3.1 Nuclear Reactor Technology

The nuclear power plant components include the reactor, radiation shield, power conditioning equipment and the waste heat radiator. Typical assemblies of these components are shown in Figure 4-4. Current electrical converters have efficiencies ranging from about 12 percent early in their design life to a "steady-state" efficiency of 9 percent. A typical 100 KWe power source must then produce 1110 KWt (thermal).

The particular power plant examined in our study is the Los Alamos TE type with a conical radiator. Data for this power plant is given in Table 4-1. Since the orbital transfer time of the proposed vehicle is a small

Table 4-1. Typical Power Plant

Type: Los Alamos TE type with conical radiator

Lifetime	7 years	
Reactor Power (KWt)	1110	
Specific Mass (We/Kg)	61	
Total System Mass (Kg)	2131	
	<u>Efficiency (%)</u>	<u>Power (KWe)</u>
Life	12	130
-State	9	100

portion of the reactor design life, it can be assumed that the vehicle will have at its disposal a power level corresponding to the early life electrical efficiency (12 percent) throughout the transfer. The vehicle then has about 130 KWe for use by the ion thruster subsystem. The system mass given in Table 4-1 includes the mass of the conical type radiator.

Figure 4-4. Typical Power Plant Assemblies

4.3.2 Ion Engine Technology

An important part of the preliminary design study is the choice of the thruster subsystem. Which and how many thrusters we use influences the amount of payload the vehicle can place into GEO in a given time. Four thrusters were compared on the basis of their performance of the desired mission, LEO to GEO. Performance data of these engines are given in Table 4-2.

Table 4-2. Typical Ion Engine Performance Data

<u>Type</u>	<u>Thrust N</u>	<u>Specific Impulse-sec</u>	<u>Efficiency %</u>	<u>Power Req'd KWe</u>	<u>System Mass Kg</u>
<u>30 cm-diameter HG Bombardment Type Thrusters</u>					
NASA-Lewis	.129	2900	61	3.06	51.36
JPL/Hughes	.370	9000	80	22.68	245.78
NASA-Lewis	.500	9000	80	30.65	325.46
<u>50 cm-diameter HG Bombardment Type Thruster</u>					
Aerospace Corporation	.428	2071	63	7.28	96.34

*Note: All system masses calculated with assumed power processor specific mass of 10 Kg/KWe and electrical efficiency of 90 percent. A fuel tank mass of 12 Kg for each thruster is also included.

The first thruster listed is a typical low thrust, low specific impulse and low efficiency type whose only impressive feature is a low power requirement. The following two thrusters are representative hi-thrust, hi-Isp devices with corresponding high power requirements and system masses. One advantage of hi-Isp thrusters is their inherent low mass flowrate. Also included in the table is a 50 cm-diameter thruster described in a study performed by the Aerospace Corporation. This is a hi-thrust, low-Isp thruster with power and mass characteristics somewhere between that of the previous lo-thrust, lo-Isp and the hi-thrust, hi-Isp 30 cm-diameter devices. The 50 cm-diameter thruster was referred to as a "sized up 30 cm-diameter thruster."

Notice that with a fixed power supply the number of thrusters one can use is limited by their individual power requirements and size. The maximum thrust that is attainable with a given thruster subsystem therefore is also limited.

4.3.3 Mission Constraints/Objectives

Size and Weight Constraints. The vehicle is to be carried to LEO by the Space Shuttle and therefore its maximum size is limited by the dimensions of the Shuttle bay. The maximum length and diameter of the Shuttle bay is 60 ft. and 15 ft., respectively. The maximum weight is a function of the required initial altitude. The Shuttle can deliver 65,000 lbs of payload to 160 nm altitude. Higher initial altitudes require the addition of OMS Kits and thereby reduce the maximum allowable size and weight of the proposed vehicle.

Orbit Considerations. The initial altitude where the vehicle begins transfer to GEO is chosen to give the vehicle a "safe" orbital decay time. For this preliminary study the "safe" decay time was defined as 500 years. Estimates of vehicle size, shape and weight were used to calculate a ballistic coefficient which was then related to the minimum initial altitude for a 500 year lifetime as determined by drag studies (see Appendix B).

4.3.4 Time of Transfer Calculations

What was needed for this study was an easy straightforward approach to calculate the minimum propulsion time for transfer between inclined circular orbits taking into consideration the vehicle mass and available thrust. A closed form solution of the orbital equations of motion was found that was easily programmed and enabled a quantitative evaluation

of the various thruster/power plant combinations. For a specific vehicle powered by "N" number of a given thruster, the time of transfer from the "safe" initial orbit to GEO can be found by:

$$\text{Time of Transfer} = \frac{V_o * \text{Mass}}{N * \text{Thrust}} \sqrt{1 - 2\left(\frac{V_f}{V_o}\right) \cos(\sqrt{2} \text{ Incl}) \left(\frac{V_f}{V_o}\right)^2}$$

where: Thrust/Mass ratio is assumed constant throughout the transfer

V_o is the velocity in the initial orbit

V_f is the velocity in the final orbit (GEO)

Incl is the inclination change (28.5°)

Once the mission time is established the amount of fuel required and payload can be calculated.

4.3.5 Results

Table 4-3 shows the results of a typical analysis. The mission is defined by an initial vehicle mass out of the Shuttle, an initial "safe" altitude, final altitude (GEO) and the inclination change. All such analyses were performed using power and mass characteristics associated with the Los Alamos TE type reactor power system. From the Table, a 10,000 Kg vehicle using 36 NASA-Lewis thrusters can arrive at GEO in 136 days, 16 hours. The payload delivered to GEO is defined by taking the initial vehicle mass and subtracting from it; the mass of the propulsion system, the mass of the fuel and the mass of the power plant.

For comparison the results obtained for one of the hi-thrust, hi-Isp thrusters has been included. Five of these can place a 6022 Kg payload into GEO in 340 days, 14 hours. The results of our study to date have been summarized in the form of mission design charts. These charts (drawn for each thruster studied) give the payload ratio possible at GEO as a function of mission time and initial vehicle mass (see Appendix B).

```

                                DATA
MISSION:  INITIAL VEHICLE MASS  10000 KG
          INITIAL ALTITUDE      875 KM
          FINAL ALTITUDE        GEO
          INCLINATION CHANGE     28.5 DEG
*****
POWER PLANT:  LOS ALAMOS TE TYPE
              OUTPUT POWER 130KWe
              SYSTEM MASS  2132 KG
*****
THRUSTER:  NASA-LEWIS 30 CM-DIA HG BOMBARDMENT TYPE
           THRUST .129 N      Isp 2900 SEC      EFF .67
           POWER REQD. 3.06 KWe      SYSTEM MASS 51.4 KG/UNIT
           MASS FLOWRATE .454E-06 KG/SEC
*****
NO# OF      SYSTEM      T/M      FUEL      PAYLOAD      TIME
THRUSTERS  MASS-KG      KM/SEC2    KG      KG      DAYS      HOURS
    36      1848.9      .464E-06    1814.3    4104.9    135      16.3
*****
THRUSTER:  JPL/HUGHES 30 CM-DIA HG BOMBARDMENT TYPE
           THRUST .370 N      Isp 9000 SEC      EFF .80
           POWER REQD. 22.68 KWe      SYSTEM MASS 245.78 KG/UNIT
           MASS FLOWRATE .419E-05 KG/SEC
*****
NO# OF      SYSTEM      T/M      FUEL      PAYLOAD      TIME
THRUSTERS  MASS-KG      KM/SEC2    KG      KG      DAYS      HOURS
    5      1228.9      .185E-06    616.8    6022.3    340      14.2
*****

```

Table 4-3. Typical Analysis Data

4.3.6 Summary

It was determined that there exists an optimum value of specific impulse that will produce the maximum payload at GEO. The best thruster for our particular mission is the low specific impulse type for which we have two choices of thrust level. One, the low thrust type represented by the NASA-Lewis device (thrust = .129 N) of which 36 are required. This thruster has the advantage of being a fully tested off-the-shelf item. Or, we may use the high thrust (.428 N) 50 cm-diameter model suggested in the study performed by the Aerospace Corporation. Only half as many of these would be needed if they were to become available. An important consideration is that the 50 cm-diameter thruster would have to be developed.

The maximum payload that can be placed into GEO in six months is from 6700 to 9100 Kg depending upon which of the two thrusters is used.

The conclusion of the preliminary study is that it is technically feasible to design a vehicle which can raise large amounts of payload and power to Geosynchronous altitude and is compatible with the NASA Space Shuttle. In addition the concept can be shown to be more economical than present solar powered vehicles proposed for similar missions.

4.4 Structural and Thermal Analysis Capabilities

One of the newest and most popular numerical techniques which engineers are using is the finite element method. With high-speed digital computers, the finite element method has greatly enlarged the range of engineering problems amenable to numerical analysis. The method of finite elements started some 20 years ago in the study of aircraft structures. It began as an extension of matrix methods for structural analysis, but now it is recognized as a powerful tool in many other problems.

Exploiting the finite element method, the University of California at Berkeley developed the SAP-IV program. The current version of SAP-IV has proven to be a very flexible and efficient program. The linear structural systems to be analyzed in SAP-IV may be composed of combinations of nine different structural elements and perform both static and dynamic analyses.

One important application of finite element method is the evaluation of the General Purpose Heat Soruce (GPHS), which must sustain reentry and impact intact. Should a launch or onboard explosion take place, these fuel modules would probably separate and follow independent trajectories back into the atmosphere. In addition to the studies of orbital decay and reentry dynamics already mentioned, simulations of stress analysis and thermal heating were developed to simulate the situation during the reentry phase. Bulk graphites and carbon-carbon composites are considered to be the best material candidates for the GPHS due to the reentry requirements. The strength of graphite increases with temperature, while most materials lose strength at higher temperatures. Due to the anisotropic properties, pyrolytic graphite cannot sustain high strength along the direction of layers of carbon atoms arranged in two-dimensional rings. A block made of three-dimensional graphite fibers shows more desirable properties at high temperatures.

Thermal and stress analyses were carried out by the SAP-IV program. Preliminary development of the GPHS design program uses only plain stress and plain strain elements, three-dimensional elements, and thin shell elements. The SAP-IV program for static analysis has been modified to generate thermal and stress analyses. The displacements from the program can be used in analogy to the temperature input data. The heat flux from

the aerodynamic heating and fuel pellets obtained from the calculation of convective heat transfer, is the only input data required by the program. An example problem has been tested to calculate the temperature distribution and stress distribution in a graphite block. The heat flux distribution on a flat-faced side was used as data input for the program. For simplicity, the heat flux from isotope fuel and the heat transfer from the leeward surface of a reentry member were all neglected. Results were presented in an earlier report.

Appendix A: Results of GPHS Reentry Stability Simulations

Problem Description

This study is to investigate the reentry stability characteristics of the GPHS module so that predictions of aerodynamic heating can be ascertained. Since aerodynamic heating is most important when the reentering body is in the continuum flow regime (less than 50 miles altitude), this study will be restricted to continuum hypersonic flow where the laws of classical fluid mechanics are valid.

The prediction of aerodynamic loading is necessary for understanding the attitude stability characteristics of a blunt reentry body. The aerodynamic loading is obtained from the computation of the flowfield pressure distribution about the body. The calculation of blunt body reentry flowfields has been the focus of numerous investigations during the past 15 or 20 years¹⁻⁸. The reentry flowfield includes regions of supersonic and subsonic flow, where viscous effects are considered near the body (boundary layer) and neglected away from the body (inviscid region). Because of the complexity of the flowfield, accurate methods of solution use detailed numerical techniques.

For a blunt, flat-faced, sharp-cornered body like the GPHS module, the flow can be classified as three-dimensional and asymmetric, and produces a flowfield similar to that in Fig. A-1. Although a numerical technique is needed to accurately predict the three-dimensional pressure distribution, a first order approximation can be made by analyzing the entire flowfield in three separate reference planes and thus obtain three distinct pressure

Figure A-1. Blunt Body Reentry Flowfield

distributions. Although this avoids the difficulty in determining the three-dimensional pressure distribution, it may yield unreliable results.

Procedure

From references 9 and 10, we found experimental and computational single-plane pressure distributions on flat-faced bodies in hypersonic flow at 0° , 10° and 20° angle of attack. Distributions for higher angles of attack were extrapolated from this reference data. With pressure distribution available, the aerodynamic moments can be obtained. Since we have uncoupled the initially assumed random three dimensional motion of the module into a separate rotation about each body axis, the moments for angular motion about each axis are computed. Plots are shown for the y and z body axes (Figures A-2 and A-3). A plot for the angular motion about the x-axis is not shown since it would be very similar to the z-axis plot.

A shift of the center of gravity of the GPHS module was introduced in an attempt to favorably alter the stability characteristics of the module. Plots of moment versus angle of attack with center of gravity shifts are shown (Figures A-4 to A-8).

References

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Figure A-2. GPHS Module Moment Plot for Z-axis

Figure A-3. GPHS Module Moment Plot for Y-axis

C. G. Shift: $\Delta x = 0.0$ mm

$\Delta y = 5.0$ mm

Figure A-4. GPHS Module C. G. Shift Moment Plot for Z-axis

C. G. Shift: $\Delta x = 8.0 \text{ mm}$
 $\Delta y = 8.0 \text{ mm}$

Figure A-5. GPHS Module C. G. Shift Moment Plot for Z-axis

C. G. Shift: $\Delta x = 6.0 \text{ mm}$

$\Delta y = 6.0 \text{ mm}$

Figure A-6. GPHS Module C. G. Shift Moment Plot for Z-axis

C. G. Shift: $\Delta x = 6.0 \text{ mm}$
 $\Delta y = 6.0 \text{ mm}$

Figure A-7. GPHS Module C. G. Shift Moment Plot for Y-axis

C. G. Shift: $\Delta x = 8.0 \text{ mm}$
 $\Delta y = 2.0 \text{ mm}$

Figure A-8. GPHS Module C. G. Shift Moment Plot for Y-axis