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Produced by the NASA Center for Aerospace Information (CASI)
STUDY OF REACTOR Brayton POWER SYSTEMS FOR NUCLEAR ELECTRIC SPACECRAFT

FOR

CALIFORNIA INSTITUTE OF TECHNOLOGY
JET PROPULSION LABORATORY

CONTRACT 955008

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AIRESERCH MANUFACTURING COMPANY OF ARIZONA

A Division of The Garrett Corporation
Phoenix, Arizona
SUMMARY

The study of Brayton power systems for nuclear electric spacecraft was performed to provide a basis for comparison between this system and others that have been under study for some time. Most significantly, this initial study has yielded performance parameters for the Brayton system that are very competitive with the alternative systems and envelope dimensions that are compatible with the Space Shuttle payload bay.

The primary performance parameters of system mass and radiator area were determined for systems from 100 to 1000 kW_e. Mathematical models of all system components were used to determine masses and volumes. Two completely independent systems provide propulsion power so that no single-point failure can jeopardize a mission. The waste heat radiators utilize armored heat pipes to limit meteorite puncture. The armor thickness was statistically determined to achieve the required probability of survival.

A 400-kW_e reference system received primary attention as required by the contract. The components of this system were defined and a conceptual layout was developed with encouraging results. An arrangement with redundant 400-kW_e Brayton power systems having a 1500°K (2240°F) turbine inlet temperature (TIT) was shown to be compatible with the dimensions of the Space Shuttle orbiter payload bay. The spacecraft is deployed from within the cylindrical primary radiator in a manner similar to the present Jet Propulsion Laboratory (JPL) thermionic system design. The preliminary mass determination for the complete power system is close to the desired 20 kg/kW_e for the specified Jovian environment. With further refinement, that the current Brayton conceptual design can better this goal. Study results have also shown that use of more advanced technology (higher TIT) will substantially improve system performance characteristics.
Because certain near-term missions with nuclear electric power systems are of present interest, a preliminary design concept of a 100-kWe Brayton system was also developed. This system was designed with essentially current Brayton technology (i.e., TIT = 1325°K) for operation in the geostationary orbital environment. A flight version of this system could be available by the late 1980s.

Further studies and analyses of refined nuclear reactor Brayton space power systems are recommended for continued attention. Brayton system technology efforts should be undertaken in the near future to assure a proper base for development of flight systems in the late 1980s and 1990s.
ACKNOWLEDGMENTS

The excellent working relationship which has been established with JPL has contributed substantially to this study. Especially recognized are the efforts of Wayne Phillips, who was technical manager of the study, Jack Mondt, Leader of the Nuclear Thermal to Electric Power Group, and Teh Hsieh, who monitored technical aspects throughout this study. The support of James Lazar and Jerome Mullin of the NASA Office of Aeronautics and Space Technology Space Power and Propulsion Division is greatly appreciated. The continuing interest of Mr. Robert English of the NASA Lewis Research Center has been very helpful and is acknowledged with much appreciation.

In support of this study, JPL arranged for data to be provided by the Los Alamos Scientific Laboratory (Dave Buden, Dan Koerig and Ken Cooper) and by Thermacore, Inc. (Yale Eastman and Don Ernst). The extensive dialog and numerous meetings with the above named persons and others at these organizations have greatly enhanced this study.
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1.0 INTRODUCTION

Studies are currently underway at the Jet Propulsion Laboratory (JPL) and at the Los Alamos Scientific Laboratory (LASL) to demonstrate the technical feasibility of nuclear reactor-powered spacecraft propelled by electric rocket thrusters. Such vehicles would be capable of performing detailed explorations of the solar system including rapid trips to the outer planets with massive payloads during the 1990s and into the 21st century. Particular emphasis has been placed on the definition of and on technology development for the power conversion subsystem with thermionics currently receiving primary attention.

The purpose of this study is to provide comparative information on an alternative conversion system, the Closed Brayton power system, to allow meaningful comparisons.

As a result of the large technological data base available from the development of numerous gas turbines as well as the significant R&D funding on Closed Brayton Cycle (CBC) engines over the past ten years, such engines should be considered an available technology with excellent potential for future development. Major questions to be resolved include definition of optimum operating parameters and effective integration with spacecraft elements including the launch vehicle, the nuclear subsystem (reactor and shield), the waste heat rejection system, and the space science payload. These topics are addressed in the three tasks that have been defined for this study, as described in Section 2.0. Estimation of system reliability and lifetime characteristics is of great interest, but could only be addressed
in a very preliminary way within the confines of this study. The remainder of this introduction provides additional definition of the requirements for the Nuclear Electric Spacecraft.

1.1 Study Background

Since the 1950s, the limitations of chemical rockets for extensive exploration of the solar system and other high-energy missions have been well understood. Electric-rocket propulsion was given considerable analytical and development attention during the past two decades and space flight tests were conducted. In comparison studies, nuclear electric rocket propulsion was repeatedly shown to be performance and economically effective for the more demanding missions when they would be flown.

In the early 1970s, the post-Apollo emphasis on Earth applications and, especially, the development of the Space Shuttle transportation system caused space program planners to terminate all work on nuclear systems except for radioisotope thermoelectric generators (RTGs), some advanced reactor concepts, and compatible power conversion research.

During the past several years, projections of future space mission requirements, both military and civil, have resulted in a renewed interest in advanced nuclear systems. The Department of Energy (DOE) has technology development programs in advanced nuclear energy sources for space at LASL. The NASA Office of Aeronautics and Space Technology (OAST) Space Power and Electric Propulsion Division is funding power conversion technology developments, primarily in thermionics and thermoelectrics. Although Brayton power conversion in space has a history of over 20 years, the present study represents the first effort in recent years to assess the component and system aspects in some detail using both available and obtainable technology. In particular, this study addresses the critical issue of space environment.
compatible radiator design which has been recognized for some time as the major drawback to application of CBC technology.

1.2 Missions for Nuclear Electric Rocket Propelled Spacecraft

The primary missions identified by JPL for this study are solar system exploration of the outer planets with massive payloads. Figure 1 shows the net* 400-kWₑ nuclear electric, rocket propelled spacecraft mass versus time of flight for various thruster exhaust velocities. Two cases are shown with different masses of shielding for the nuclear reactor. The required shielding mass is probably between these cases. Performance is also shown for a 60-kWₑ solar-electric rocket-propelled spacecraft. As can be seen, substantial masses can be placed in Jupiter orbit(1)** which would represent a likely first use for the nuclear electric spacecraft. Reference 1 also contains data on flights to other outer planets and on a solar escape mission with high net mass and reasonable trip times. Further trajectory optimization of these and other high-energy missions are expected to result in a strong recommendation for the development of nuclear electric rocket propulsion capability.

In a more recent paper(2), Phillips and Pawlik discuss the design of a nuclear electric propulsion system, including the selection of thrusters and propellant for outer planet (Saturn, Uranus and Neptune) exploration. A power level between 200 and 250 kWₑ is recommended with current technology for the early missions and growth potential for more difficult later missions. These missions could be accommodated without significant changes in the basic nuclear reactor heat source and heat rejection system.

*Total spacecraft mass less the following term for Cases A and B--(1.03 propulsion system mass plus shielding mass).
**Numbers in parenthesis refer to the list of references in Section 6.0.
Figure 1. Net Spacecraft Mass in Jupiter Orbit Vs Time of Flight.
Other high-energy missions in the 1990s and beyond will include such candidates as orbital transfer vehicles, both in geocentric orbits and throughout cislunar space, highly maneuverable military spacecraft, and the initial versions of solar system cruisers.

1.3 Overall Study Approach

The study of CBC systems depends on the use of computer-based analytical methods. Only with such methods can thousands of candidate systems be designed and evaluated parametrically. A computer model based on appropriate guidelines and constraints has been created showing the variables intrinsic to CBC systems to be studied. The guidelines for the model are discussed in Section 1.4. The computer study method is described in Section 2.1.1.

A reference system design at 400 kWₑ was evaluated in substantial detail and is discussed at some length in Section 2.1.2. Because of prospective interest in lower power systems, a preliminary layout of a 100-kWₑ system was prepared and is shown in Section 2.1.3. Analytical results for systems from 100 to 1000 kWₑ using near-term and obtainable Brayton technologies are given in Section 2.1.4.

The major technical challenge of this study was the identification of a credible heat-pipe radiator. Early in the study, the Brayton power conversion system design parameters were selected from computer results which did not include all system components and which included a liquid-cooled radiator. A heat-pipe radiator was then designed using a separate radiator computer program and the mass adjusted accordingly. In the latter phase of the study, these computer models were merged and analytical representations of all system components were included. Achievement of this overall design tool is a major accomplishment of this study. Throughout this investigation, layouts of radiators were made and evaluated against two constraints—reasonable mass and ability to fit into the Space Shuttle bay.
Specific heat-pipe designs were evaluated by Thermacore, Inc. under a JPL contract. The study results are discussed in Section 2.2.4 and presented in toto in Appendix A. The radiator geometry is discussed in greater detail in Section 2.3.

1.4 Study Guidelines

There were two primary goals of this study—first, to study nuclear electric propulsion (NEP) power systems from 100 to 1000 kW\textsubscript{e}, and second, to create a reference design including a system layout at 400 kW\textsubscript{e}. The following constraints and guidelines were given in the JPL contract (3) and were expressed as highly desirable by JPL representatives:

(a) The system should be designed for technology attainable in the 1985 to 1990 time frame.

(b) The system must produce the voltage level desired by the ion thrusters.

(c) System components must be placed within the shadow of the reactor shield.

(d) The 400-kW\textsubscript{e} system and payload should fit within the Space Shuttle bay.

(e) These systems should be designed to operate in a recently defined Jovian micrometeoroid environment throughout the mission life.

(f) System lifetime is 120,000 hours.

(g) The system specific mass at 400 kW\textsubscript{e} should be less than 20 kg/kW\textsubscript{e}.  

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The following additional guidelines were assumed by AiResearch:

(a) No single-point failures are allowed; hence, all systems include the mass of a redundant system.

(b) The 100-kWₑ system would use essentially state of the art technology.

(c) The 400- and 1000-kWₑ systems can utilize longer term technology.

(d) Turbomachinery design is current state of the art.
2.0 TECHNICAL DISCUSSION

2.1 Task 1 - Power System Conceptual Design Studies

The method and the results of the study of power systems between 100 and 1000 kW_e are described in the following sections. Conceptual designs at 400 and 100 kW_e are presented in greater detail.

2.1.1 Study Method

The CBC computer design program was used to design thousands of candidate systems. This program requires input of key thermodynamic parameters to begin the cycle design. The output is complete preliminary design of the resultant systems, including masses of all components in both tabular and plotted forms. These systems are examined in detail and a reference system is selected. From the geometry of the components, a layout of the selected design can be made.

Table 1 lists the array of parameters that were studied. The most significant parameter is power level because system mass is a strong function of power level. The TIT and cycle temperature ratio* are the next most important parameters. The cycle temperature ratio dictates the cycle efficiency (from the Carnot efficiency equation) depending upon the other parameters selected. TIT coupled with the cycle temperature ratio affects radiator size. The compressor specific speed, rotor speed, and power level determine the performance level of the turbomachinery and system pressure level. Rotor speed also determines the mass of the turbomachinery. Recuperator effectiveness affects thermal input, the mass of the recuperator, and radiator size. The pressure loss parameter has a strong effect on the

*Ratio of compressor inlet temperature (CIT) to TIT.
### TABLE 1

**INITIAL BRAYTON POWER SYSTEM STUDY PARAMETERS**

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<thead>
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<th>Parameter</th>
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<th>Values</th>
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<tr>
<td>Net Output Power Level</td>
<td>kW</td>
<td>100 400 1000</td>
</tr>
<tr>
<td>Turbine Inlet Temperature</td>
<td>°K</td>
<td>1150 1325 1500 1650</td>
</tr>
<tr>
<td>Cycle Temperature Ratio (CIT/TIT)</td>
<td></td>
<td>0.25 to 0.40</td>
</tr>
<tr>
<td>Compressor Specific Speed</td>
<td></td>
<td>0.07 to 0.15</td>
</tr>
<tr>
<td>Rotating Speed</td>
<td>krpm</td>
<td>12 to 48</td>
</tr>
<tr>
<td>Recuperator Effectiveness</td>
<td></td>
<td>0.88 to 0.97</td>
</tr>
<tr>
<td>Pressure Loss Parameter</td>
<td></td>
<td>0.92</td>
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mass of the heat exchangers and system performance. The value that was selected (0.92) allows good system performance and reasonable heat exchanger mass.

Other variables that affect system mass include compressor pressure ratio, heat exchanger pressure drop, radiator sink temperature, and meteoroid flux. Compressor pressure ratio is selected to yield maximum system performance. Heat exchanger pressure drops are split between the heat exchangers for minimum system mass. Reactor thermal power affects both reactor and shield mass. The meteoroid flux can drastically affect radiator mass. All of these parameters are modeled in the computer code.

The computer program is a series of overlay programs, i.e., all of the thermodynamic cycles are defined first; then, the recuperator for each cycle is designed, next the radiator for each cycle is designed, etc. Finally, these results are matched, listed, and plotted. Figure 2 shows the manner in which information is transferred between these programs.

The first and most important step is the cycle analysis. This program uses the input parameters shown in Table 1. Some other secondary inputs, such as alternator design characteristics, are also used. This program, based on empirical performance maps of the compressor and turbine, will design a thermodynamic cycle for a given combination of the above parameters. Among the information defined is compressor and turbine efficiencies and sizes, alternator windage and size, cycle efficiency, and the thermodynamic state points. From the thermodynamic state point and rotor size, the rotating unit mass is calculated. This design point information is stored on the computer disk. The program continues to design cycles until all combinations of parameters are exhausted.
INPUT: AERODYNAMIC INLET TEMPERATURES, RECUPERATOR EFFECTIVENESS, ROTOR SPEED, COMPRESSOR AND TURBINE MAPS, PRESSURE LOSS PARAMETER, FIXED LOSSES AND EMPIRICAL CONSTANTS.

Figure 2. Brayton Space Power System Design Methodology
The next step is the design of the recuperator. The recuperator core matrix and other minor inputs are read in. Next, the cycle state point data are read from the computer disk. The recuperator is designed, and its mass and geometry are stored on the computer disk. After all of the recuperators are designed, the radiator design begins.

The heat-pipe radiator design program was added as a program option during this study. The calculation method is discussed in Section 2.3.6 (Radiator Conceptual Design). Like the recuperator program, it requires some basic input such as heat-pipe diameter, spacing, and length; gas heat exchanger data; micrometeoroid model; etc. It also uses the cycle state point data to design a heat-pipe radiator. The dimensions and mass of each radiator are stored on the computer disk. After a heat pipe radiator has been designed for each cycle, the calculation proceeds to the summing program.

In the summing program, the information stored on the computer disk is merged to form a complete system description. The mass of the remaining system components is calculated as a function of the appropriate cycle variables. Examples are duct mass, reactor mass, shield mass, and insulation mass. After the mass of every component is defined, the total system mass, system specific mass, and specific radiator area are calculated. An abbreviated cycle description is printed, and the specific mass and area are plotted. The plots are shown and discussed in Section 2.1.4. When a candidate system is selected, an option that prints the geometry and performance of all of the components is used. From this geometry, a system layout can be made.

2.1.2 Reference System Design at 400 kW_e

The 400-kW_e system is illustrated in Figure 3. This configuration uses technology expected to be available at least by 1990 and is
Jovian Environment TIT = 1500*K (2240*F)

**Mass Summary**

- Reactor: 850 kg
- Reactor Shield: 420 kg
- Heat Source Heat Exchangers (2): 400 kg
- CRU (2): 120 kg
- Alternator Radiator: 200 kg
- Recuperators (2): 80 kg
- Ducting & Miscellaneous: 10 kg
- Power Conditioning: 150 kg
- Structure: 300 kg

**Specific Mass = 20.7 kg/kW**

![Diagram of Nuclear Electric Spacecraft Design with a 400-kW<sub>e</sub> Brayton Power System]

**Figure 3.** Nuclear Electric Spacecraft Design with a 400-kW<sub>e</sub> Brayton Power System
designed for operation near Jupiter. The largest and most noticeable component is the primary heat rejection radiator. Because this entire system must fit into the Space Shuttle bay, the radiator length was selected with care.

The spacecraft is located forward of all other components. To fit the payload bay envelope, several components are deployed after the unit is released from the Shuttle. The spacecraft and power-conditioning radiator both telescope from inside the primary heat rejection radiator (this is also a feature of the baseline thermionic system). The ion thruster panels are rotated to a position normal to the axis of the spacecraft.

At the aft end of the spacecraft are the reactor and closed cycle power conversion systems. The reactor is the rearmost component. Inside the sputter shield and alternator radiator are the dual rotating groups, recuperators, and heat source heat exchangers. This configuration is simple and very compact.

Figure 3 shows that the specific mass is 20.7 kg/kWe. With further refinement, the system specific mass could be decreased to meet or be less than the 20 kg/kWe design goal. For example, relaxation of the micrometeoroid environment to reflect the relatively low fraction of the mission duration spent close to Jupiter would result in the goal being surpassed without further refinement. More complete detail on this system is given in Section 2.3.

2.1.3 Preliminary Conceptual Design at 100 kWe

The 100-kWe conceptual design was studied in a very cursory fashion near the end of the study because of indications of early mission interest in this power level. Figure 4 shows the power system applied to a large telescoping and deploying space antenna. This
MASS SUMMARY

<table>
<thead>
<tr>
<th>Component</th>
<th>kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>REACTOR</td>
<td>350</td>
</tr>
<tr>
<td>REACTOR SHIELD</td>
<td>220</td>
</tr>
<tr>
<td>HEAT SOURCE HEAT EXCHANGERS (2)</td>
<td>120</td>
</tr>
<tr>
<td>CRU (2)</td>
<td>150</td>
</tr>
<tr>
<td>ALTERNATOR RADIATOR</td>
<td>60</td>
</tr>
<tr>
<td>RECUPERATORS (2)</td>
<td>350</td>
</tr>
<tr>
<td>RADIATOR</td>
<td>1340</td>
</tr>
<tr>
<td>STRUCTURE, DUCTING &amp; MISCELLANEOUS</td>
<td>350</td>
</tr>
<tr>
<td>POWER CONDITIONING AND CONTROLS</td>
<td>100</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td>3040</td>
</tr>
</tbody>
</table>

SPECIFIC MASS = 30.4 kg/kW_e

Figure 4. Preliminary 100-kW_e Nuclear Electric Spacecraft Design
power system configuration will fit easily into the Space Shuttle payload bay. The component arrangement is generally similar to the 400-kW system described previously. The mass summary given in Figure 4 reflects a conservative design based essentially on currently available technology. Two completely independent systems provide propulsion power so that no single-point failure can jeopardize a mission. Although the radiator is "Y" shaped, a cylindrical radiator could also be used which would be more compact but more massive.

The specific mass of 30.4 kg/kW\(_e\) could quite clearly be significantly reduced by the use of more advanced technology (higher TIT). Even at the lower TIT, appreciable reduction could be achieved with further refinement. Unfortunately, such refinement was not possible within the resources available for this study.

2.1.4 Analytical Results from 100- to 1000-kW\(_e\) Studies with Near-Term and Obtainable Brayton Technologies

Figures 5 through 12 are "shotgun" plots generated by the previously described method (Section 2.1.1). Representative plots are included for three output powers (100, 400, and 1000 kW\(_e\)). These plots are presented as representative examples of the analytical approach but do not reflect a significant improvement (use of dual diameter or necked heat pipes), which was made relatively late in the study. The effects of this improvement are described later in this section. Each point on these plots represents a specific system design according to the parameters of Table 1. Each set of results consists of separate plots of specific mass and specific radiator area. The specific mass includes the heat source, two completely redundant loops for all the power conversion components, the waste heat radiator, and required power conditioning components.

Plots of the 400-kW\(_e\) system, designed for a 1995 flight with a 1500\(^\circ\)K (2240\(^\circ\)F) TIT are shown in Figures 5 through 8. A five-year
Figure 5. Specific Mass vs Overall System Efficiency of 400-kWe System at a Turbine Inlet Temperature of 1500°K (2240°F) in a Jovian Environment
Figure 6. Specific Radiator Area vs Overall System Efficiency of 400-kWe System at a Turbine Inlet Temperature of 1500°K (2240°F) in a Jovian Environment
Figure 7. Specific Mass vs Overall System Efficiency of 400-kW System at a Turbine Inlet Temperature of 1500°K (2240°F) in a Near-Earth Environment
Figure 8. Specific Radiator Area vs Overall System Efficiency of 400-kWe System at a Turbine Inlet Temperature of 1500°K (2240°F) in a Near Earth-Environment
Figure 9. Specific Mass vs Overall System Efficiency of 100-kW System at a Turbine Inlet Temperature of 1325 °K (1925 °F) in a Near-Earth Environment
Figure 10. Specific Radiator Area vs Overall System Efficiency of 100-kWe System at a Turbine Inlet Temperature of 1325°K (1925°F) in a Near-Earth Environment
Figure 11. Specific Mass vs Overall System Efficiency of 1000-kW System at a Turbine Inlet Temperature of 1650°K (2510°F) in a Jovian Environment
Figure 12. Specific Radiator Area vs Overall System Efficiency of 1000-kWe System at a Turbine Inlet Temperature of 1650°K (2510°F) in a Jovian Environment
flight system development is assumed with the result that this TIT, which can be attained with high-strength refractory materials, should be state-of-the-art by 1990. The inferences of this technology development schedule are discussed subsequently. The waste heat radiators for these systems employ the fixed cylindrical geometry shown in Figure 3. Previously, a hinged, three-panel design had been considered that was somewhat less massive but required in-space assembly operations (automated welding or brazing at the 400-kW\(_e\) power level. Comparison of the specific mass data for the Jovian (Figure 5) and near-Earth (Figure 7) environments shows the substantial effect of the meteoroid armor requirement. These systems have masses that are well within the capability of a single Shuttle launch and dimensions that fit within the payload bay.

Figures 9 and 10 show the specific mass and specific radiator area for 100-kW\(_e\) systems designed for the near-Earth micrometeoroid environment and for a TIT of 1325\(^\circ\)K (1925\(^\circ\)F). These systems would be based on essentially existing technology (mostly superalloy with some well-characterized refractory hot section components) which results in relatively large masses and radiator areas. The system configuration with a three-panel radiator is shown previously in Figure 4 and fits easily within the Shuttle payload envelope.

The specific mass and radiator areas characteristic for 1000-kW\(_e\) systems are shown in Figures 11 and 12. The TIT for these systems, 1650\(^\circ\)K (2510\(^\circ\)F), is commensurate with ceramic technology which should be available by 1995 (yielding a projected operational date of 2000). Specific mass and radiator area are the lowest of all the systems analyzed, illustrating most significantly the payoff of advanced technology. As a result of a number of on-going programs (four to six), AiResearch concludes that the ceramic technology will be available as outlined above. Indeed, these time frame projections may be conservative rather than optimistic.
Table 2 shows the effect of environment, power level, and turbine inlet temperature on specific mass and radiator area. The table lists the specific radiator area of the system that has minimum specific mass. The table shows that both specific mass and radiator area decrease as power level and/or turbine inlet temperature increase. The requirement to operate in the Jovian environment has an adverse effect on system mass.

In Table 2, the values in the column labeled "Specific System Mass" were determined directly from the "shotgun" plots. As noted previously, the radiator is by far the most massive component in the power system. As described in Section 2.2.5, a modification to use "dual-diameter" heat pipes was defined late in the study. In this approach, a large diameter is used in the evaporator section to yield adequate heat transfer from the cycle working fluid and a smaller diameter is used for the condenser. This modification allowed the radiator to be redesigned for a much lower mass. Estimates were made of the reductions possible, and the resultant modifications to the specific mass are listed in the column labeled "Specific System Mass with Refined Radiator". The plots may still be used to determine the relative merits of alternative system design points.

The most important parameter in Table 2 is the specific mass of the 400-kW_e system. For the Jovian environment, the specific mass is 21 kg/kW_e which is within 5 percent of the design goal. With further refinement, this value could probably be made less massive than the goal. 400 kW_e systems designed for the near-Earth environment are lighter than the design goal of 20 kg/kW_e. The advanced 1000-kW_e system for Jovian environment has the highest performance of all with a specific mass of 15 kg/kW_e.
TABLE 2

SUMMARY OF SELECTED BRAYTON SYSTEM DESIGNS

<table>
<thead>
<tr>
<th>Power Level $kW_e$</th>
<th>Turbine Inlet Temperature °K</th>
<th>Environment</th>
<th>Specific System Mass kg/kW$_e$</th>
<th>Specific System Mass With Refined Radiator kg/kW$_e$</th>
<th>Specific Radiator Area m$^2$/kW$_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>400</td>
<td>1500</td>
<td>Jovian</td>
<td>28</td>
<td>21</td>
<td>0.42</td>
</tr>
<tr>
<td>400</td>
<td>1500</td>
<td>Near-Earth</td>
<td>23</td>
<td>19</td>
<td>0.42</td>
</tr>
<tr>
<td>100</td>
<td>1325</td>
<td>Jovian</td>
<td>46</td>
<td>41</td>
<td>1.0</td>
</tr>
<tr>
<td>100</td>
<td>1325</td>
<td>Near-Earth</td>
<td>34</td>
<td>30</td>
<td>1.0</td>
</tr>
<tr>
<td>100</td>
<td>1500</td>
<td>Near-Earth</td>
<td>29</td>
<td>26</td>
<td>0.72</td>
</tr>
<tr>
<td>1000</td>
<td>1500</td>
<td>Jovian</td>
<td>26</td>
<td>20</td>
<td>0.38</td>
</tr>
<tr>
<td>1000</td>
<td>1650</td>
<td>Jovian</td>
<td>21</td>
<td>17</td>
<td>0.30</td>
</tr>
<tr>
<td>1000</td>
<td>1800</td>
<td>Jovian</td>
<td>18</td>
<td>15</td>
<td>0.25</td>
</tr>
</tbody>
</table>
2.2 Task 2 - Primary Radiator Conceptual Design

In this task, primary waste heat radiator layout studies were undertaken. An analytical model of the radiator was defined and used in Task 1 to create the designs. Finally, the radiator design was checked against the Thermacore heat-pipe data. The geometry of the radiator selected for the 400-kWe system is discussed in Section 2.3.5 below.

2.2.1 Configuration Studies

The radiator configurations derived during the layout study are shown in Figure 13. There are four designs labeled (A) through (D).

All of these configurations are similar in their design approach. Each has a gas-to-heat-pipe heat exchanger where the heat is transferred to the evaporator section of the heat pipe. Each has a condensing section and fin from which the waste heat is radiated. Each has armor protection for the condenser section. Some radiate from only one side of the panel.

Configuration (A) is based on a LASL design approach. It has four heat-pipe panels with a cruciform gas to heat pipe heat exchanger. Inside the heat exchanger are small diameter tubes which are joined to the evaporator. These tubes carry the working fluid and provide additional heat transfer surface.

Configuration (B) has eight slightly curved panels which together make a right circular cylinder. Each panel has two gas-to-heat-pipe heat exchangers because there are two power conversion systems. Each gas heat exchanger is protected from meteoroid impact by the adjacent heat-pipe panels that overlap the heat exchangers.
Figure 13. Conceptual Primary Radiator Designs
Configuration (C) is a three-panel design with axial heat pipes. There is a double heat exchanger located midway the axial length of the panel. This heat exchanger has heat pipes that exit from both the top and bottom.

The last radiator concept configuration (D), has a number of telescoping panels. The heat pipes are parallel to the axis of the radiator. The gas heat exchanger is located at the top of each panel. The major problem with this design is the flexible joints that must seal the working fluid loop.

For this study, configuration (B) was selected for the 400-kWe system. A combination of the features of (A) and (C) were used for the 100-kWe layout.

2.2.2 Meteoroid Protection

The armor thickness is based on the equation shown on Figure 14. This information was supplied by JPL and includes the effect of operation in the Jovian environment. The number of failures is based upon the binomial distribution. For this study, it was found advantageous to design for a high probability of non-puncture. Table 3 lists shows the effect of non-puncture probability on armor thickness.

<table>
<thead>
<tr>
<th>Probability of Non-puncture of An Individual Tube</th>
<th>Percentage of Tubes Not Punctured*</th>
<th>Armor Thickness Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.85</td>
<td>83.5</td>
<td>1.000</td>
</tr>
<tr>
<td>0.90</td>
<td>88.8</td>
<td>1.134</td>
</tr>
<tr>
<td>0.95</td>
<td>94.1</td>
<td>1.397</td>
</tr>
<tr>
<td>0.99</td>
<td>98.6</td>
<td>2.242</td>
</tr>
</tbody>
</table>

*99 percent probability that no more than this percentage of tubes will be punctured. The specific design for the 400-kWe system was based on 95 percent non-puncture.
- BASED ON PROTECTION FOR A SINGLE HEAT PIPE

\[ t = C \left[ \frac{AT}{-\ln(P)} \right] 0.2902 \]

WHERE
- \( t \) IS ARMOR THICKNESS, cm
- \( C \) IS 0.00110 FOR LOCKALLOY
- \( A \) IS VULNERABLE AREA, cm²
- \( T \) IS MISSION TIME, HOURS
- \( P \) IS NO PENETRATION PROBABILITY

- NUMBER OF HEAT PIPE FAILURES BASED ON BINOMIAL DISTRIBUTION

\[ P(i) = \sum_{m = 0}^{i} \frac{P^m(1-P)^{n-m}}{m! (n-m)!} \]

\( P(i) \) IS PROBABILITY OF \( i \) OR FEWER PUNCTURES (\( i \leq n \))
- \( n \) IS TOTAL NUMBER OF HEAT PIPES
- \( m \) IS NUMBER OF FAILED HEAT PIPES

Figure 14. Meteoroid Protection Criteria
It can be seen that increasing the non-puncture probability from 0.85 to 0.95 increases the armor thickness (and mass) by 40 percent. This is a worthwhile tradeoff when the major mass is the heat exchanger and heat pipes. If a low probability is selected, more heat pipes and heat exchanger mass must be added to compensate for the failed heat pipes. Excess heat transfer area on both the gas convection surface and the radiating surface will ensure that this radiator will function as designed when 6 percent of the tubes have failed.

2.2.3 Analytical Design

Analysis of the radiator utilizes a computer program. This program has been integrated into the cycle design program so that radiators can be designed at the same time the thermodynamic cycle is derived. Figure 15 summarizes the design method. Input from the cycle design program constitutes the major variables, such as:

- Heat rejection rate
- Flow
- Temperature
- Fluid properties
- Pressure drop

Other input, which applies to the particular configuration to be studied, is read by the radiator program. This input includes:

- Heat pipe diameter and wall thickness
- Condenser length
- Gas heat exchanger width
- Heat transfer data
- Armor model

With this input, the gas heat exchanger size and radiating area are calculated. The frontal area of the heat exchanger (and therefore
Figure 15. Radiator Design Method
the evaporator length) is a function of the pressure drop. The heat transfer conductance has a strong effect on radiator size. The computer program calculates the length of the heat exchanger based on the conductance and radiating temperature. Evaporator length is changed as necessary to satisfy pressure drop. The program iterates until both heat transfer and pressure drop requirements are satisfied simultaneously.

When the calculation has converged, the mass of the radiator is calculated. This mass includes heat pipes, fin, armor, two gas-to-heat-pipe heat exchangers, and associated heat exchanger components (wrapup, headers, duct extension, and flanges).

The last step is to compare the computer heat pipe results with data on specific designs supplied by Thermacore. If the result is favorable, the conceptual design is accepted. If not, iteration is required.

2.2.4 Heat-Pipe Data

Appendix A includes the results of the Thermacore radiator heat pipe study (7). The important conclusions are:

- Rubidium is the preferred working fluid for 1 in. OD heat pipes when the temperature is above 650°K (710°F).

- Mercury is acceptable for temperatures as low as 550°K (530°F) if the heat-pipe diameter is less than 1 in. In fact, the power transferring capability of the heat pipe increased as the diameter decreased.

- Dowtherm A is the preferred fluid below 550°K (530°F) [minimum radiating surface temperature is 492°K (426°F)].

- Other advanced designs might offer increased performance and lower mass.
2.2.5 Advanced Heat-Pipe Concepts

A comparison of the performance characteristics of the evaporator and condenser sections of constant diameter heat pipes led to the conclusion that this type of heat pipe was not the optimum design. Thermacore agreed that it was possible to design and build heat pipes in which the evaporator diameter is greater than the condenser diameter. This results in a heat-pipe radiator in which the evaporation area is sufficient for convective heat transfer from the gas working fluid, and the condenser section is operated somewhat closer to the maximum heat transfer capability. The smaller heat-pipe condenser section minimizes vulnerable area and heat-pipe mass; consequently, armor mass is also minimized. This design concept reduced the radiator mass of the 400-kW$_e$ reference system by 45 percent. Use of alternative advanced heat-pipe geometries may provide further substantial mass savings.

2.3 Task 3, Reference System Configuration and Component Conceptual Design

The overall reference system design concept is described in Section 2.1.3 above. The 400-kW$_e$ spacecraft design that will fit in the Space Shuttle orbiter payload bay is shown in Figure 3 with major elements identified. The mass summary discloses the radiator to be, by far, the major mass element of the 8270-kg total mass. Further refinement of this heat-pipe radiator design and of the other components will permit appreciable reduction in the specific mass of 20.7 kg/kW$_e$.

2.3.1 Reference System Configuration

The configuration of the 400-kW$_e$ Brayton power system is shown in Figure 16 with the nuclear subsystem farthest aft, away from the

*Approximate dimensions for the power conversion components may be scaled from the figure.
Figure 16. Configuration of 400-kW Brayton Power System for a Nuclear Electric Spacecraft.
spacecraft, and the compactly clustered components of the two power conversion systems next to the panel-mounted ion engines. The cylindrical radiator encloses the spacecraft during launch and, thus, is between the spacecraft and the power system in the deployed configuration.

A schematic of the dual Brayton power systems used to eliminate the single-point failure mode in the nuclear electric spacecraft is given in Figure 17. Both completely independent systems, each of which is capable of producing 400 kW\textsubscript{e}, are operated at half power under normal conditions. In the unlikely event that one of the systems becomes inoperable, the failed system is turned off and the pressure level doubled in the remaining system to restore full power output. Other means of assuring the required reliability for long durations are conceivable but the above method is preferred, at least until quantitative reliability and mass trade-off studies are accomplished.

Brayton cycle state points for the 400-kW\textsubscript{e} reference system are given in Figure 18. The reactor with an outlet temperature of 1600°K provides the thermal energy to the heat source heat exchanger that provides the temperature rise from 1114 to 1500°K. The primary radiator provides the compressor inlet temperature of 500°K. The mass flow is 7.5 kg/sec.

### 2.3.2 Nuclear Subsystem

The nuclear subsystem configuration is delineated in Figure 19. The two major components are the reactor and its lithium hydride neutron shield. Controls, insulation, shield cooling heat pipes and radiator, and the mercury propellant tank, which serves as a gamma shield, are also shown in the figure.
NOTE: DUAL FULL POWER CONVERSION SYSTEMS ARE COMPLETELY INDEPENDENT

Figure 17. Nuclear Electric Spacecraft Dual Brayton Power Systems Schematic

31-3321
38
Figure 18. 400 kW_e Reference Power System Brayton Cycle State Points
Figure 19. Space Nuclear Subsystem Reference Configuration
The relation of heat-pipe cooled reactor characteristics to the characteristics of the nuclear subsystem are diagrammed in Figure 20. Preliminary determinations have been made of reactor and subsystem specific mass; the other characteristics remain for future analysis.

**Reactors**

LASL has provided parametric data on heat-pipe cooled reactors with uranium oxide (UO$_2$) and uranium carbide (UC) fuels. These data (8,9) are included in Appendix B. Data were also provided on gas cooled reactors (10) but they have not been used in this study. Characteristics of the nominal 1650-kWt reactor selected for the 400-kWe reference power system are shown in Table 4. The hexagonal fuel elements are made from a 60% UO$_2$-40% molybdenum mixture and have a central heat pipe for removing the thermal power. This reactor is a 0.6 m "square" cylinder with a total mass of 875 kg. The reactor specific mass is 0.53 kg/kWt. The design concept for this LASL reference reactor is shown in Figure 21.

Another reference reactor with 400-kWt nominal thermal power was identified for the preliminary conceptual design of the 100-kWe power system with the characteristics listed in Table 5. This reactor has Uranium carbide-Zirconium carbide fuel elements. It has a 0.24-m diameter and a 0.24-m length, and a mass of 346 kg so that the specific mass is 0.87 kg/kWt. The configuration of the 400-kWt reactor can be seen in Figure 22 to be similar to the 1650-kWt reactor.

LASL has recently published data on a new layered core heat-pipe cooled reactor design concept (11). The 1200-kWt thermal power version is shown in Figure 23. Data on these new reactors have been made available too recently to be incorporated in this study although the layered core offers many improved characteristics. The reactor mass at 1200 kWt is currently given as 470 kg for a specific mass of 0.39 kg/kWt which should result in considerably improved system parameters.
## REACTOR CHARACTERISTICS

- Thermal Design Concept
- Materials Temperatures
- Materials Characteristics
- Operating Stresses
- Controls Design
- Fuel and Other Core Materials
- Fuel Temperatures
- Heat Pipe Temperature
- Heat Pipe Characteristics
- Reactor Thermal Power
- Core Dimensions
- Core Void Fraction
- Core Power Density
- Reactor Dimensions
- Reactor Power Density
- Shielding Design
- Thermal Losses

## DESIGN CHARACTERISTICS

- Structural Integrity
- Fuel Burnup
- Thermal Efficiency
- Reactor Mass
- Fuel Inventory
- Shielding Mass
- Specific Volume

## NUCLEAR SUBSYSTEM CHARACTERISTICS

- Safety
- Reliability
- Lifetime
- Reactor Specific Mass
- Subsystem Specific Mass
- Costs

---

**Figure 20.** Relation of Heat Pipe Cooled Reactor Characteristics to Nuclear Subsystem Characteristics
| TABLE 4  
LA SL REFERENCE REACTOR CHARACTERISTICS - 1650 kWt (nom.) |
<table>
<thead>
<tr>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>REACTION TYPE</strong></td>
</tr>
<tr>
<td>THERMAL POWER</td>
</tr>
<tr>
<td>LIFETIME</td>
</tr>
<tr>
<td>FUEL TYPE</td>
</tr>
<tr>
<td>FUEL ELEMENT CLAD</td>
</tr>
<tr>
<td>HEAT PIPE WALL/WORKING FLUID</td>
</tr>
<tr>
<td>NO. OF FUEL ELEMENTS (AND HEAT PIPES)</td>
</tr>
<tr>
<td>FUEL ELEMENT WIDTH (ACROSS HEX. FLATS)</td>
</tr>
<tr>
<td>FUEL ELEMENT LENGTH</td>
</tr>
<tr>
<td>MAXIMUM FUEL TEMPERATURE</td>
</tr>
<tr>
<td>AVERAGE POWER IN FUEL SPACE</td>
</tr>
<tr>
<td>FISSION DENSITY</td>
</tr>
<tr>
<td>FUEL SWELLING</td>
</tr>
<tr>
<td>FUEL (²³⁵U) BURNUP</td>
</tr>
<tr>
<td>CORE DIAMETER</td>
</tr>
<tr>
<td>CORE LENGTH</td>
</tr>
<tr>
<td>CORE VOLUME</td>
</tr>
<tr>
<td>CORE VOID FRACTION</td>
</tr>
<tr>
<td>CORE POWER DENSITY</td>
</tr>
<tr>
<td>REFLECTOR MATERIAL</td>
</tr>
<tr>
<td>STRUCTURAL MATERIAL</td>
</tr>
<tr>
<td>REA C T O R DIAMETER</td>
</tr>
<tr>
<td>REACTOR HEI GHT</td>
</tr>
<tr>
<td>REACTOR VOLUME</td>
</tr>
<tr>
<td>REA C T O R POWER DENSITY</td>
</tr>
<tr>
<td>REACTOR OUTLET (HEAT PIPE) TEMPERATURE</td>
</tr>
<tr>
<td>REACTOR MASS SUMMARY, kg</td>
</tr>
<tr>
<td>FUEL (²³⁵U MASS = 150.6 kg)</td>
</tr>
<tr>
<td>REFLECTOR</td>
</tr>
<tr>
<td>HEAT PIPES (112.24 kg/m)</td>
</tr>
<tr>
<td>CONTROL SYSTEM</td>
</tr>
<tr>
<td>SUPPORT STRUCTURE</td>
</tr>
<tr>
<td>T C TAL MASS</td>
</tr>
<tr>
<td>REACTOR SPECIFIC MASS</td>
</tr>
</tbody>
</table>
Figure 21. LASL Reference Reactor Design Concept - 1650 kW_t (nom.)
| **TABLE 5** |
| LASL REFERENCE REACTOR CHARACTERISTICS - 400 kWe (nom.) |

<table>
<thead>
<tr>
<th><strong>REACTION TYPE</strong></th>
<th><strong>THERMAL POWER</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>FAST SPECTRUM, HEAT PIPE COOLED</td>
</tr>
<tr>
<td><strong>LIFETIME</strong></td>
<td>400 kWe</td>
</tr>
<tr>
<td><strong>FUEL TYPE</strong></td>
<td>87.6 X 10^3 h</td>
</tr>
<tr>
<td><strong>FUEL ELEMENT CLAD</strong></td>
<td>UC - ZrC</td>
</tr>
<tr>
<td><strong>HEAT PIPE WALL WORKING FLUID</strong></td>
<td>Mo</td>
</tr>
<tr>
<td><strong>NO. OF FUEL ELEMENTS (AND HEAT PIPES)</strong></td>
<td>Mo/Li</td>
</tr>
<tr>
<td><strong>FUEL ELEMENT WIDTH (ACROSS HEX FLATS)</strong></td>
<td>84</td>
</tr>
<tr>
<td><strong>FUEL ELEMENT LENGTH</strong></td>
<td>0.0246 m</td>
</tr>
<tr>
<td><strong>MAXIMUM FUEL TEMPERATURE</strong></td>
<td>0.2381 m</td>
</tr>
<tr>
<td><strong>AVERAGE POWER IN FUEL SPACE</strong></td>
<td>1554.2 K</td>
</tr>
<tr>
<td><strong>FISSION DENSITY</strong></td>
<td>47.93 MW/m^3</td>
</tr>
<tr>
<td><strong>FUEL SWELLING</strong></td>
<td>4.474 \times 10^2 Fissions/cm^3</td>
</tr>
<tr>
<td><strong>FUEL BURNUP</strong></td>
<td>6.44 VOLUME %</td>
</tr>
<tr>
<td><strong>CORE DIAMETER</strong></td>
<td>2.15 ATOM %</td>
</tr>
<tr>
<td><strong>CORE LENGTH</strong></td>
<td>0.2381 m</td>
</tr>
<tr>
<td><strong>CORE VOLUME</strong></td>
<td>0.2381 m</td>
</tr>
<tr>
<td><strong>CORE VOID FRACTION</strong></td>
<td>0.0106 m</td>
</tr>
<tr>
<td><strong>CORE POWER DENSITY</strong></td>
<td>0.3295</td>
</tr>
<tr>
<td><strong>REFLECTOR MATERIAL</strong></td>
<td>37.74 MW/m^3</td>
</tr>
<tr>
<td><strong>STRUCTURAL MATERIAL</strong></td>
<td>Be, Be^2</td>
</tr>
<tr>
<td><strong>REACTION DIAMETER</strong></td>
<td>Mo</td>
</tr>
<tr>
<td><strong>REACTION LENGTH</strong></td>
<td>0.4681 m</td>
</tr>
<tr>
<td><strong>REACTION VOLUME</strong></td>
<td>0.4481 m</td>
</tr>
<tr>
<td><strong>REACTION POWER DENSITY</strong></td>
<td>0.0771 m</td>
</tr>
<tr>
<td><strong>REACTION OUTLET (HEAT PIPE) TEMPERATURE</strong></td>
<td>5.188 MW/m^3</td>
</tr>
<tr>
<td><strong>REACTION MASS SUMMARY, kg</strong></td>
<td>1425 K</td>
</tr>
<tr>
<td><strong>FUEL (\text{^{235}U} MASS - 78.2)</strong></td>
<td>92.0</td>
</tr>
<tr>
<td><strong>REFLECTOR</strong></td>
<td>162.1</td>
</tr>
<tr>
<td><strong>HEAT PIPES</strong></td>
<td>36.5</td>
</tr>
<tr>
<td><strong>CONTROLS</strong></td>
<td>33.0</td>
</tr>
<tr>
<td><strong>SUPPORT STRUCTURE</strong></td>
<td>22.7</td>
</tr>
<tr>
<td><strong>TOTAL MASS</strong></td>
<td>346.3</td>
</tr>
<tr>
<td><strong>REACTION SPECIFIC MASS</strong></td>
<td>0.60E kg/kWe</td>
</tr>
</tbody>
</table>
Figure 22. LASL Reference Reactor Design Concept - 400 kW_t (nom.)
Figure 23. LASL Layered Core Heat Pipe Cooled Space Power Reactor Design Concept - 1200 kWt.
Radiation Shields

The nuclear radiation shielding has not been given detailed attention since the requirement is similar to the design used for the thermionic systems. Tailoring of the lithium hydride neutron shield to reduce its mass is shown in Figure 19. The propellant tank is located so that it can be used as a gamma radiation shield and is sized to hold an additional quantity of mercury for this purpose.

2.3.3 Heat Source Heat Exchanger

The heat source heat exchanger (HSHX) is the highest temperature component of the closed cycle system(s). This component looks like a typical tube fin heat exchanger and is illustrated in Figure 24. The geometry and performance are also summarized on this chart. The operation differs from a normal heat exchange because this design has equal heat flux from each tube. This occurs because each tube is actually the condensing end of a heat pipe. The heat pipe receives its heat in the nuclear reactor and gives it up in the heat exchanger. The heat is transferred to the working fluid by convection from the heat pipes and fins. In the reference system, the HSHX receives working fluid from the recuperator at 1114°K and provides it to the turbine at 1500°K.

There is a heat source heat exchanger for each power system. Because of the nature of heat pipes, when each evaporator section is operated at half power (the nominal operation), the maximum metal temperature is reduced from the 1583°K (the value when only one section is in use). This heat exchanger is all-molybdenum construction. This material is also used in the heat pipes.
CHARACTERISTICS

GEOMETRY:
FINNED TUBE
  TUBE OD = 2.5 cm (1 in.)
  NO. FIN/cm = 10 (25 fins/inch)
  FIN LENGTH = 0.5 cm (0.2 in.)
  FIN THICKNESS = 0.25 mm (0.010 in.)
  NO. FINNED TUBES = 162
  CONDENSING LENGTH = 41.2 cm (16.2 in.)
  GAS FLOW LENGTH = 67.8 cm (26.7 in.)
  HEAT EXCHANGER WIDTH = 33.0 cm (13 in.)

PERFORMANCE
  MAX WALL TEMPERATURE = 1583°F (2390°F)
  CONDUCTANCE = 21 kW/K (118 Btu/sec/°F)
  FIN EFFECTIVENESS = 67 PERCENT
  EQUAL HEAT FLUX PER TUBE
  ALL MOLYBDENUM CONSTRUCTION

Figure 24. Heat Source Heat Exchanger Concept and Characteristics
2.3.4 Combined Rotating Unit

The combined rotating unit (CRU) is a highly efficient, single shaft, closed Brayton cycle design that has resulted from many years of development and test in industry and government, especially under NASA sponsorship. Figure 25 is a rendering of the engine. The three primary components are the compressor, turbine, and alternator.

The compressor is a state of the art design. It is radial outflow type with backward curved blades for maximum efficiency. The turbine is the radial inflow type with straight radial blades. It is also state of the art aerodynamic design.

Both the compressor and turbine are relatively small wheels. Moderate specific speed and relatively high Reynolds number result in high component efficiency. The actual design parameters are shown in Table 6.

Prior experience indicates that the CRU bearings are one of the most critical components for a long life space power system. The alternator is mounted on one pair of foil journal bearings. The compressor and turbine are mounted on a larger pair of similar bearings. Two sets of foil thrust bearings absorb the aerodynamic thrust of the compressor and turbine. Foil-type gas-lubricated bearings are designed such that all excursions are absorbed by a film of gas, which together with the foil, has a definable spring constant. With proper design, the rotor does not contact any bearing surface after it achieves a small fraction of the normal rotational speed during start. Because nothing rubs, there is no wear-out mode.

The alternator has a high performance samarium cobalt rotor. This rotor is smaller and lighter than a Rice alternator. Because it is smaller, the windage loss is much smaller. The alternator has the following performance:
## TABLE 6

TURBINE AND COMPRESSOR WHEEL CHARACTERISTICS

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<thead>
<tr>
<th></th>
<th>Turbine</th>
<th>Compressor</th>
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<tbody>
<tr>
<td><strong>Pressure Ratio</strong></td>
<td>2.01</td>
<td>2.18</td>
</tr>
<tr>
<td><strong>Tip Speed</strong></td>
<td>440 m/sec (1440 ft/sec)</td>
<td>400 m/sec (1300 ft/sec)</td>
</tr>
<tr>
<td><strong>Mean Specific Speed</strong></td>
<td>62.0 rpm-ft$^{3/4}$/sec$^{1/2}$</td>
<td>58.5 rpm-ft$^{3/4}$/sec$^{1/2}$</td>
</tr>
<tr>
<td><strong>Tip Diameter</strong></td>
<td>23.4 cm (9.2 in.)</td>
<td>21 cm (8.3 in.)</td>
</tr>
<tr>
<td><strong>Reynolds Number</strong></td>
<td>380,000</td>
<td>24 x 10$^6$</td>
</tr>
<tr>
<td><strong>Mass</strong></td>
<td>11.4 kg (25 lb) Refractory or Advanced Superalloy</td>
<td>2.7 kg (6 lb) Titanium</td>
</tr>
<tr>
<td><strong>Efficiency</strong></td>
<td>91 Percent</td>
<td>86 Percent</td>
</tr>
<tr>
<td><strong>Comments</strong></td>
<td>o State of the art aero dynamic design</td>
<td>o High efficiency because of low pressure ratio, moderate specific speed and Reynolds number</td>
</tr>
<tr>
<td></td>
<td>o Relatively small wheel with low tip speed</td>
<td>o Low risk aero dynamic design</td>
</tr>
</tbody>
</table>
Efficiency  96% without windage  
Output  408 kW<sub>e</sub>  
Frequency  3000 Hz  
Voltage  500 Line-to-Neutral

The alternator is mounted adjacent to the compressor rather than the turbine so that it has a lower temperature environment. The alternator is cooled by heat pipes. The heat is dumped by the alternator heat pipe radiator.

2.3.5 **Recuperator**

The recuperator is the component which enables the high efficiency of closed Brayton cycle engines. It exchanges the heat from the turbine discharge gas to the colder gas leaving the compressor. Extensive recuperation leads to relatively low-pressure ratios in the turbomachinery. Low-pressure ratio yields simple, highly efficient compressors and turbines. The mass of the turbomachinery is also reduced. All of these beneficial results require increased recuperator mass. Shotgun plots such as Figures 5 through 12 illustrate this effect, revealing the best combination of components to be selected for each application.

The recuperator is shown in Figure 26. It is a pure counter flow design to minimize mass. Each flow is split and moves through alternate finned passages. The heat from the turbine discharge gas is exchanged by convection to the fin and wall and thence to the other gas stream. Each stream is completely sealed from the other.

The selected recuperator uses a conventional fin design of 8 fins/cm (20 fins/in.). The heat transfer data were derived from AiResearch development testing. Similar finning is used in present production units. The computer code uses this data to...
### Characteristics

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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<tr>
<td>EFFECTIVENESS</td>
<td>88%</td>
</tr>
<tr>
<td>WELL WITHIN STATE-OF-THE-ART</td>
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<tr>
<td>TOTAL PRESSURE DROP (ΔP/P)</td>
<td>1.6%</td>
</tr>
<tr>
<td>OVERALL LENGTH</td>
<td>48 cm (19 INCHES)</td>
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<tr>
<td>HEIGHT</td>
<td>79 cm (31 INCHES)</td>
</tr>
<tr>
<td>WIDTH</td>
<td>41 cm (16 INCHES)</td>
</tr>
<tr>
<td>MASS</td>
<td>365 kg (805 lb)</td>
</tr>
<tr>
<td>HEAT TRANSFER RATE</td>
<td>1552 kWt (1471 BTU/SEC)</td>
</tr>
<tr>
<td>MATERIAL</td>
<td>HOT END MUST BE REFRACTORY (Cb)</td>
</tr>
<tr>
<td></td>
<td>COLD END COULD BE SUPERALLOY (HAST-X)</td>
</tr>
<tr>
<td>OTHER ASSEMBLY OPTIONS</td>
<td>REFRACTORY HEAT PIPE HOT END, HAST-X</td>
</tr>
<tr>
<td></td>
<td>USED AT TEMPERATURES BELOW 1033°K (1400°F)</td>
</tr>
</tbody>
</table>

Figure 26. Recuperator Design Concept and Characteristics
gas properties, state point, and desired effectiveness and pressure drop to calculate the geometry and mass of this heat exchanger.

Each recuperator has a mass of 365 kg (805 lb). The effectiveness of 88 percent is easily within the state of the art. (Effectiveness defines the percentage of heat available from the turbine exhaust gas which is transferred to the compressor discharge gas.) The design is compact, with dimensions shown on Figure 26. The only area needing development is manufacturing technology. Analytical study is needed to define the assembly method. The refractory materials are well-characterized, but some work is needed to demonstrate joining techniques. Other heat exchange/manufacturing options are available and should be explored.

2.3.6 Heat-Pipe Radiator Design

The heat-pipe radiator is the largest and most massive component in the power system. This radiator rejects the fraction of the input heat that is not converted to electricity to the sink of space. Figure 27 illustrates the heat balance for the entire system. The geometry of the radiator is defined by the closed cycle engine design program. This geometry is a function of heat rejection rate, compressor inlet temperature, pressure drop, and flow rate. This radiator was designed to fit into the Space Shuttle bay.

The cylindrical radiator is composed of eight identical panels. The amount of bending of the heat pipes required to yield the cylindrical geometry has no deleterious effect on the heat-pipe performance, according to Thermacore. The manner in which these panels overlap is shown in Figure 28. The gas heat exchanger of each radiator is protected from micrometeoroid penetration by the overlapping heat pipes from the adjacent panel. A multifoil insulation blanket is also sandwiched between the gas heat exchanger and heat rejection panel to provide thermal isolation and additional micrometeoroid protection.
Figure 27. Heat Balance for 400-kW<sub>e</sub> Brayton Power System.
Figure 28. Cylindrical Heat Pipe Radiator Conceptual Design
Figure 29 is an illustration of the heat-pipe radiator that shows the gas heat exchanger, heat pipes, and fin. There are two gas heat exchangers, either of which can carry the entire thermal load to the heat pipes. When both redundant power systems are operated at half power, each heat exchanger carries half of the thermal rejection load. In any event, the radiator panel always carries the entire thermal load.

Figure 29 also lists the performance of the hot-end and cold-end heat pipes as well as the geometry of the gas heat exchanger. Diameter of the evaporator heat pipes is 2.5 cm (1 in.) to achieve adequate gas-side heat transfer area. The diameter of condenser heat pipes varies from 0.6 to 1.3 cm. This use of dual diameters greatly reduces the mass of armor from that which otherwise would have been required. The mass of the heat pipes is also reduced.

As the data in Appendix A show, the smaller diameter heat pipes have adequate heat-transfer capacity with reasonable temperature drop down the pipe. Clearly, a larger diameter heat pipe would have a greater heat transfer capacity. While analytical methods have not been fully characterized for a tapered pipe (e.g., a large diameter evaporator coupled to a smaller diameter condenser with a short tapered transition), such pipes have been fabricated and tested. Thermacore has concurred that this approach is basically sound and that there should be very little uncertainty of the feasibility of such a pipe.

A mass summary for the radiator is given in Table 7. The two largest contributors are the gas heat exchanger and heat pipes. Some mass reduction in the heat pipes is possible if thinner walls are used (the present design has a wall thickness of 3 to 6 percent of diameter). Mass reduction is also possible with the new armor design being investigated by Thermacore. Furthermore, the mass of the gas heat exchanger could be reduced by use of composite materials. Some
Figure 29. Heat Pipe Radiator Heat Exchanger Design Concept and Characteristics.
TABLE 7

MASS SUMMARY FOR RADIATOR WITH DUAL-DIAMETER HEAT PIPES

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass, kg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evaporator Heat Pipes</td>
<td>766</td>
</tr>
<tr>
<td>Heat Exchanger Wrap Up</td>
<td>1433</td>
</tr>
<tr>
<td>Condenser Heat Pipes</td>
<td>650</td>
</tr>
<tr>
<td>Armor</td>
<td>439</td>
</tr>
<tr>
<td>Fins</td>
<td>752</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>4040</td>
</tr>
</tbody>
</table>
slight reduction in fin mass is also possible. Summing these contributions would result in a total radiator mass of less than 3800 kg. This would reduce the system specific mass (Jovian environment) to 20 kg/kWₑ.

Stainless steel was selected for the heat pipes because of its compatibility with the heat pipe working fluids. Steel was also selected for the gas heat exchanger because of its strength to weight ratio. Beryllium or Lockalloy (Be38Al) was selected for the armor because of its low density, high modulus of elasticity and high thermal conductivity. Either of these materials could also be used for the fin because of low density and high conductivity.

2.3.7 Power Conditioning and Associated Heat Rejection

The power conditioning is accomplished by a solid state device which converts 500 VAC line to neutral to 1100 VDC. This device is basically a bridge rectifier. Efficiency is 98 percent.

The waste heat from this device must be rejected to space. A separate heat-pipe radiator is used. The evaporator is thermally attached to the appropriate electronics. The condenser is attached to a fin and radiates the waste heat to space. For the 400-kWₑ NEP, this radiator is a right circular cylinder 0.6 m high and 4 m in diameter. During launch, this radiator is stored inside the main radiator with the payload. After launch, the radiator and payload are deployed, allowing the closed cycle engines and thrusters to be activated.

2.3.8 Alternator Radiator

As shown in Figure 27, the alternator radiator must remove 20 kWₑ. This radiator comprises the aft 2 m of the 3.2 m diameter cylindrical enclosure of the power system which is sufficient to maintain the alternator temperature at 390°K (240°F). Contact with ion engine designers indicates that there will be minimal interaction with ion beam and that thin graphite coatings (ε ≈ 0.85) will provide satisfactory erosion resistance.
3.0 CONCLUSIONS

Current results clearly show that a nuclear electric spacecraft with a 400-kW\textsubscript{e} reactor Brayton power system can be placed in orbit by a single Shuttle launch. The 400-kW\textsubscript{e} reference system identified by this study employs a 1990 technology turbine inlet temperature of 1500\textdegree{}K (2240\textdegree{}F) using available refractory alloys and other conservative design parameters. Practical systems over the power range from 100 to 1000 kW\textsubscript{e} have been identified with TITs from 1325 to 1650\textdegree{}K, and possibly 1800\textdegree{}K. Essentially current (1985) to projected (1995) technologies are represented, utilizing materials from superalloys to high-temperature refractory alloys and, ultimately, to ceramics. Use of a heat-pipe-cooled reactor, independent redundant power conversion loops, and heat-pipe radiators eliminates the single-point failure modes. The specific mass performance parameter for the 400-kW\textsubscript{e} power level is within 5 percent of the goal of 20 kg/kW\textsubscript{e} which compares favorably with power systems based on other conversion means. Further refinement of the 400-kW\textsubscript{e} system design with the new LASL layered core reactor, specifically tailored Brayton components, and more detailed design of the primary radiator based on new heat-pipe concepts will provide specific system masses below 20 kg/kW\textsubscript{e}.

The heat-pipe cooled reactors now being defined by LASL utilize a relatively new concept that employs advanced technology. These reactors have great promise for broad applicability. Substantial research and technology work as well as subsequent development and testing are needed and should be strongly supported.

While closed Brayton cycle technology is receiving support because of its breadth of recognized applications, the special requirements for space service (e.g., performance parameters such as low specific mass, high efficiency, and reasonable specific radiator area; very high reliability with long life; and low comparative costs) need to be evaluated by parametric systems analysis and subsequent
research and technology work. Typical topics that need to be addressed include high-temperature materials, advanced heat exchangers, rotating machine elements including bearings, heat-pipe space radiator concepts, power processing elements, etc. Broad research and technology efforts in applicable types of advanced heat pipes are especially needed.

Future space missions are currently not well enough defined to permit proper focusing of technology and development efforts. More detailed optimizations of various classes of advanced missions are needed combining spaceflight trajectory analysis and parametric systems analysis with programmatic factors in the 1990 to 2010 time frame and beyond. This work is needed to help identify the kinds of technology that will be most useful and its timing.

Based on the study results, space power systems that use closed Brayton cycles may well find application in future nuclear electric spacecraft when definitive comparisons with other systems that include all pertinent factors are completed. Clearly, further work is needed to ascertain the degree and extent of the promise of CBC system vis-a-vis the competing power conversion systems.
4.0 RECOMMENDED FURTHER STUDIES AND ANALYSES

Based on results of the work accomplished in this study as well as previous efforts over many years on space power system development, the following recommendations are made for further studies and analyses of reactor Brayton power systems for nuclear electric spacecraft. In order to keep a technology viable, some continuity of effort is needed that keeps a minimum level of effort active. This is especially true at present when the new capabilities of the Space Shuttle transportation system are beginning to be understood and exploited. The Shuttle will have an increasing influence on the course of solar system exploration in the late 1980s, 1990s, and beyond, especially as the contribution of nuclear electric rocket propulsion is realized. Closed Brayton cycle power conversion, in both its established and advanced forms, has a role to play in the space power systems that are needed for solar system exploration, as well as a wide variety of other missions.

4.1 Refined System Designs, Including Reliability-Life Characteristics

The conceptual design of the 400-kW$_e$ reference system should be refined to include LASL's new layered core reactors, specifically designed Brayton components, and detailed design of space radiators based on well-developed heat-pipe data. It may be desirable to investigate other specific power levels; for example, the currently identified 1200-kW$_e$ LASL layered core reactor would provide between 250 and 350 kW$_e$ using a Brayton power conversion system. In addition to determination of performance parameters in greater detail, it is timely to undertake the introduction of reliability and life factors in the analysis. The conversion of the present system design code into a parametric systems analysis code with modular elements should also be investigated.
4.2 Advanced Component Design

Current analytical techniques do not allow tailoring each Brayton component in detail for specific mission as well as system requirements. AiResearch recommends that the effect of novel heat transfer concepts, materials, configurations, and other requirements be investigated for the major Brayton components. A typical system design, such as the current 400-kWe approach, would form the basis for this effort. Such important considerations as reliability, life, and cost need to be included as well as performance tradeoffs.

4.3 Space Radiator Designs with Advanced Heat Pipes

The primary heat rejection radiator is the dominant element in Brayton power systems for space applications. Special attention should be given to further conceptual design and analysis of space radiators with advanced heat pipes configured especially for this use. Many neoteric heat pipe designs, with wall materials and working fluids matched to the specific requirements of temperature, shape, meteoroid protection, and other pertinent requirements, should be evaluated.

4.4 System Operations and Safety

A study is recommended of the operational requirements of Brayton systems in space power service. The various operational phases such as system assembly, ground checkout, launch operations, orbital transfer, automated start-up, and power system regulation in space need to be studied and analyzed, especially with respect to their effect on overall system safety. Interactions of the Brayton components with the nuclear subsystem, spacecraft, and space transportation systems should be evaluated in, at least, an introductory manner. Preliminary outlines of the required system safety documents should be generated for interactive discussions with cognizant agencies.
4.5 Probability of Mission Success

The influence of the power system on the probability of mission success and the design and operational characteristics of the Brayton components are recommended for study in detail. This will require definition of typical missions in terms of mission goals and operational sequences. Since nuclear electric spacecraft will be used for complex missions throughout the solar system for durations of ten or more years, these reliability/availability studies are required to maximize the probability of performing a wide variety of missions successfully.

4.6 Economic Analyses Including Risks

Although non-recurring and recurring costs of Brayton power systems for space cannot be determined now with satisfactory accuracy (since only conceptual system designs and sketchy mission application information are available), it is not too soon to begin to develop the methodology for economic analysis. At the least, this will result in the necessary data being identified. Economic analyses of advanced systems, especially if they are to deal with risk, must be conducted on a probabilistic basis. Since it is necessary to keep such analyses as simple and clearly defined as possible, as appropriate to the available data and sophistication of the results, it is strongly recommended that the methodology for such analyses be formulated relatively early in the development program.

4.7 Space Shuttle Compatibility

An understanding of the Space Shuttle transportation system in some detail is necessary to be sure the Brayton-powered, nuclear electric spacecraft will be compatible with ground, launch, and space operations. Early attention to the detailed interfacing of the Brayton power system with the nuclear electric spacecraft and the Space Shuttle orbiter in all regimes is recommended.
5.0 RECOMMENDED TECHNOLOGY EFFORTS

In general, the closed Brayton power conversion system can be characterized as a mature technology ready for application (e.g., flight system development). The rather unusual operating conditions* required for the optimal systems defined in this study engenders a requirement for technology development in certain areas. Also, it must be recognized that there is currently very little supporting research or advanced technology either underway or being proposed which is aimed specifically at the requirements of space Brayton systems. Therefore, this section addresses these supporting technology needs and defines a preliminary schedule. This program would result in the required technology being demonstrated by target dates that are commensurate with current projections of flight system applications.

As summarized in Figure 30, a scenario of projected technology utilization for prospective flight applications has essentially been developed in Section 2.0 of this report. This figure indicates that the power requirements will increase exponentially with time. As described previously, a five-year flight system development and qualification program is assumed; therefore, technology readiness** needs to have been demonstrated five years before the proposed launch date.

*In terms of past space studies as well as more contemporary analyses of terrestrial power systems, the results of this study are characterized by lower efficiencies, higher ratios of CIT to TIT and lower recuperator effectivenesses to minimize the radiator mass and, thereby, the system mass.

**Technology readiness is that stage of system, subsystem, or component development where all major problems associated with achieving the specified on performance goals have been solved and where the solutions to problems have been successfully demonstrated through actual hardware design, fabrication, and test programs. At this stage, there remain no major risks for an agency or contractor in scaling up the technology (if full-scale demonstration has not been performed) and in proceeding with mission/commercial development of the system, subsystem, or component.
Figure 30. Prospective Nuclear Spacecraft Power Requirements Versus Technology Readiness.
Figure 30 shows three increasingly stringent levels of nuclear reactor powered system applications:

- 100-kW_e power systems in the early 1990s
- 400-kW_e power systems in the mid 1990s
- 1000-kW_e power systems at the turn of the century

A schedule which lists the technology development areas required for increasingly sophisticated missions is shown in Figure 31, and discussed in some detail subsequently. It is important to note that approaches to the required technology can be defined at this time, e.g., no fundamentally new technology or "technical breakthrough" is required.

In projecting the technology requirements, the reactor heat source is not included. It was assumed that the current LASL development program will continue under independent sponsorship and that this program will yield the reactor technology as it becomes required.

5.1 100 kW_e System Technology

The current application forecast for this system is geocentric orbital power. Because of the large Shuttle lift capability for this class of missions, it is not necessary to achieve minimum system mass or volume to have a viable approach. This resulted in the choice of the 1325°C TIT, as noted previously.

The most necessary technology for this class of missions is in the area of materials. Current superalloys are limited to 1144 to 1172°C (1600 to 1650°F). Late developments in alloy modification using rapid solidification with powder metallurgy have currently resulted in allowable TIT increases of 56 to 83°C (100 to 150°F) with further improvement possible.
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<td><strong>100 kW$_{e}$ SYSTEM</strong></td>
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<td>HEAT SOURCE DEVELOPMENT</td>
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<td>FOIL BEARING DEVELOPMENT</td>
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<tr>
<td>SPACE RADIATOR</td>
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<td>HEAT PIPE LIFE DEMO</td>
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Figure 31. Schedule of Key Power Conversion Technology Elements Required for Reactor/Brayton Space Power Systems.
The relatively well characterized refractory metals such as niobium have adequate stress carrying capabilities but questions regarding potential degradation due to even the low oxygen partial pressure which exists in near-Earth space must be resolved. For example, the durability of existing anti-oxidation coatings in the hard vacuum of space must be established.

A substantiated bank of standardized design data needs to be assembled, including definition of design nominals and minimums as well as an accepted methodology for life projection. Thus, a fairly comprehensive materials characterization effort will be required.

The reactor heat pipes are exposed to the highest temperatures in the closed loop and, as previously noted, will be made from refractory metals such as molybdenum or niobium. Methods of efficiently integrating these heat pipes into the heat source heat exchanger need to be studied, analytically and empirically. Potential approaches include an all-refractory metal design as well as one in which the heat exchanger wall could be made from metal, using internal insulation to limit hot spot exposure. In the latter case, either a thermally resilient seal between the refractory and superalloy or a weldment/brazement into a diaphragm-type thermal stress relief might be used.

In recent years, foil type gas bearings have come into increasingly wide-spread use in various commercial turbomachinery. For example, the bearings on the DC-10 air-conditioning air cycle units have accumulated over $53 \times 10^6$ bearing operating hours of operation and currently exhibit a mean time between bearing failure of 249,000 hours. Concurrently with these applications, dramatic strides advanced this technology from an empirical base to a discipline solidly supported by analysis and field operation. However, this analytical characterization effort has recently stagnated. To provide a proper technology base, this effort needs to be re-instituted to
establish a uniform methodology (including analytical, fabrication, inspection, and performance verification) for a variety of applications including space power systems. An important element is the development of a hydrodynamic/elastic computer model. The derivation and empirical verification of the predictions of such a model will be extremely significant in the avoidance and/or timely correction of problems during future applications.

The heat-pipe radiator for the 100-kW system (Figure 4) requires very little extension to existing technology. A ground-based, horizontal, extended life test of heat pipes using Dowtherm A and either mercury or rubidium working fluids should be instituted as early practical to demonstrate that no unanticipated life-limiting mechanisms will be encountered. The data base for rubidium, especially, and mercury, to a certain extent, is insufficient for the heat-pipe designer's needs and should be expanded. The thermal decomposition or other life-limiting behavior of Dowtherm A should be investigated thoroughly as a function of temperature. To cut down the radiator mass, a statistically significant number of dual diameter (large evaporator, small condenser) heat pipes should be fabricated and subjected to thermal performance limit testing. Space testing of representative heat pipe designs should be undertaken at the earliest practical opportunity.

5.2 400-kW System Technology

Since the interplanetary spacecraft propulsion system uses the full Shuttle launch capability both in terms of injected mass and payload bay volume, power system performance is critical. Therefore, a higher TIT was selected for this system. In discussing the technology development implications for support of this system, it has been assumed that the items described in the preceding paragraph will have been completed, either in support of the 100-kW system development or under other program sponsorship in the intervening period.
The biggest payoff for the 400-kW\textsubscript{e} system is in the area of heat-pipe space radiator technology development. A comprehensive effort should be completed to evolve the most realistic set of environmental design requirements, particularly in the definition of micrometeoroid flux levels. The variations in such exposure over the candidate missions should be defined so that the armor is designed realistically.

Armor geometries, materials, and manufacturing and application techniques should be investigated to minimize the penalty due to this factor. The results of the current Thermacore study suggest that this topic has only recently begun to be pursued in the required depth. However, it may well have been completed prior to 1985, as the dashed line in Figure 31 indicates.

A concomitant effort on the investigation of the performance improvements possible by using advanced geometry heat pipes should also be completed, if not accomplished in the intervening years. Configuration-pumped and mechanically-pumped heat pipes are examples of the advanced types that need to be considered.

Additional materials development will be required to enable the 1500°K TIT (Figure 18) to be attained. Molybdenum and tantalum alloys are the leading candidates. The data base on these materials is sketchy and quite dated; thus, a significant effort in this area is indicated. Machinability, manufacturability, joining, and space environment tolerance under operating conditions are additional topics that will need to be addressed.

It will also be necessary to integrate the more advanced refractory materials into the heat source heat exchanger. It is believed that techniques which will have been developed for the 100-kW\textsubscript{e} heat source will be applicable, but this needs to be confirmed.
5.3 1000-kW<sub>e</sub> System Technology

The projected missions and launch vehicles for this class of power systems are in the very early definition phase. Thus, it cannot be stated unequivocally that the higher performance selected for this system will absolutely be required. In the eventuality that lower performance is acceptable, the 1000-kW<sub>e</sub> missions could be accomplished by ganging three of the 400-kW<sub>e</sub> systems with a fourth as the redundant spare to yield an overall system with fairly respectable performance specifics.

However, it must be recognized that the historical trend in aerospace is to use the available technological capability to the fullest. Few rocket-powered vehicles have been launched that used only a fraction of their lifting capability, and there is little reason to suspect that this trend will change in the future (early projections regarding the usage of the space transportation system notwithstanding). Therefore, this section will address technology development required to support the CBC systems operating at a TIT of 1650°K (2510°F) as listed in Figure 30.

In common with the systems described previously, the largest implication is on the materials needed for the high temperature components. As noted in Section 2.1.4 and indicated by the dashed line in Figure 31, the ceramic technology needed for this system is currently under active development for a number of programs. The differing requirements of the space power system will necessitate that a thorough analytical study, with possibly some supporting empirical effort, be undertaken to define how this technology may best be applied.

Following this effort, three fabrication/demonstration efforts associated with materials integration into critical components should be pursued. The ceramic turbine and associated static components
should be fabricated and assembled unless prior efforts have shown that components of the appropriate scale and materials have already been achieved. Most probably, ceramics will have to be used extensively in the reactor and ceramic heat pipes will be used between the reactor and heat source heat exchanger. The approach for providing extended surface on the condenser end in the heat source heat exchanger and the methods for sealing and integrating the heat pipes through the wall (ceramic or metallic) of the heat exchanger must be developed and demonstrated. Higher temperature capability materials are also needed for the recuperator. However, this should be within the range of the advanced refractories that will have been demonstrated at that point. Therefore, a fabrication/assembly technology demonstration program with these materials should be accomplished.
6.0 REFERENCES


3. JPL Cost-Plus-a-Fixed Fee Research and Development Contract No. 955008.


6. Conceptual Design Study of Improved Gas Turbine Powertrain, NASA Contracts DEN 3-37 with the Ford Motor Company and DEN 3-38 with Detroit Diesel Allison Division of General Motors, sponsored by DOE.


APPENDIX A

PRELIMINARY LETTER REPORT #1
FROM
THERMACORE, INC.

(56 Pages)
April 1979

PRELIMINARY LETTER
REPORT
#1

CONTRACT 955437

METEOROID PROTECTION METHODS
FOR SPACECRAFT RADIATORS
USING HEAT PIPES

PREPARED FOR

CALIFORNIA INSTITUTE OF TECHNOLOGY
JET PROPULSION LABORATORY
PASADENA, CALIFORNIA
HEAT PIPE DESIGN FOR CBC RADIATOR

The 400 kW Closed Brayton Cycle power system for the Nuclear Electric Propulsion Spacecraft has been designed by Garrett AiResearch to use heat pipes to achieve a thermally effective radiator which has a high survival probability. It is also anticipated that the heat pipe design will lead to a low specific mass. The heat pipe design evaluated in this work is for use in a cylindrical array as seen in Figure 3.1. This design has eight dual gas-to-radiator heat pipe heat exchangers fed from a dual central duct. The heat pipes are attached to both gas ducts over a length of 43 cm on each duct. Thus, the heat pipes provide armor protection for the gas ducts.

In normal operation, the total 86 cm length attachment over the heat pipes to the gas ducts will be used as heat pipe evaporators. The condenser is 176 cm long. If either gas duct or engine fail, then the whole power load will be transferred to the heat pipes through only one of the 43 cm attachments. Accordingly, for design consideration, the heat pipe must be sized as though it had a 43 cm evaporator, 43 cm adiabatic and 176 cm condenser.

Four different sets of heat pipe designs were analyzed with respect to mass and performance. However, no consideration was given to the required heat pipe armor and tradeoffs in the heat pipe diameter versus T-bar fins for total mass. The overall heat pipe cell dimension as designed by GAR is 3.175 cm (1.25") and includes heat pipe and fins. All heat pipes discussed in the Sections 3.1 and 3.2 have computer printouts of their performance tabulated in Appendix 1.
3.1 **Baseline Design**

The total power to be dissipated is $1.1 \times 10^6$ watts. From the gas side of the radiator heat exchanger, heat pipe temperatures were calculated by Garrett AiResearch to range from $707^\circ K$ down to $492^\circ K$. The power levels are 720 watts per heat pipe at $707^\circ K$ and 169 watts per heat pipe at $492^\circ K$. Thus, $\sigma A \varepsilon$ can be computed to be $2882 \times 10^{-12}$ watts/$^\circ K^4$ from:

$$P = \sigma A \varepsilon T^4$$

Equation 3.1

where

- $P = \text{power radiated - watts}$
- $\sigma = \text{Stefan Boltzman Constant} = 5.67 \times 10^{-12}$ watts$^2$ cm$^{-2}$ $^\circ K^{-4}$
- $T = \text{heat pipe temperature - } ^\circ K$
- $A = \text{individual heat pipe radiating area - cm}^2$
- $\varepsilon = \text{effective thermal emissivity}$

Table 3.1 shows the required heat pipe power for each of the end temperatures and each temperature divisible by $25^\circ K$.

Garrett AiResearch's baseline design is a 2.54 cm (1") O.D. heat pipe with a 0.0762 cm (.03") wall. The optimum heat pipe designs under these conditions are seen in Table 3.2. Rubidium is the preferred heat pipe fluid from $707^\circ K$ down to $650^\circ K$. Below $650^\circ K$ Dowtherm A (DTA) is the preferred fluid. In both cases, a screen covered groove design is found to be the lowest mass system. The rubidium heat pipes have a 1.75 Kg mass. The DTA heat pipes have a 1.74 Kg mass.

Table 3.3 shows the same heat pipes, which have been, for the most part, optimized with respect to the number of grooves and their aspect ratio. The rubidium heat pipes have a 1.48 Kg mass. The DTA heat pipes have a 1.55 Kg mass.
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REQUIRED POWER PER HEAT PIPE AT ELEVEN DIFFERENT TEMPERATURES
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## Table 3.3

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<td></td>
<td></td>
<td>3.55</td>
<td>555-C</td>
<td>1.55</td>
</tr>
</tbody>
</table>
The average mass reduction is 14%. Further optimization may result in an additional 1 or 2% mass reduction. However, far greater mass reduction can be realized by O.D. and/or wall thickness reduction.

Table 3.4 shows the 2.54 cm (1") heat pipe with a 0.025 cm (.01") wall. This wall thickness is 0.01 times the diameter and has been shown to be acceptable for use as a heat pipe containment vessel where external buckling is the ultimate constraint, i.e., the internal pressure of the heat pipe was less than 14.7 psi, thus long term creep due to hoop stress was low.

The use of a wall thickness 0.01 times the diameter was developed for Niobium, which has a modulus of elasticity of $15 \times 10^6$ psi. This includes a safety factor of 2. Stainless steels have moduli of about $28 \times 10^6$ psi which reduces the thickness/diameter ratio to about 0.008 with a safety factor of 2. However, the use of 0.01 as a thickness to diameter ratio will be used to assure success.

Examination of DTA at $625^0K$ shows a fluid pressure of 85 psi which develops a hoop stress of 4250 psi. This stress is acceptable, since 316 SS will only creep 0.1% in $10^5$ hours at $1100^0F$ under a stress of 6000 psi.

The rubidium heat pipes have a mass of 0.69 Kg and the DTA heat pipes have a mass of 0.78 Kg.

3.2 Design Optimization

Examination of Tables 3.2, 3.3 and 3.4 reveals that a reduction in diameter of the rubidium heat pipes would soon result in the heat pipe going sonic. However, the DTA pipes are capillary limited, thus a reduction in O.D. is possible. Accordingly, a higher pressure fluid, mercury,
**TABLE 5.4**

OPTIMIZED HEAT PIPE MASS & PERFORMANCE FOR THIN WALLED BASELINE DESIGN

<table>
<thead>
<tr>
<th>Evaporator - 43 cm</th>
<th>Fluid: Rb</th>
<th>Vessel: 304 SS</th>
<th>Fluid: DTA</th>
<th>Vessel: 204 SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adiabatic - 43 cm</td>
<td>O.D.: 2.54 cm</td>
<td>Wall: 0.0254 cm</td>
<td>O.D.: 2.54 cm</td>
<td>Wall: 0.0254 cm</td>
</tr>
<tr>
<td>Condenser - 176 cm</td>
<td># Grooves: 25</td>
<td>Groove Width: 0.275 cm</td>
<td># Groove: 25</td>
<td>Groove Width: 0.275 cm</td>
</tr>
<tr>
<td>S = Sonic Limit</td>
<td>C = Capillary Limit</td>
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<td></td>
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</table>

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Req. Power (Watts)</th>
<th>ΔT @ Req. Power (°C)</th>
<th>Power Limit (Watts)</th>
<th>Mass (Kg)</th>
<th>Groove Depth (Cm)</th>
<th>ΔT @ Req. Power (°C)</th>
<th>Power Limit (Watts)</th>
<th>Mass (Kg)</th>
<th>Groove Depth (Cm)</th>
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</thead>
<tbody>
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<td>707</td>
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<td>720</td>
<td>1.55</td>
<td>820-C</td>
<td>0.69</td>
<td>0.02</td>
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<tr>
<td>700</td>
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<tr>
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<td>377</td>
<td>514</td>
<td>4.56</td>
<td>705-C</td>
<td>0.69</td>
<td>0.02</td>
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<tr>
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<td>352</td>
<td>440</td>
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</table>

Notes: O.D. = Outer Diameter, Wall = Wall Thickness.
was used in small diameter pipes in place of rubidium. These results are seen in Table 3.5.

The mercury heat pipes are 0.635 cm (.250") in diameter with a wall to diameter ratio of 0.01. The mass of the mercury heat pipes are 0.45 Kg and have a hoop stress of 625 psi at 7070K.

The DTA heat pipes are 0.9525 cm (.37") in diameter with a wall to diameter ratio of 0.01. They have 12 grooves 0.275 cm wide by a depth that varies from 0.075 cm down to 0.05 cm. Accordingly, their mass varies from 0.31 Kg down to 0.27 Kg. The DTA heat pipes at 6250K will have a hoop stress of 1600 psi.

The mercury heat pipes of Table 3.5 have eight grooves 0.2 cm wide by 0.02 cm deep. Optimizing the number of 0.275 cm wide by .02 cm deep grooves for different power levels results in a reduction in mass. At 7070K, a five-groove heat pipe has a mass of 0.29 Kg. At 6750K, four grooves have a mass of 0.28 Kg and at 5500K, three grooves have a mass of 0.27 Kg. These results are seen in Table 3.6. Also shown in Table 3.6 is the thermal performance of two of the mercury heat pipes with 86 cm evaporators, which shows an increase in maximum power capability and a reduction in total ΔT.

Both the DTA heat pipes of Table 3.5 and the mercury heat pipes of Table 3.6 have a performance ΔT. Accordingly, one asks what does a ΔT in the heat pipe mean in increased mass (length of condenser) to be able to radiate the required power? Appendix 2 develops Equation 3.2 which is the increase in mass of heat pipe due to its ΔT.

\[
\frac{dm}{m} = \frac{1}{t} \left[ \frac{1}{T_0} \left( \frac{T}{T_0} \right)^4 - 1 \right]
\]
Equation 3.2
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</thead>
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<td>707K 434C 720 Watts</td>
<td>2.69 930-S 0.45 0.02</td>
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<tr>
<td>700 427 692</td>
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<tr>
<td>675 402 598</td>
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<tr>
<td>625 352 440</td>
<td>1.98 900-C 0.45 0.02</td>
<td>15.04 515-C 0.31 0.075</td>
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<tr>
<td>600 327 373</td>
<td>10.73 420-C 0.29 0.065</td>
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<tr>
<td>575 302 .315</td>
<td>8.38 370-C 0.29 0.06</td>
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<tr>
<td>550 277 264</td>
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<td>6.49 355-C 0.28 0.055</td>
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<tr>
<td>525 252 219</td>
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<tr>
<td>492 219 169</td>
<td>4.05 215-C 0.27 0.05</td>
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</tr>
</tbody>
</table>
## Table 5

**Optimized Heat Pipe Mass & Performance - Alternate Design**

<table>
<thead>
<tr>
<th>Evaporator - 43 cm</th>
<th>Fluid: Hg</th>
<th>Vessel: 304 SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adiabatic - 43 cm</td>
<td>0.635 cm</td>
<td>0.00635 cm</td>
</tr>
<tr>
<td>Condenser - 176 cm</td>
<td># Grooves: 3-5</td>
<td>Groove Width: 0.2 cm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Req. Power (Watts)</th>
<th>ΔT @ Req. Power (°C)</th>
<th>Power Limit (Watts)</th>
<th>Mass (Kg)</th>
<th>Groove Depth (Cm)</th>
<th>ΔT @ Req. Power (°C)</th>
<th>Power Limit (Watts)</th>
<th>Mass (Kg)</th>
<th>Groove Depth (Cm)</th>
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</thead>
<tbody>
<tr>
<td>707</td>
<td>434</td>
<td>720</td>
<td>4.13</td>
<td>770-C</td>
<td>0.24</td>
<td>(5) .02</td>
<td>2.5</td>
<td>1625-C</td>
<td>0.29</td>
</tr>
<tr>
<td>700</td>
<td>427</td>
<td>692</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>675</td>
<td>402</td>
<td>598</td>
<td>3.62</td>
<td>610-C</td>
<td>0.28</td>
<td>(4) .02</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>650</td>
<td>377</td>
<td>514</td>
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</tr>
<tr>
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<td>352</td>
<td>440</td>
<td>3.30</td>
<td>445-C</td>
<td>0.27</td>
<td>(3) .02</td>
<td></td>
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<tr>
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<td>327</td>
<td>373</td>
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</tr>
<tr>
<td>550</td>
<td>277</td>
<td>264</td>
<td>8.35</td>
<td>350-C</td>
<td>0.27</td>
<td>(3) .02</td>
<td>4.79</td>
<td>560-S</td>
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</tr>
<tr>
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</tbody>
</table>
where $dm = \text{increase in mass}$

- $m = \text{initial mass of heat pipe}$
- $l_c = \text{length of heat pipe condenser}$
- $l_t = \text{total length of heat pipes}$
- $T_o = \text{desired operating temperature}$
- $T = \text{actual operating temperature}$
- $T_o - T = \Delta T \text{ down heat pipe}$

From Table 3.5 and 3.6, using the lowest mass heat pipes, the increase in mass was calculated using Equation 3.2 and is tabulated in Table 3.7. Therefore, to a first approximation, one can say that the heat pipes for the CBC radiator will have a mass of 0.3 Kg each.

The performance of the mercury heat pipes is based on perfect wetting, that is, the wetting angle is zero (0). For long term stability, this may not be the case. Wetting angles from 0-60 degrees have been observed, with 30-60 degree angles, the most common. Since the capillary force is a function of the cosine of the wetting angle, the mercury heat pipes may have a reduction of capillary force of up to 50% ($\cos 60 = .5$). This reduction in performance will then require a reoptimization of the heat pipes with a small increase in mass.
### Table 3.7

<table>
<thead>
<tr>
<th>Temperature (°K)</th>
<th>Power (W)</th>
<th>Fluid</th>
<th>Mass (Kg)</th>
<th>ΔT (°C)</th>
<th>dM (Kg)</th>
<th>New Mass (Kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>707</td>
<td>720</td>
<td>Hg</td>
<td>0.291</td>
<td>4.13</td>
<td>4.6 x 10^-3</td>
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<td>700</td>
<td>692</td>
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<td></td>
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<td></td>
</tr>
<tr>
<td>675</td>
<td>598</td>
<td>Hg</td>
<td>0.280</td>
<td>3.63</td>
<td>4.6 x 10^-3</td>
<td>0.284</td>
</tr>
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<td>514</td>
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</tr>
<tr>
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<td>440</td>
<td>Hg</td>
<td>0.273</td>
<td>3.30</td>
<td>3.9 x 10^-3</td>
<td>0.277</td>
</tr>
<tr>
<td>600</td>
<td>373</td>
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<td></td>
</tr>
<tr>
<td>575</td>
<td>315</td>
<td>Hg</td>
<td>0.273</td>
<td>5.81</td>
<td>7.5 x 10^-3</td>
<td>0.280</td>
</tr>
<tr>
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<td>264</td>
<td>DTA</td>
<td>0.280</td>
<td>6.49</td>
<td>1 x 10^-2</td>
<td>0.290</td>
</tr>
<tr>
<td>525</td>
<td>219</td>
<td>DTA</td>
<td>0.273</td>
<td>4.98</td>
<td>7.1 x 10^-3</td>
<td>0.280</td>
</tr>
<tr>
<td>500</td>
<td>180</td>
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<td></td>
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</tr>
<tr>
<td>492</td>
<td>189</td>
<td>DTA</td>
<td>0.273</td>
<td>4.05</td>
<td>6.2 x 10^-3</td>
<td>0.279</td>
</tr>
</tbody>
</table>
3.3 Advanced Heat Pipe Concept

The groove heat pipe designs of Sections 3.1 and 3.2 optimized to an approximate mass of 0.3 Kg per heat pipe, exclusive of fins and armor. This mass is quite low and may be acceptable in the overall system. However, there are several heat pipe design concepts which may offer further reduced mass with increased performance. These include but are not limited to arterial wick heat pipes and configuration pumped heat pipes.

3.3.1 Artery/Wick Heat Pipes

There is a natural division in heat pipe fluids which takes place at approximately 600°C. Above 600°C, the liquid metals are useful working fluids. Below 600°C, one generally deals with non-metallic fluids and devises structures which compensate for their inferior physical properties. The low temperature fluids, taken as a class, have relatively low latent heats of vaporization, low surface tension, and low thermal conductivity. The consequences are that for a given heat transfer rate, heat pipes using these fluids must move relatively large quantities of liquid with unusually low pressure losses, yet must maintain very thin liquid films in the heat flow path. The arterial wick structures of Figure 3.2 have been used to offset these property limitations. The artery provides the primary liquid return to the evaporator. This passage has a large hydraulic radius and provides a very low drag path. In the evaporator and condenser, a thin film of liquid is distributed circumferentially. The distribution wick is often a thin layer of screen or circumferential grooves.

The artery is removed from the evaporator and condenser heat flow paths. The thin films provided by the circumferential wick prevent the
Figure 3.2 Representative Wick Geometries
development of excessive temperature gradients. Arterial wicks provide very high performance, sometimes even approaching that obtainable with liquid metals in more conventional wicks. Lengths in excess of ten meters have been reported. The primary limitations of arterial wicks lie in their difficulty of fabrication and their consequent lack of reproducible performance. The wick structures are quite difficult to form and to insert into the heat pipe vessel so as to maintain uniform close fit to the wall. There has been repeated difficulty with the priming of arteries, that is, the ability to fill an artery with fluid and keep it filled.

Two methods of priming are in use. Capillary priming, as the name implies, depends on capillary forces to maintain the fluid within the artery. The basic condition for capillary priming is that the largest single pore at the artery surface in the evaporator must provide sufficient capillary pressure to offset all counter forces including accelerations. Consequently, the evaporator ends of the arteries must be closed and there must be no single inadvertently large pore on the entire periphery of the enclosing surface. Due to the adverse effect of accelerations, capillary primed arteries can be more fractious during ground testing than in subsequent zero g operation. Yet ground testing is essential to establish the operability of the heat pipe.

If the artery is so located in the heat pipe temperature gradient that it always is the coldest spot, it will operate at a lower vapor pressure than the balance of the heat pipe. If the magnitude of the vapor pressure difference is sufficient, it will cause priming to take place. This is known as vapor pressure or Clapeyron priming. The process is highly temperature dependent. The pressure difference caused by a given temperature difference varies enormously with temperature. Thus, a heat pipe which primes reliably
and quickly at high temperature (i.e. high pressure) may fail to prime at all at low temperature. It has also been reported that vibration has caused arteries to lose their prime and that subsequent re-priming can be unreliable.

In spite of their apparent drawbacks, the performance of arterial heat pipes is sufficiently high to justify further work to improve their reliability and reproducibility. In general, arterial wicks require less total mass of wicking material, and may also require less fluid inventory than conventional heat pipes. They are, therefore, serious candidates for use in space radiator.

### 3.3.2. Wickless (Configuration Pumped) Heat Pipes

A crevice has capillary properties. Therefore, if the wall of a non-round heat pipe is formed so as to produce longitudinal crevices, these may serve the purpose of wicks. That is, the configuration of the wall provides the capillary pumping force. Several potential configuration pumped heat pipe geometries are shown in Figure 3.3. Configuration pumped heat pipes have been built (Figure 3.4) and have been shown to operate. However, there has been very little work in the field, and the mathematical prediction of performance is incomplete.

The driving pressure difference which causes liquid flow in a heat pipe is determined by the surface tension and the difference in the radius of the liquid meniscus in the condenser and evaporator. Evaporation in the heat input section tends to depress the liquid level while condensation at the heat output end tends to increase the level. Thus, during operation, the liquid level in the evaporator of a configuration pumped heat pipe recedes into the crevice, increasing the pumping pressure but decreasing
Figure 3.3 Configuration Pumped Geometries
Photograph of a Configuration Pumped Heat Pipe
(Courtesy of U.S. Air Force)

FIGURE 3.4
the flow area. The inverse occurs in the condenser. This makes for a delicate tradeoff of liquid fill versus power handling capability. The problem is somewhat alleviated in the configuration/artery geometry of Figures 3.3d and 3.3f.

Configuration pumped heat pipes tend by their nature to have relatively low capillary pumping forces and low liquid drag. They therefore lend themselves well to consideration as elements in low temperature space radiators where large radiating areas require long heat pipes. The liquid inventory requirement of configuration pumped heat pipes appears to be comparable to that of the arterial structures discussed previously. The complete absence of conventional wicks is a substantial mass reduction. However, the non-round shapes are relatively poor pressure vessels so that the gain in mass due to elimination of the wick may be at least partially offset by a thicker wall requirement unless fluid vapor pressures are kept relatively low. Thus the operating temperature range for a configuration pumped heat pipe of low mass may be narrower than that for other geometries.

The ability of configuration pumped heat pipes to hold their shape is a function of the creep strength of the heat pipe envelope. Thermacore previously identified the iron alloy, A-286, which exhibits an exceptionally high creep strength, and may well serve as a containment for configuration pumped heat pipes. (A-286 has a 0.1% creep at 1100°F in $10^5$ hours under a 38,000 psi stress load).

3.3.3. Hybrid Wick/Pumped Heat Pipes

Since the dissipating capacity of a space radiator declines as the fourth power of any temperature loss, there is a strong incentive to minimize
losses. One of the principal advantages of the heat pipe is the low temperature loss it incurs while moving large amounts of heat. This low ΔT operation is characteristic of vapor heat transfer. There may, therefore, be reason to make use of vapor heat transfer even at power levels which cannot be sustained by capillary pumping alone. Alternative or hybrid pumping means are possible and deserve consideration. This may be true not only for the radiators themselves, but also for the primary loops feeding them. A practical hybrid system may use an alternative pumping means for liquid transport over appreciable distances with capillary pumping for local distribution and collection.

The heat transfer capability of a conventional heat pipe can be limited by entrainment of liquid from the walls by the high velocity, counterflowing vapor. Separation of the liquid and vapor passages will permit greater heat flow under these conditions. Figure 3.5 is a hybrid system where the liquid and vapor flow are in the same direction. Therefore, the vapor shear forces may aid rather than inhibit liquid flow.

Hybrid heat pipes are directly analogous to two-pipe steam heating systems for buildings which use condensate pumps for liquid return. The principle has been extended to liquid metals by Philips Laboratories for use in Stirling engines.

The main disadvantages of the hybrid system are the increased probability of a leak at pump seals and joints and the dependence of operation on an external power source. For maximum redundancy, there should be a pump for each heat pipe, a serious penalty in complexity for a space radiator, making the approach seem more applicable to primary loops.

It may be possible to make use of the "heat of the radiator" to pump the liquid, much the same way that a capillary pump makes use of the "heat
Figure 3.5 Mechanically Pumped Hybrid Heat Pipe
of the radiator."

Thermacore has recently begun the exploration of a "liquid piston pump" as part of its internal R&D effort. This pump uses a localized high heat flux, into the fluid, to develop a vapor bubble of sufficient pressure to push the liquid forward. Backward flow is prevented by the use of a check valve. A forward spring loaded valve allows the pressure at which the pump activates to be regulated.

Initial work to date has concentrated on gravity feed liquid systems with encouraging results. The extension of this concept to two phase systems with freedom from gravity will pose challenging work but may be worth a cursory investigation.

3.3.4. Other Concepts

There are numerous concepts which have been suggested as possible fluid pumping mechanisms for heat pipes and includes electro-magnetic, electrolytic, electrohydrodynamic and electrophoretic pumping. All of these are not suited for individual spacecraft radiator heat pipes. However, osmotic pumped heat pipes and artificial gravity are two possible mechanisms which are suited for spacecraft use.

If a spinning spacecraft can be so arranged that its centrifugal force will aid liquid return in heat pipes, it may be possible to eliminate pumping and depend entirely or predominantly on artificial gravity for this function. The result may be mass reduction (by wick elimination and, possibly, reduced fluid inventory) and an added degree of freedom in fluid selection (fluid need not have high surface tension).

Osmotic pressures can exceed capillary pressures by a factor of 100 to
1,000. An osmotically pumped heat pipe is feasible in principle. Several designs have been proposed, but no hardware tests have been reported. The proposed designs all make use of gravity in one way or another: to keep liquid in place, to redistribute salt by natural convection, etc. It may be possible to devise a geometry which will function in gravity-free space. If so, osmotic heat pipes may avoid entirely the capillary limitations on available pumping pressure.

Flow rates through semi-permeable membranes are low; i.e., large areas are required to permit useful heat flow. There is, however, an interesting factor which may favor further consideration for low temperature space radiators. These radiators also require large areas because of the low radiant power densities. The osmotic process is such that the membrane must be located at the condenser (heat dissipating) end of the system, which is the radiating surface of a radiator. At temperatures below about 900 K, the power density from a black body radiator is less than the power density sustainable by flow of the best fluids (e.g. water) through membranes. That is, below this temperature the unit liquid flow rate through a membrane is more than sufficient to support the unit radiant heat load from a radiator of equal area, and a basic condition of successful operation has been satisfied.

The geometries considered to date are relatively massive, having two walls and a large liquid inventory. Membranes do not exist for operation above about 400 K. However, since an osmotic heat pipe would need no auxiliary power (comparable to a capillary heat pipe), it deserves further consideration.
APPENDIX 1

This appendix has complete performance printouts of all the heat pipes tabulated in Section 3.1 and 3.2. The heat pipe program used is Thermacore's GROOVE27. Figure A.1 depicts the placement and definitions of many of the symbols in the printout.

<table>
<thead>
<tr>
<th>Evaporator</th>
<th>Adiabatic</th>
<th>Condenser</th>
</tr>
</thead>
<tbody>
<tr>
<td>TE</td>
<td>TE-A</td>
<td>TC</td>
</tr>
<tr>
<td>(vapor)</td>
<td>TA-C</td>
<td></td>
</tr>
<tr>
<td>PE</td>
<td>PE-A</td>
<td>PA-C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>PC</td>
</tr>
</tbody>
</table>

Evaporator Temp. ← (Outside Wall) → Condenser Temp.

DPVE = Pressure drop in vapor in evaporator
DPLEG = Pressure drop in liquid in evaporator grooves
DPUA = Pressure drop in vapor in adiabatic
DPLAG = Pressure drop in liquid in adiabatic grooves
DPVC = Pressure drop in vapor in condenser - (+) means drop, (-) means recovery or increase
DPLGG = Pressure drop in liquid in condenser grooves
This appendix develops Equation 3.2 which shows how the mass of a radiator heat pipe increases with the performance \( T \) of the heat pipe.

\[ T_o = \text{desired heat pipe temperature} \]
\[ \Delta T = \text{temperature drop down heat pipe} \]
\[ T = T_o - \Delta T, \text{actual heat pipe radiating temperature} \]
\[ A_o = \text{radiating area of heat pipe at } T_o \]
\[ A = A_o + da, \text{actual heat pipe radiator area required at } T \]
\[ Q = \text{power to be radiated from heat pipe} \]

\[
\frac{da}{dt} = \frac{\Delta A}{T_o - T} \quad \text{Eq. A.1}
\]

\[
\text{but } A = \frac{Q}{\epsilon_o (T_o - T)^4} \quad \text{and } \quad A_o = \frac{Q}{\epsilon_o T_o^4}
\]

therefore, with substitution into Equation A.1 and proper rearranging,

\[
\frac{da}{dt} = \frac{A_o \Delta T}{(T_o / T)^4 - 1} \quad \text{Eq. A.2}
\]

Now, since area is a function of length, we have

\[
dl = l_c [(T_o / T)^4 - 1] \quad \text{Eq. A.3}
\]

where \( l_c = \text{condenser length} \), but \( \frac{dl}{l_t} = \frac{dm}{m} \) where \( l_t = \text{total heat pipe length} \),
\( m = \text{mass} \), we obtain with substitution and rearrangement -

\[
\frac{dm}{l_t} = \frac{m l_c}{l_t} [\frac{T_o}{T} - 1] \quad \text{Eq. A.4}
\]

which is Equation 3.2.
REFERENCES


RUN CONDITIONS:  
3:59 P.M. 4/5/70

FLUID = RUBIDIUM  WALL MATL=304SS
EVAP TEMP = 434  VAPOR DELTA-T = 50 DEG C
GAS ANG = 0.00  VTO ANG = 0.00 DEG

EVAP LENGTH 16.0291 IN 63.0000 CM
ADD LENGTH 16.0291 IN 63.0000 CM
COND LENGTH 69.713 IN 176.0000 CM
TOTAL LENGTH 105.1800 IN 262.0000 CM

O.D. 1.00 IN 2.5400 CM
WALL THICK 0.0700 IN 0.0762 CM
GROOVE WIDTH 0.0787 IN 0.2000 CM
GROOVE HEIGHT 0.0197 IN 0.0500 CM
LAND WIDTH 0.0346 IN 0.0876 CM
25 GROOVED (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT ------- 720 WATTS

--------- TOTAL DELTA-T = 2.66 DEG C
--------- TOTAL MASS = 1.749 KG

WATT PERFORMANCE DETAIL: (Y or N) ? Y

<table>
<thead>
<tr>
<th>PE</th>
<th>PE-A</th>
<th>PA-C</th>
<th>PC</th>
<th>DTHES/CM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>31291.9</td>
<td>30261.1</td>
<td>29954.9</td>
<td>30641.8</td>
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<table>
<thead>
<tr>
<th>P2</th>
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<th>PA-C</th>
<th>PC</th>
<th>DTHES/CM2</th>
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<td>430.502</td>
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EVAP TEMP 434  VAPOR DELTA-T 2.56104

<table>
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<tr>
<th>DPC-18214</th>
<th>DPC=0</th>
<th>DPC DPC=18214 DTHES/CM2</th>
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<table>
<thead>
<tr>
<th>DPV-1030</th>
<th>DPV=350</th>
<th>DPV DPLAG</th>
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</thead>
<tbody>
<tr>
<td>350</td>
<td>350</td>
<td>1115</td>
</tr>
</tbody>
</table>

| DPV-687 | 739 |

SONIC LIMITS:  EVAP= 2197  ADD= 2197 WATTS

G/A'S=  EVAP  COND  AXIAL  WATTS/CM2
| 2   | 0    | 142    |

E R R EY#  K A R EY#  L13 R EY#  C A R EY#  C R R EY#
| 21  | 3244  | 109    | 3247  | 8  |

HOT FLUID CHARGE 129.61 GRAMS
ROOM TEMP. VOLUME OF HOT FLUID CHARGE 94.6019 CM3

COLD FLUID CHARGE 151.635 GRAMS
98.6783 CM3

HEAT PIPE: (MESH) & 2 ENDCAPS 1596.3 GRAMS

DELTA-T VALUES:

<table>
<thead>
<tr>
<th>EVAP WALL</th>
<th>EVAP LGS</th>
<th>EVAP MASH</th>
<th>EVAP ASH</th>
<th>EVAPORATION</th>
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</thead>
<tbody>
<tr>
<td>328351</td>
<td>1208545-01</td>
<td>6688362-02</td>
<td>306233</td>
<td>DTHES/CM2</td>
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</tbody>
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<table>
<thead>
<tr>
<th>VAPOR (E)</th>
<th>VAPOR (A)</th>
<th>VAPOR (C)</th>
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</thead>
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<tr>
<td>1.3542</td>
<td>34.5683</td>
<td>-1.2173</td>
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<table>
<thead>
<tr>
<th>COND MESH</th>
<th>COND LG</th>
<th>COND WALL</th>
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</thead>
<tbody>
<tr>
<td>0.07337</td>
<td>-147542-02</td>
<td>29631015-02</td>
</tr>
</tbody>
</table>

POWER OF 1775 WATTS CAUSES ---------- ADD SONIC LIMIT

LAST NON-LIMITED POWER CALCULATION WAS AT ---------- 1760 WATTS

--------- TOTAL DELTA-T = 7.16 DEG C
--------- TOTAL MASS = 1.743 KG
**RUN CONDITIONS:**

- **FLUID:** HUBBIDON
- **WALL MATL:** 304 SS
- **EVAP TEMP:** 377°F
- **VAPOR DELTA-T:** 30°F
- **GRAY AM:** 0.00
- **WBD AM:** 0.00

**FLUID**

- **EVAP LENGTH:** 16.8291 in, 45.0000 cm
- **ADD LENGTH:** 16.8291 in, 45.0000 cm
- **COLD LENGTH:** 68.2913 in, 176.1000 cm
- **TOTAL LENGTH:** 103.1800 in, 262.0000 cm

**GARDEN FOC**

1.0000 in, 2.8600 cm

**VAPOR TEMPERATURE**

- **GROOVE WIDTH:** 0.0787 in, 0.2000 cm
- **GROOVE HEIGHT:** 0.0197 in, 0.0500 cm
- **LAND WIDTH:** 0.0344 in, 0.0870 cm
- **GROOFS (CLOSED) COVERED WITH 200 MILL

**NO LIMIT ENCOUNTERED AT **-

---

**TOTAL DELTA-T:** 6.44 Deg C

**TOTAL MASS:** 1.7449 lb

### WATT PERFORMANCE DETAILS (Y OR N) Y

<table>
<thead>
<tr>
<th>FE</th>
<th>PE-A</th>
<th>PA-C</th>
<th>FC</th>
<th>DITN/CM2</th>
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</thead>
<tbody>
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<td>8292.16</td>
<td>7777.6</td>
<td>3926.82</td>
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<table>
<thead>
<tr>
<th>TE</th>
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<th>TA-C</th>
<th>TC</th>
<th>DITN/CM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>370.772</td>
<td>367.761</td>
<td>364.907</td>
<td>370.863</td>
<td>DITN/CM2</td>
</tr>
</tbody>
</table>

**EVAP TEMP**

- **COND TEMP:** DELTA-T 377°F, 6.46312

**DPC:**

- **DPC-0:** 10141
- **DPC+DPC-0:** 10141

**DPFE:**

- **DPFE:** 1153

**DPVC:**

- **DPVC:** 543

**SONIC LIMITS:**

- **SONIC LIMITS:** \( \text{EVAP} = 740 \text{ ADD} = 703 \text{ WATTS} \)

**COLD FLUID CHARGE:**

- **132.019 Grams**

**COOL PORT VOLUME:**

- **Volume of Hot Fluid Charge:** 36.1741 cm³

**COOL FLUID CHARGE:**

- **151.836 Grams**

**HEAT PIPE:** (INSC) & 2 EMDCAPS 1596.9 Grams

**DELTA-T VALUES:**

- **EVAP GAP:**
  - \( 0.15904 \)
  - \( 0.7123102 - 02 \)
  - \( 0.30763 - 02 \)
  - \( 0.002528 \)

- **TAPE (3):**
  - \( 0.01133 \)
  - \( 2.85352 \)
  - \( 0.96902 \)

- **CONDENSATION:**
  - \( 0.01926 \)
  - \( 0.485383 - 03 \)
  - \( 0.149764 \)

**POWER OF 600 WATTS CAUSES **--- **ADD SONIC LIMIT**

**LAST ADD-LIMITED POWER CALCULATION WAS AT **--- **600 WATTS**

**TOTAL DELTA-T:** 7.34 Deg C

**TOTAL MASS:** 1.7449 lb
RUN CONDITIONS:

FLUID = SOYBEAN A WALL MAT=SCARCE
RTAP TEMP = 362 VAPOR DELTA-T = 60 DEG C
GAS AMB = 0.00 VIB AMB = 0.00 DEG C

Evap Length 14.006 in 43.0000 CM
Add Length 14.006 in 43.0000 CM
Cool Length 60.20515 in 176.0000 CM
Total Length 100.20515 in 252.0000 CM

0.06 1.0000 in 2.0000 CM
Wall Thkess 0.0300 in 0.0076 CM
Grove Width 0.0737 in 0.0000 CM
Grove Height 0.0285 in 0.0000 CM
Land Width 0.0285 in 0.0007 CM
27 Grooves (Closed) Covered With 800 Mesh

No Limit Encountered At ----------------- 460 Watts

----------------- TOTAL DELTA-T = 3.80 DEG C
----------------- TOTAL Mass = 1.766 EN

Vapor Performance Details (F or h) (F)

FE A 0.566112E+07 0.566106E+07 0.566101E+07 PC
TE 346.876 346.876 346.876
Evap Temp Cond Temp Delta-T
362 346.09 3.8399

DPC = 3160 DPc = 0 DPC+DPc = 3160 DTHM/LH

DPVE DPVE DPA DPA
19 223 2 1539
DPTC DPTC
8 508

Sonic Limits:

Evap = 156626 Add = 186077 Watts

C/A's-

Evap Cond Axial Vatts/GH
1 0 35

B R Ret# E A Ret# Liq Ret# C A Ret# C R Ret#
1 905 346 806 1

Hot Fluid Charge 114.997 Grams
Cond Temp Volume Of Hot Fluid Charge 107.667 CM3

Cold Fluid Charge 133.501 Grams

132.001 CM3

Alat Pipe, (MESH) & 2 NPT Caps 1610.42 Grams

Delta-T Values:

Evap Fall Evap Ld Evap MSh Evaporation
0.35983 1.31221 0.9441 1.0009 DeG C

Vapor (G)

Vapor (L)
+0.392921-03 +0.338212-03 +0.4416-03

Condensation Cond MSh Cond Ld Cond Wall
-0.24467L-01 -0.45745L 4.50042 +0.131558 DeG C

Power Of 650 Watts Causes ----------------- Capillary Limit; DPL > DPV

Last Non-Limited Power Calculation Was At ----------------- 340 Watts

----------------- TOTAL DELTA-T = 4.70 DEG C
----------------- TOTAL Mass = 1.766 EN
RUN CONDITIONS: 0161 A.M. 3/23/79

FLUID = DOWTHERM A VALL MALI = 30665
EVAP TEMP = 219 VAPOR DELTA-T = 80 DEG C
TAT AMD = 0.00 STG AMD = 0.00 DEG

EVAP LMD TH 16.8921 IN 63.0000 CM
ADD LMD TH 16.8921 IN 63.0000 CM
COND LMD TH 66.2913 IN 176.0000 CM
TOTAL LMD TH 103.1800 IN 263.0000 CM

0.01 1.0000 IN 2.4000 CM
FALL THEISS 0.0300 IN 0.0762 CM
GROOVE WIDTH 0.0747 IN 0.0289 CM
3 ROUGE DC = 0.0266 IN 0.0650 CM
LAND WIDTH 0.0247 IN 0.0627 CM

27 GROOVER (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT 160 WATTS

TOTAL DELTA-T = 1.73 DEG C
TOTAL MASS = 1.744 KG

FAST PERFORMANCE DETAILS (Y OR N) ? Y

Q/A'S = EVAP 0.00 COND 0.00 AXIAL 33 WATTS/CM2

VAPOR E = LIG REY = C A REY = CR REY = 2 328 42 328 0

HOT FLUID CHARGE 112.977 GRAMS
ROOM TEMP. VOLUME OF HOT FLUID CHARGE 105.784 CM3
COLD FLUID CHARGE 133.501 GRAMS
128.001 CM3

HEAT PIPE (MESH) = 2 ENDCAPS 1810.62 GRAMS

DELTA-T VALUES:

EVAP WALL EVAP LMD EVAP MESH EVAPORATION
.226854 .760453 .272907 .100098 DEG C

VAPOR (E) TAPOR (A) VAPOR (C)
.321982-02 .320962-02 .320956-02

CONDENSATION COND MESH COND LMD COND WALL
.244697-01 .648602-01 .130864 .065916 DEG C

POWER OF 715 WATTS CAUSES CAPILLARY LIMIT; DPL > DPV
LAST NON-LIMITED POWER CALCULATION WAS AT 710 WATTS

TOTAL DELTA-T = 0.37 DEG C
TOTAL MASS = 1.744 KG
RUA MADITI
OII
SI 10197 A.N. 3/26/79
PLatD - ROKta- VALL MATL-30461
ETA! IW - 434 VAPOR DLT-
60 on C
OUT M - 0.00 VICANN - 0.00 M
STAP LA> U 16.9291 10
63.0000 CN
WL TI 16.0291 14 43.0000 CM
COD D I =?R 69.2913 IR 17&0000 WI
TO?AL LUG TA103.1600 to262.0000 CM
O. D• 1.0000 IS 2.660 CM
IALL ?IIEM3S 0.0300 IA 0.0762 CM
0!90T EVID TR 0.1063 to 0.2760 CM
10011 [Etas? 0.0079 Ix 0.0200 CM
GR0OVESICLOSADI COULD
200 an
10 LIMIT INCOOI?1R1D A? ••••••••	 720 VAM
------------ TOTAL DATA
* - 2.43 DO C
------•----- tOTAL MASS - 1.4d4 Kj
VAR? PRSPOAMAICE DETAILSTT 01 Al TT
PA Pd-A PA-0	 PC
31296.6 30370.4 30100.3 30716.1
4329661 431.242 430.762 431.649
ETAP ?ENP CORD TEMP D1LTA-1
434 431.57 2.42903
DPC- 18214 DPa- 0 DPC-DPO- 16214 DTASS/CM=
DPTE DPLZ DPTA	 DPLAa
026 1196 269 0336
DPTC DPLOa
-615 4900
SOMIC LIVI?St OAP- 23:4	 ADII-	 2631
VAT" C/A'S- EVA? CORD	 AlIAL
2 0	 142
C R RL
' Tr l A UTl LIC IV# 	 C A IETN
21 3161 92 3163
HOT TLUID CHAROI' 02.1796	 0RA S
ROOK ?EMP- TOLUNE Of HOT TLUID CHAAOZ	 60.1694	 CM3
COLT TLUID CHAFE 	 1CJT.
.24 GRANS
70.3614 C93
ORIGINAL PAGE 13
OF POOR QUALITY

RUN CONDITIONS:

FLUID = RUBIDIUM WALL MATL-30468
EVAP TEMP = 436 VAPOR DELTA-T = 60 DMB C
GRAY AMO = 0.00 VTO AMO = 0.00 DEG

EVAP LENGTH 16.0291 IN 63.0000 CN
ADD LENGTH 15.0291 IN 63.0000 CN
COND LENGTH 60.2013 IN 176.0000 CN
TOTAL LENGTH 135.1600 IN 262.0000 CN

O.D. 1.0000 IN 2.660 CM
WALL THICK 0.0300 IN 0.0762 CM
GROOVE WIDTH 0.1063 IN 0.2760 CM
GROOVE HEIGHT 0.0079 IN 0.0200 CM
LAND WIDTH 0.0079 IN 0.0200 CM
25 GROOVES (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT ----------- 720 WATTS

---------- TOTAL DELTA-T = 2.63 DMB C
---------- TOTAL MASS = 1.434 Kj

WATT PERFORMANCE DETAILS (T OR H) ??

PE PE-A PA-C PG DTHES/CM2
31296.6 30370.4 30100.3 30716.1
TE TE-A TA-C TC DMB C
4329661 431.242 430.762 431.649
EVAP TEMP COND TEMP DELTA-T
436 651.87 2.42903
DPC= 18214 DPO= 0 DPC-DPO= 18214 DTHES/CM2
DPTE DPLE DPA DPLA
926 1196 269 3336
DPTE DPLE DPA DPLA
-615 4900
SONIC LIMITS: EVAP = 23.4 ADD = 2631 WATTS

G/A'S=

EVAP COND AXIAL WATTS/CM2
2 0 142

K R EY= K A EY= LIQ EY= C A EY= C R EY=
21 3161 92 3163 6

HOT FLUID CHARAC 92.1756 GRAMS
ROOM TEMP. VOLUME OF HOT FLUID CHARGE 60.1694 CM3
COLD FLUID CHARGE 107.824 GRAMS 70.3614 CM3

HEAT PIPL. (MESS) & 2 ENDCAPS 1375.52 GRAMS

DELTA-T VALUES:

EVAP WALL EVAP LAG EVAP MESH EVAPORATION
.828031 .352215-02 .3933752-02 .300235 DMB C
VAPOR (E) VAPOR (A) VAPOR (C)
1.41014 .1479736 -1.108667
CONDENSATION COND MESH COND LAG COND WALL
.1473307 .143464-02 .394733-03 202311 DMB C

POWER OF 320 WATTS CAUSd ------------- CAPILLARY LIMIT, DPL > DPV
LAST AXI-LIMITED POWER CALCULATION WAS AT ----------- 316 WATTS

---------- TOTAL DELTA-T = 2.67 DMB C
---------- TOTAL MASS = 1.434 KJ
RUN CONDITIONS:

FLUID = RUBIDIUM
COLD WALL = 30483
EVAP TEMP = 377
VAPOR DELTA-T = 50 DEG C
G/W ANG = 0.00
W/G ANG = 0.00 DEG

<table>
<thead>
<tr>
<th>EVAP LENGTH</th>
<th>ADD LENGTH</th>
<th>COND LENGTH</th>
<th>TOTAL LENGTH</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.5291 IN</td>
<td>15.5291 IN</td>
<td>60.2913 IN</td>
<td>103.1500 IN</td>
</tr>
<tr>
<td>43.0000 CM</td>
<td>43.0000 CM</td>
<td>175.0000 CM</td>
<td>222.0000 CM</td>
</tr>
</tbody>
</table>

O.D. = 1.0000 IN  2.5400 CM
WALL THICKNESS = 0.0500 IN  0.0762 CM
GROOVE WIDTH = 0.1083 IN  0.2750 CM
GROOVE RADIUS = 0.0079 IN  0.0200 CM
LAND WIDTH = 0.0079 IN  0.0200 CM

25 GROOVES (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT ************ 614 WATTS

************ TOTAL DELTA-T = 6.63 DEG C
************ TOTAL MASS = 1.464 KG

WANT PERFORMANCE DETAILS (Y OR N)? Y

<table>
<thead>
<tr>
<th>PE</th>
<th>PE-A</th>
<th>PA-C</th>
<th>PC</th>
<th>DYNES/CM²</th>
</tr>
</thead>
<tbody>
<tr>
<td>8928.78</td>
<td>8689.64</td>
<td>8051.69</td>
<td>9003.7</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TE</th>
<th>TA-A</th>
<th>TA-C</th>
<th>TC</th>
<th>DEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>375.677</td>
<td>366.863</td>
<td>366.466</td>
<td>371.468</td>
<td></td>
</tr>
</tbody>
</table>

DELTA-T VALUES:

<table>
<thead>
<tr>
<th>EVAP WALL</th>
<th>EVAP LAG</th>
<th>EVAP MESH</th>
<th>EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.15994</td>
<td>-0.204109E-02</td>
<td>-0.350865E-02</td>
<td>-0.3004E-02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VAPOR (E)</th>
<th>VAPOR (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.01489</td>
<td>2.40698</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COND MESH</th>
<th>COND LAG</th>
<th>COND WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.122573</td>
<td>-0.232236E-03</td>
<td>-0.50008E-03</td>
</tr>
</tbody>
</table>

ROOM TEMP. VOLUME OF HOT FLUID CHARGE 93.8783 CM³
COLD FLUID CHARGE 107.824 GRAMS
HEAT PIPE (MESH) & 2 ENDCAPS 1375.82 GRAMS

DELTA-T VALUES:

<table>
<thead>
<tr>
<th>DELTA-T</th>
<th>DEG</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.13</td>
<td>50 DEG C</td>
</tr>
</tbody>
</table>

POWER OF 646 WATTS CAUSES ************ ADS SONIC LIMIT

LAST NON-LIMITED POWER CALCULATION WAS AT ************ 640 WATTS

************ TOTAL DELTA-T = 7.13 DEG C
************ TOTAL MASS = 1.464 KG
**Run Conditions:**

<table>
<thead>
<tr>
<th>Fluid = Dowtherm A</th>
<th>Wall Mat = 304SS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evap Temp = 352</td>
<td>Vapour Delta-T = 50 Deg C</td>
</tr>
<tr>
<td>Gray Ang = 0.00</td>
<td>Wtu Ang = 0.00 Deg</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Evap Length = 16.3201 in</th>
<th>43,0000 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Adv Length = 16.3201 in</td>
<td>43,0000 cm</td>
</tr>
<tr>
<td>Cond Length = 86.2813 in</td>
<td>178,0000 cm</td>
</tr>
<tr>
<td>Total Length = 103.1500 in</td>
<td>262,0000 cm</td>
</tr>
</tbody>
</table>

- O.D. = 1.0000 in | 2.5400 cm |
- Wall Thick = 0.0300 in | 0.0762 cm |
- Groove Width = 0.1063 in | 0.2700 cm |
- Groove Height = 0.0217 in | 0.0560 cm |
- Land Width = 0.0044 in | 0.0112 cm |

25 Grooves (Closed) Covered with 200 Mesh

No Limit Encountered at 9440 Watts

| Watts = Total Delta-T = 9.23 Deg C |
| Watts/cm2 = 1.549 Kelvin |

Watt Performance Details (Watts or Watt)

<table>
<thead>
<tr>
<th>PE</th>
<th>PE-A</th>
<th>PA-C</th>
<th>PC</th>
<th>DYNES/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>.511061E+07</td>
<td>.511061E+07</td>
<td>.511061E+07</td>
<td>.511061E+07</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>T</th>
<th>TE-A</th>
<th>TA-C</th>
<th>TC</th>
<th>Deg C</th>
</tr>
</thead>
<tbody>
<tr>
<td>344.591</td>
<td>344.591</td>
<td>344.591</td>
<td>344.591</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Evap Temp</th>
<th>Cond Temp</th>
<th>Delta-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>352</td>
<td>342.773</td>
<td>9.23</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DPC</th>
<th>3294</th>
<th>DPG = 0</th>
<th>DPC+DPG = 3294</th>
<th>DYNES/cm²</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>DPY</th>
<th>DPLE</th>
<th>DPYA</th>
<th>DPGA</th>
</tr>
</thead>
<tbody>
<tr>
<td>18</td>
<td>212</td>
<td>7</td>
<td>1630</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DPC</th>
<th>DPLG</th>
</tr>
</thead>
<tbody>
<tr>
<td>7</td>
<td>896</td>
</tr>
</tbody>
</table>

**Sonic Limits:**

<table>
<thead>
<tr>
<th>Watts = Evap</th>
<th>Cond</th>
<th>Axial</th>
<th>Watts/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>1,000,000</td>
<td>1</td>
<td>0</td>
<td>86</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>K R % #</th>
<th>K A % #</th>
<th>LIG % #</th>
<th>C A % #</th>
<th>C R % #</th>
</tr>
</thead>
<tbody>
<tr>
<td>797</td>
<td>291</td>
<td>797</td>
<td>1</td>
<td></td>
</tr>
</tbody>
</table>

**Hot Fluid Charge:**

| 120,205 Grams |

**Room Temp: Volume of Hot Fluid Charge:**

| 112,551 cm³ |

**Cold Fluid Charge:**

| 141.404 Grams |
| 132.401 cm³ |

**Heat Pipes (Mesh) & 2 Endcaps:**

| 1405.22 Grams |

**Delta-T Values:**

<table>
<thead>
<tr>
<th>Evap Low</th>
<th>Evap High</th>
<th>Evaporation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.13104</td>
<td>0.30104</td>
<td>0.17098</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Vapour (X)</th>
<th>Vapour (A)</th>
<th>Vapour (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.24412E-03</td>
<td>2.24412E-03</td>
<td>2.24412E-03</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Condensation</th>
<th>Cond Low</th>
<th>Cond High</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.34587E+01</td>
<td>1.30465</td>
<td>1.32792</td>
</tr>
</tbody>
</table>

**Total of 379 Watts Causes:**

<table>
<thead>
<tr>
<th>Cast Ag-Mol-Limited Power Calculation (Watts)</th>
</tr>
</thead>
<tbody>
<tr>
<td>379 Watts</td>
</tr>
</tbody>
</table>

| Watts = Total Delta-T = 11.02 Deg C |
| Watts/cm² = 1.549 deg K |
PLUID • DOVIA • WALL
NATL-10469
STAP • IMF
VAPOR DELTA-T = 60 DEG C

<table>
<thead>
<tr>
<th>RUN CONDITIONS</th>
<th>11150 A.M.</th>
<th>3/28/79</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLUID = DOWTHREN A</td>
<td>WALL MATT=30455</td>
<td></td>
</tr>
<tr>
<td>EVAP TEMP = 219</td>
<td>VAPOR DELTA-T = 50 DEG C</td>
<td></td>
</tr>
<tr>
<td>GROSS AM = 0.10</td>
<td>WGT AM = 0.00 DEG</td>
<td></td>
</tr>
</tbody>
</table>

| EVAP LENGTH | 16.9281 IN | 43.0000 CM |
| ADD LENGTH  | 16.9291 IN | 43.0000 CM |
| TOTAL LENGTH | 103.1500 IN | 262.0000 CM |
| C.D. | 1.0000 IN | 2.5600 CM |
| WALL THICKS | 0.0300 IN | 0.0762 GA |
| GROOVE WIDTH | 0.1083 IN | 0.2750 CM |
| GROOVE HEAT | 0.0197 IN | 0.0500 CM |
| LAND WIDTH | 0.0040 IN | 0.0128 CM |

25 GROOVES (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT ------ 100 WATTS

---------- TOTAL DELTA-T = 3.56 DEG C
---------- TOTAL MASS = 1.555 KG

VAPOR PERFORMANCE DETAILS (T OR M) ??

PE PE-A PE-C PE DYES/CM2
397562 397580 397503 397479

PE TE-A TE-C TE DYES C
216.162 216.146 216.146 216.146

EVAP TEMP COND TEMP DELTA-T
219 216.446 3.83463

DPC= 7307 DPC= 0 DPC+DPC= 7307 DYES/CM2

DYTE DPLMD DTPA DPLAG
24 179 20 1200

DPTC DPLCG
29 736

SONIC LIMITS: EVAP= 14043 ADD= 16332 WATTS

Q/A'S=
EVAP COND AXIAL WATTS/CM2
0 0 33

2 3 RET# H A RET# LIQ RET# C A RET# C B RET#
2 321 36 321 0

HOT FLUID CHARGE 111.829 GRAMS
COLD FLUID CHARGE 131.842 GRAMS
HEAT PIPES (MESH) & 2 EJICAPS 1402.35 GRAMS

DELTA-T VALUES:

EVAP WALL EVAP MESH EVAP MESH EVAP MESH
-220389 -24923 -26986 -26986

VAPOR (E) VAPOR (A) VAPOR (C)
-3260.06-02 -392692-02 -392692-02

CONDENSATION COND MESH COND MESH COND MESH
-164097E-01 -669721-01 -550474 -569925-01

559 WATTS CAUSES -------- CAPILLARY LIMIT, DPL > DPF

LAST NON-LIMITED POWER CALCULATION #13 AT -------- 553 WATTS

---------- TOTAL DELTA-T = 11.48 DEG C
---------- TOTAL MASS = 1.555 KG
**FLUID = RUBIDIUM**
**WALL MAT = 304SS**
**EVAP TEMP = 434**
**VAPOR DELTA-T = 50**
**GROUT ANG = 0.00**
**VTO ANG = 0.00**

**EVAP LENGTH** 16.9291 in 43.0000 cm
**ADD LENGTH** 16.9291 in 43.0000 cm
**COND LENGTH** 69.2913 in 176.0000 cm
**TOTAL LENGTH** 103.1500 in 262.0000 cm
**GROUT** 1.0000 in 2.5400 cm
**WALL THICK** 0.0300 in 0.0762 cm
**GROOVE WIDTH** 0.1063 in 0.2700 cm
**GROOVE HEIGHT** 0.0079 in 0.0200 cm
**LAD WIDTH** 0.0079 in 0.0200 cm

25 GROOVES (CLOSED) COVERED WITH 200 MESH

**NO LIMIT ENCOUNTERED AT --------- 720 WATTS**

**TOTAL DELTA-T = 2.43**
**TOTAL MASS = 1.484**

**WANT PERFORMANCE DETAILS (T OR R) **

<table>
<thead>
<tr>
<th>PK</th>
<th>PE-A</th>
<th>PA-C</th>
<th>PC</th>
<th>DTNS/CM²</th>
</tr>
</thead>
<tbody>
<tr>
<td>31295.3</td>
<td>30370.4</td>
<td>30100.3</td>
<td>30715.1</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TE</th>
<th>TE-C</th>
<th>TA-C</th>
<th>TC</th>
<th>DMB C</th>
</tr>
</thead>
<tbody>
<tr>
<td>432.861</td>
<td>431.262</td>
<td>430.762</td>
<td>431.849</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>EVAP TEMP</th>
<th>CORD TEMP</th>
<th>DELTA-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>434</td>
<td>431.97</td>
<td>2.4293</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>DPC= 18214</th>
<th>DPO= 0</th>
<th>DPC+DPO= 18.14</th>
<th>DTNS/CM²</th>
</tr>
</thead>
<tbody>
<tr>
<td>DPE=</td>
<td>DPLD=</td>
<td>DPV=</td>
<td>DPLAG</td>
</tr>
<tr>
<td>926</td>
<td>1496</td>
<td>260</td>
<td>9336</td>
</tr>
<tr>
<td>-015</td>
<td>4900</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**CONIC LIMITS:**
**EVAP= 2314**
**ADD= 2631 WATTS**

**J/A'S=**
**EVAP**
**COND**
**AXIAL**
**WATTS/CM²**

<table>
<thead>
<tr>
<th>2</th>
<th>0</th>
<th>142</th>
</tr>
</thead>
<tbody>
<tr>
<td>A R RET#</td>
<td>LIA RET#</td>
<td>C A RET#</td>
</tr>
<tr>
<td>21</td>
<td>3161</td>
<td>92</td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**HOT FLUID CHARGE** 92.1796 GRAMS
**WATER TEMP / VOLUME OF HOT FLUID CHARGE** 60.1694 CM³

**COLD FLUID CHARGE** 107.324 GRAMS
**70.3914 CM³**

**HEAT PIPE (INNER) @ 2 ENDCAPS 1375.92 GRAMS**

**DELTA-T VALUES:**

<table>
<thead>
<tr>
<th>EVAP ALL</th>
<th>EVAP LAD</th>
<th>EVAP MAX</th>
<th>EVAPATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.33831</td>
<td>-0.52612-02</td>
<td>-0.933738-02</td>
<td>-0.300293</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>(I)</th>
<th>(A)</th>
<th>(C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.0134</td>
<td>1.1719736</td>
<td>1.038667</td>
</tr>
</tbody>
</table>

**COND MAX**

<table>
<thead>
<tr>
<th>COND LAD</th>
<th>COND WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>-0.73367</td>
<td>-0.6494E-02</td>
</tr>
</tbody>
</table>

**POWER OF 920 WATTS CAUSES -------------- CAPILLARY LIMIT, DPL > DPV**

**LAST NPN-LIMITED POWER CALCULATION 643 AT --------------- 643 WATTS**

**TOTAL DELTA-T = 2.47**
**TOTAL MASS = 1.484**
RUN CONDITIONS: 111: 6 A.M. 3/29/70

FLUID = SUBSIDIUM WALL MATT=5048S
EVAP TEMP = 377 VAPOR DELTA-T = 30 DEG C
GRAY ANG = 0.00 WOT ANG = 0.00 DEG

EVAP LENGTH 16.9291 IN 43.0000 CM
ADD LENGTH 16.9291 IN 43.0000 CM
COND LENGTH 69.2913 IN 176.0000 CM
TOTAL LENGTH 103.1500 IN 262.0000 CM

O.D. 1.0000 IN 2.5400 CM
WALL THICK 0.0100 IN 0.0254 CM
GROOVE WIDTH 0.1063 IN 0.2700 CM
GROOVE HEIGHT 0.0079 IN 0.0200 CM
LAND WIDTH 0.0128 IN 0.0326 CM
26 GROOVES (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT ----------- 514 WATTS

---------- TOTAL DELTA-T = 4.58 DEG C
---------- TOTAL MASS = 0.661 KG

WAT PERFORMANCE DETAILS (Y OR N) YY

PB PB-A PA-C PC DTHRS/CM2
10019.5 8548.07 9499.41 9239.81

TE TE-A TA-C TC DEG C
376.293 370.666 365.84 372.611

EVAP TEMP COND TEMP DELTA-T
377 372.438 4056226

DPC= 19133 DPG= 0 DPC+DPG= 19133 DTHRS/CM2

DPVS DPLO DPVA DPLAG
1170 876 353 6860

Sonic LIMITS: EVAP= 817 ADD= 87 C WATTS

Q/A'S=
1

K R RAT=
10

HOT FLUID CHARGE 95.38 GRAMS
ROOM TEMP. VOLUME OF HOT FLUID CHARGE 62.5663 CM3

COLD FLUID CHARGE 110.102 GRAMS
71.9663 CM3

HEAT PIPE (MESH) 4 2 END CAPS 560.957 GRAMS

DELTA-T VALUES:

EVAP WALL EVAP LAG EVAP MESH EVAPORATION
.201129 .30798125-02 .35602202 .500469 DEG C

E VAP (E) VAPOR (A) VAPOR (C)
S 628.96 1.32544 -3.77051

CONDENSATION COND MESH COND LAG COND WALL
.122278 .310205E-03 .5014491-03 .497989E-01 DEG C

POWER OF 710 WATTS CAUSES ----------- ADD SONIC LIMIT

LAST NON-LIMITED POWER CALCULATION WAS AT ---------- 705 WATTS

---------- TOTAL DELTA-T = 6.12 DEG C
---------- TOTAL MASS = 0.91 KG
CONSIDERATIONS:

ID = DOWNWEB A  WALL MATT = 3046S  
P TEMP = 352  VAPOR DELTA-T = 50 DEG C  
V ARS = 0.00  VTS ARS = 0.00 DEG  

P = 16.9291 IN  63.0000 CM  
L LENGTH = 16.9291 IN  63.0000 CM  
D LENGTH = 69.2913 IN  176.0000 CM  
V LENGTH = 103.1500 IN  262.0000 CM  

L TAKES = 0.0100 IN  0.0254 CM  
O VR WIDTH = 0.1883 IN  0.4778 CM  
OVER HEIGHT = 0.0217 IN  0.0550 CM  
D WIDTH = 0.0094 IN  0.0240 CM  

GROOVES (CLOSED) COVERED WITH 200 MESH

LIMIT ENCOUNTERED AT----------- 640 WATTs  

--------- TOTAL DELTA-T = 0.72 DEG C  
--------- TOTAL MASS = 0.777 KG  

T PERFORMANCE DETAILS (T OR M) TV  

<table>
<thead>
<tr>
<th>PE-A</th>
<th>PA-C</th>
<th>PC</th>
<th>DTHRES/CM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>3387E+07</td>
<td>.553872E+07</td>
<td>.553872E+07</td>
<td></td>
</tr>
<tr>
<td>TE-A</td>
<td>TA-C</td>
<td>TC</td>
<td>DEG C</td>
</tr>
<tr>
<td>7.603</td>
<td>347.402</td>
<td>347.402</td>
<td></td>
</tr>
</tbody>
</table>

P TEMP  = COND TEMP  DELTA-T  
2 = 346.275  5.72465

= 3206  DPC = 0  DPC+DPC = 3206  DTHRES/CM2

E = DPLDA  DPLPA  DPLBA  
218  61428  

2 = DPLCA  
994

IC LIMITS:  
EVAP = 170527  ADD = 203879  WATTs

'S' =  
EVAP  CONTR  AXIAL  WATTs/CM2  
1  0  86

REY#  & A REY#  LID REY#  C A REY#  C B REY#  
784  297  784  1

FLUID CHARGE = 123.66 GRAMS  
4 TEMP. VOLUME OF HOT FLUID CHARGE = 116.787 CM3  
3 FLUID CHARGE = 142.992 GRAMS  
133.388 CM3

T P (MESH) = 2 CNDCAPS = 34.002 GRAMS

TA-T VALUES:

<table>
<thead>
<tr>
<th>T WALL</th>
<th>T STAP LTS</th>
<th>T STAP ABC</th>
<th>T STAP CASH</th>
<th>T STAP EVAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>.5328</td>
<td>3.70369</td>
<td>.611273</td>
<td>.190098</td>
<td>.190098</td>
</tr>
</tbody>
</table>

3 T (31) VAPOIR (A) VAPOIR (C)  
46215-03  .2461415-03  0

REVISION  CONTR ABC  CONTR LTS  CONTR WALL  
4567-01  .149982  .998027  .1901513-01  

OF 560 WATTS CAUSIS = CAPELLANT LIMIT; DPL = DPH

'NON-LIMITED POWER CALCULATION WAS AT' = 555 WATTS
**RUN CONDITIONS:**

- **FLUID:** Dowtherm A
- **WALL MAT.:** S-304SS
- **EVAP TEMP:** 219 Deg C
- **VAPOR DELTA-T:** 50 Deg C
- **GRAY ANG:** 0.00
- **VTD ANG:** 0.00 Deg

**EVAP LENGTH:** 16.9231 in 43.0000 cm
**ADD LENGTH:** 16.9231 in 43.0000 cm
**COND LENGTH:** 68.2913 in 176.0000 cm
**TOTAL LENGTH:** 103.1800 in 262.0000 cm

**FLUID TEMPS:**
- **0.0:** 1.0000 in 2.5400 cm
- **WALL THICKNESS:** 0.0100 in 0.0254 cm
- **GROOVE WIDTH:** 0.1063 in 0.2700 cm
- **GROOVE DEPTH:** 0.0217 in 0.0550 cm
- **LAND WIDTH:** 0.0004 in 0.0010 cm
- **25 GROOVES (CLOSED) COVERED WITH 200 MESH**

**NO LIMIT ENCOUNTERED AT ———— 160 WATTS**

**TOTAL DELTA-T:** 2.69 Deg C
**TOTAL MASS:** 0.7777 kg

**WANT PERFORMANCE DETAILS (Y OR X) TY**

<table>
<thead>
<tr>
<th>PE</th>
<th>PE-A</th>
<th>PA-X</th>
<th>PC</th>
<th>DYNES/CM²</th>
</tr>
</thead>
<tbody>
<tr>
<td>217.008</td>
<td>217.008</td>
<td>217.003</td>
<td>217.001</td>
<td></td>
</tr>
</tbody>
</table>

**EVAP TEMP**
- **COND TEMP:**
- **DELTA-T:**

**D²S = 7280**

**DPX :=**
- **DPX :=**

**DPX:**
- **DPL :=**

**SONIC LIMITS:**
- **EVAP = 16500**
- **ADE = 18738 WATTS**

**A/A' S :=**

**B P D R E T**
- **LIQ R ET**
- **C A R T**
- **C R R T**

**HOT FLUID CHARGE**
- 121.123 grams

**ROOM TEMP.**
- **VOLUME OF HOT FLUID CHARGE:** 113.411 cm³

**COLD FLUID CHARGE**
- 142.992 grams
- 133.4388 cm³

**HEAT PIPE (MESH) = 2 AMDCAPS 654.002 GRAMS**

**DELTA-T VALUES:**

<table>
<thead>
<tr>
<th>DELTA-T</th>
<th>EVAP WALL</th>
<th>EVAP LAG</th>
<th>EVAP MESH</th>
<th>ETAVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.56779</td>
<td>1.56779</td>
<td>1.56779</td>
<td>1.56779</td>
<td>1.56779</td>
</tr>
</tbody>
</table>

**VAPOR (E)**

<table>
<thead>
<tr>
<th>DELTA-T</th>
<th>VAPOR (E)</th>
<th>VAPOR (A)</th>
<th>VAPOR (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.44412-02</td>
<td>2.44412-02</td>
<td>2.44412-02</td>
<td></td>
</tr>
</tbody>
</table>

**CONDENSATION**

<table>
<thead>
<tr>
<th>DELTA-T</th>
<th>COND MESH</th>
<th>COND LAG</th>
<th>COND WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.44412-02</td>
<td>2.44412-02</td>
<td>2.44412-02</td>
<td></td>
</tr>
</tbody>
</table>

**POWER OF**

- **715 WATTS CAUSES ———— CAPILLARY LIMIT: DPL > DPX**

**LAST NON-LIMITED POWER CALCULATION WAS AT ———— 710 WATTS**

**TOTAL DELTA-T:** 10.06 Deg C
**TOTAL MASS:** 0.7777 kg

**ORIGINAL PAGE IS OF POOR QUALITY**
FLUID = MERCURY       WALL MTRL-3043S
EVAP TEMP = 434       VAPOR DELTA-T = 50 DEG C
GRAY ANG = 0.00       WTO ANG = 0.00 Deg

EVAP LENGTH 19.9291 IN 43.0000 CM
ADD LENGTH 19.9291 IN 43.0000 CM
COND LENGTH 69.2913 IN 178.0000 CM
TOTAL LENGTH 103.1800 IN 262.0000 CM

O.D. 0.3780 IN 0.9604 CM
WALL THICK 0.0039 IN 0.0100 CM
GROOVE WIDTH 0.0787 IN 0.2000 CM
GROOVE HEIGHT 0.0079 IN 0.0200 CM
LAND WIDTH 0.0562 IN 0.1406 CM
& GROOVES (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT 720 WATTS

WANT PERFORMANCE DETAILS (T OR H) ??

PE PE-A PA-C PC DTRES/CM2
.386603E+07 .386703E+07 .386601E+07 .386675E+07

TE TE-A TA-C TC DMB C
431.868 431.839 431.82 431.833

ETAP TEMP COND TEMP DELTA-T
434 431.311 2.66972

DPC= 114106 DPG= 0 DPC+DPG= 114106 DTRES/CM2

DPFE DPLED DPFA DPLAG
1017 6584 1007 51200

DPVC DPLCO
-282 28097

SONIC LIMITS: ETAP= 200.67 ADD= 240.67 WATTS

3/4'= ETAP COND AXIAL WATTS/CM2
3 1 1010

E R RET# E & RET# LIQ RET# C & RET# C R RET#
13 5074 330 5074 330

HOT FLUID CHARGE 281.861 GRAMS
ROOM TEMP. VOLUME OF HOT FLUID CHARGE 20.8696 CM3

COLD FLUID CHARGE 280.68 GRAMS
21.444 CM3

HEAT PIPE* (MESH) & 2 MIDCAPS 183.596 GRAMS

DELTA-T VALUES:

ETAP WALL ETAP LID ETAP MESH EVAPORATION
.284262 .732296 1.01444 .100098 DMB C

VAPOR (E) VAPOR (A) VAPOR (C)
.29022769-01 .1928712-01 .1289362-01

CONDENSATION COND MESH COND LG CRAD WALL
.2486773-01 .248109 .179150 .6268143-01 DMB C

POW 933 WATTS CAUSES CAPILLARY LIMIT: DPL > DPV

LAST NON-LIMITED POWER CALCULATION WAS A1 930 WATTS

WANT PERFORMANCE DETAILS (T OR H) ??

TOTAL DELTA-T = 5.44 DMB C
TOTAL MASS = 0.449 KG

ORIGINAL PAGE IS OF POOR QUALITY
**FLUID = MERCURY**
**WALL MATT=30455**
**EVAP TEMP = 252**
**VAPOR DELTA-T = 50**
**DRY AIR = 0.00**

**EVAPE LENGTH** 16.9200 IN 43.0000 CM
**ADD LENGTH** 16.9200 IN 43.0000 CM
**COND LENGTH** 0.00 0.0000 CM
**TOTAL LENGTH** 163.1600 IN 262.0000 CM

**O.D.** 0.3760 IN 0.9620 CM
**WALL THICK** 0.0039 IN 0.0100 CM
**GROOVE WIDTH** 0.0787 IN 0.0000 CM
**GROOVE HEIGHT** 0.0090 IN 0.0200 CM
**LAD WIDTH** 0.0062 IN 0.0150 CM

8 GROOVES (CLOSED) COVERED WITH 300 MESH

**NO LIMIT ENCOUNTERED AT**

---

**660 WATTS**

---

**TOTAL DELTA-T = 1.98**
**TOTAL MASS = 0.449 KG**

**WATT PERFORMANCE DETAILS (T OR H) **

<table>
<thead>
<tr>
<th>PB</th>
<th>PB-A</th>
<th>PA-C</th>
<th>FC</th>
<th>DETA/CM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1166022+07</td>
<td>1166502+07</td>
<td>1166515+07</td>
<td>1166515+07</td>
<td></td>
</tr>
</tbody>
</table>

**PB**
**TE**
350.000 350.000 350.003 350.050

**EVAP TEMP**
**COND TEMP**
**DELTAL-T**
352 350.023 1.97729

**DPC= 120072**
**DPO= 0**
**DPO+DPC= 120072**

**DPC**
**DPO**
1926 8347

**DPC**
**DPO**
1926 8347

**SONIC LIMITS:**
**EVAP=** 6206** ADD=** 7012 ** WATTS**

**Q/A**
3 0 617

**E & R#**
**E & R#**
3 9 3479 187 3480 2

**HOT FLUID CHARGE**
282.933 GRAMS

**BOOM TEMP. VOLUME OF HOT FLUID CHARGE**
20.8796 CM3

**COLD FLUID CHARGE**
290.8 GRAMS

21.4484 CM3

**HEAT PIPE, (MESH) & 2 EMDCAPS** 166.621 GRAMS

**DELTAT VALUES:**

<table>
<thead>
<tr>
<th>EVAP - ALL</th>
<th>EVAP L.G</th>
<th>EVAP MESS</th>
<th>EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.184194</td>
<td>0.472355</td>
<td>0.65468</td>
<td>0.100985</td>
</tr>
</tbody>
</table>

**WAP (E)**
**VAPOR (A)**
| 0.150659 | 0.60539   | 0.100985   |

<table>
<thead>
<tr>
<th>COND MESS</th>
<th>COND L.G</th>
<th>COND WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.180659</td>
<td>0.115683</td>
<td>0.4505865-01</td>
</tr>
</tbody>
</table>

**POWER OF 305 WATTS CAUSES**
**CAPILLARY LIMIT, DPL = DPV**

**LAST NON-LIMITED POWER CALCULATION WAS AT**

---

**300 WATTS**

---

**TOTAL DELTA-T = 3.63**
**TOTAL MASS = 0.146 KG**
FLUID = MERCURY  WALL MATL=304SS
EVAP TEMP = 277  VAPORE DELTA-T = 60 Deg C
GRAV ANG = 0.00  VAP ANG = 0.00 Deg

EVAP LENGTH 16.9291 IN 43.0000 CM
ADD LENGTH 16.9291 IN 43.0000 CM
COND LENGTH 89.2013 IN 176.0000 CM
TOTAL LENGTH 103.1500 IN 262.0000 CM

O.D. 0.3750 IN 0.9526 CM
WALL THICK 0.0039 IN 0.0100 CM
GROOVE WIDTH 0.0767 IN 0.2000 CM
GROOVE HEIGHT 0.0079 IN 0.0200 CM
LAND WIDTH 0.0062 IN 0.1564 CM
8 GROOVES (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT ------------ 266 WATTS

------------- TOTAL DELTA-T = 2.00 Deg C
------------- TOTAL MASS = 0.449 KG

WATT PERFORMANCE DETAILS (Y OR R) ??

PE TE EVAP TEMP COND TEMP DELTA-T
PE-A TE-A 274.921 278.165 2.0791
PA-C TA-C 275.542 278.165 2.0791
PC 259.071 253.728 253.630

DPC= 127000 DPC= 0 DPC-DPC= 127000 DTRES/CM2

DPTE DPLEG DPVA DPLAG
2308 11077 1971 20211

DPTC DPLGC
96

SONIC LIMITS:

EVAP= 1500 ADD= 1603 WATTS

G/A'S=

EVAP COND AXIAL WATTS/CM2
2 0 370

R R RET# S A RET# LIG RET# C A RET# C R RET#
6 2436 105 2441 1

HOT FLUID CHARGE 264.166 GRAMS
ROOM TEMP: VOLUME OF HOT FLUID CHARGE 23.5779 CM3

COLD FLUID CHARGE 290.43 GMNS
21.444 CM3

HEAT PIPE, (MESH) & 2 ENDCAPS 163.596 GMNS

DELTA-T VALUES:

EVAP (ALL) EVAP LOG EVAP MESH EVAP VAPORATION
+116044 +300857 +416008 +100098 Deg C

VAPORE (E) VAPORE (A) VAPORE (C)
+323220 +373779 +1356472-01

CONDENSATION COND MESH COND L.S. COND VAPOR
+5466572-01 +101731 +7354245-01 +356171-01 Deg C

POWERS OF 310 WATTS CAUSES -------------- CAPILLARY LIMIT: DEL > DP

LAST NON-LIMITED POWER CALCULATION WAS OF -------------- 365 WATTS

------------- TOTAL DELTA-T = 3.03 Deg C
------------- TOTAL MGS = 0.449 KG
**Run Conditions:**

- **Fluid:** R-114
- **Wall Max:** 304.85
- **Evap Temp:** 362
- **Vapor Delta-T:** 50 (deg C)
- **Gray Ang:** 0.00
- **Vyo Ang:** 0.00 (deg)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Evap Length</td>
<td>14.9291 in</td>
</tr>
<tr>
<td>Add Length</td>
<td>14.9291 in</td>
</tr>
<tr>
<td>Cond Length</td>
<td>68.2913 in</td>
</tr>
<tr>
<td>Total Length</td>
<td>103.1800 in</td>
</tr>
<tr>
<td>0-De</td>
<td>0.4000 in</td>
</tr>
<tr>
<td>Wall Trans</td>
<td>0.0000 in</td>
</tr>
<tr>
<td>Groove Width</td>
<td>0.1063 in</td>
</tr>
<tr>
<td>Groove Height</td>
<td>0.0236 in</td>
</tr>
<tr>
<td>Land Width</td>
<td>0.0046 in</td>
</tr>
<tr>
<td>12 Grooves (Closed) Covered with 200 Mesh</td>
<td></td>
</tr>
</tbody>
</table>

**No Limit Encountered At:** 0.00 Watts

**Total Delta-T =** 15.04 (deg C)

**Total Mass =** 0.306 kg

**Vapor Performance Details (Y OR N) TT**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>PE</td>
<td>1.0446628-07</td>
</tr>
<tr>
<td>PA-A</td>
<td>0.4767205+07</td>
</tr>
<tr>
<td>PA-C</td>
<td>0.4767205+07</td>
</tr>
<tr>
<td>PC</td>
<td>0.4767205+07</td>
</tr>
<tr>
<td>TH</td>
<td>339.936</td>
</tr>
<tr>
<td>TE-A</td>
<td>339.936</td>
</tr>
<tr>
<td>TA-C</td>
<td>339.936</td>
</tr>
<tr>
<td>TC</td>
<td>339.936</td>
</tr>
<tr>
<td>EVAPE</td>
<td>3459</td>
</tr>
<tr>
<td>ADD</td>
<td>39214</td>
</tr>
</tbody>
</table>

**Sonic Limits:**

- **Evap:** 32864
- **Add:** 39214

**Watts/cm²:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>347</td>
<td></td>
</tr>
<tr>
<td>355</td>
<td>552</td>
</tr>
<tr>
<td>1656</td>
<td></td>
</tr>
</tbody>
</table>

**Hot Fluid Charge:**

- 66.0229 grams

**Room Temp. Volume of Hot Fluid Charge:**

- 61.8192 cm³

**Cold Fluid Charge:**

- 66.3628 grams
- 30.8641 cm³

**Heat Pipes (Mesh) & Endcaps:** 219.701 grams

**Delta-T Values:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>LVAP MSL</td>
<td>176.322</td>
</tr>
<tr>
<td>LVAP LG</td>
<td>10.402</td>
</tr>
<tr>
<td>LVAP MSLA</td>
<td>1.33201</td>
</tr>
<tr>
<td>LVAP MSLA</td>
<td>1.33198</td>
</tr>
<tr>
<td>LVAP MSLA</td>
<td>1.33201</td>
</tr>
<tr>
<td>TAPOR (A)</td>
<td>40.94623-02</td>
</tr>
<tr>
<td>TAPOR (C)</td>
<td>21.7573-02</td>
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<tr>
<td>TAPOR (G)</td>
<td>7.24623-03</td>
</tr>
<tr>
<td>Cond MSL</td>
<td>25.5322</td>
</tr>
<tr>
<td>Cond MSL</td>
<td>25.5322</td>
</tr>
<tr>
<td>Cond Wall</td>
<td>25.5322</td>
</tr>
</tbody>
</table>

**Power of 515 Watts Causes**

**Capillary Limit:** D6L > DTV

**Last Non-Limited Power Calculation was at:** 0.00 Watts

**Total Delta-T =** 17.42 (deg C)

**Total Mass =** 0.306 kg
**RUN CONDITIONS:**

**FLUID** = BUTANE A  
**WALL MAT.** = 304S3

**EVAP TEMP** = 327°F  
**VAPOR DELTA-T** = 92° DBD C

**TARGET AMB.** = 0.00°F  
**VAP AMB.** = 0.00° DBD

<table>
<thead>
<tr>
<th>EVAP LENGTH</th>
<th>16.8691 in</th>
<th>43,000000 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADD LENGTH</td>
<td>16.8691 in</td>
<td>43,000000 cm</td>
</tr>
<tr>
<td>COND LENGTH</td>
<td>66.8691 in</td>
<td>174,000000 cm</td>
</tr>
<tr>
<td>TOTAL LENGTH</td>
<td>103.8691 in</td>
<td>262,000000 cm</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>O.D.</th>
<th>0.8660 in</th>
<th>2.1938 cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>WALL THICKS</td>
<td>0.0127 in</td>
<td>0.3226 mm</td>
</tr>
<tr>
<td>GROOVE WIDTH</td>
<td>0.1063 in</td>
<td>0.2700 cm</td>
</tr>
<tr>
<td>GROOVE HEIGHT</td>
<td>0.0266 in</td>
<td>0.6765 mm</td>
</tr>
<tr>
<td>LAND WIDTH</td>
<td>0.0836 in</td>
<td>0.2127 cm</td>
</tr>
</tbody>
</table>

12 GROOVES (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT ------------ 373 WATTS

TOTAL DELTA-T = 10.73° DBD C

TOTAL MASS = 0.294 EG

**WATT PERFORMANCE DETAILS (Y OR N)?**

<table>
<thead>
<tr>
<th>PE</th>
<th>PE-A</th>
<th>PA-C</th>
<th>PC</th>
<th>DTHERS/CM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>.3320912-07</td>
<td>.3320912-07</td>
<td>.3320912-07</td>
<td>.3320912-07</td>
<td>.3320912-07</td>
</tr>
<tr>
<td>TE</td>
<td>TE-A</td>
<td>TE-C</td>
<td>TC</td>
<td>DBD C</td>
</tr>
<tr>
<td>318.394</td>
<td>318.394</td>
<td>318.394</td>
<td>318.394</td>
<td>318.394</td>
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</table>

<table>
<thead>
<tr>
<th>EVAP TEMP</th>
<th>COND TEMP</th>
<th>DELTA-T</th>
</tr>
</thead>
<tbody>
<tr>
<td>327°F</td>
<td>10.7302</td>
<td></td>
</tr>
</tbody>
</table>

**DPC-** 4112  
**DPT-** 0  
**DPC+DPT=** 4112  
**DTHERS/CM2**

**SONIC LIMITS:**  
**EVAP=** 24680  
**ADD=** 29626  
**WATTS**

<table>
<thead>
<tr>
<th>3/4 S=</th>
<th>ETAP</th>
<th>CORD</th>
<th>AXIAL</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0</td>
<td>294</td>
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</table>

<table>
<thead>
<tr>
<th>E 3 RLY#</th>
<th>E A RLY#</th>
<th>LIG RLY#</th>
<th>C A RLY#</th>
<th>C 2 RLY#</th>
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<tbody>
<tr>
<td>4</td>
<td>1372</td>
<td>405</td>
<td>1372</td>
<td>1</td>
</tr>
</tbody>
</table>

**BOY FLUID CHARGE** 60.2462 GRAMS  
**ROOM TEMP. VOLUME OF HOT FLUID CHARGE** 58.4105 CM3

**COLD FLUID CHARGE** 77.0416 GRAMS  
**72.5105 CM3**

**HEAT PIPE** (MESH) A 2 ENDCAPS 216.768 GRAMS

**DELTA-T VALUES:**

<table>
<thead>
<tr>
<th>ETAP WALL</th>
<th>ETAP LEG</th>
<th>ETAP MESH</th>
<th>EVAPORATION</th>
<th>EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>.131407</td>
<td>7.22302</td>
<td>1.12047</td>
<td>.160098</td>
<td>DBD C</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VAPOR (A)</th>
<th>VAPOR (A)</th>
<th>VAPOR (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.3271092-02</td>
<td>.2529692-02</td>
<td>.235513-02</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>COND MESH</th>
<th>TORD LEG</th>
<th>COND WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>.248578-01</td>
<td>.273541</td>
<td>1.77823</td>
</tr>
</tbody>
</table>

**POWER OF** 121 WATTS CAUSING -------------- CAPILLARY LIMIT: DPL > DP7

**LAST NON-LIMITED POWER CALCULATION WAS AT** ------------ 420 WATTS

**TOTAL DELTA-T =** 12.06° DBD C

**TOTAL MASS** = 0.294 EG
WALL NAPL=30433
EVAP TEMP = 302 VAPOR DELTA-T = 50 DEG C
GRAT ANG = 0.00 VTS ANG = 0.00 DEG

EVAP LENGTH 16.9291 IN 63.0000 CM
ADD LENGTH 16.9291 IN 63.0000 CM
COND LENGTH 68.2913 IN 174.0000 CM
TOTAL LENGTH 103.1800 IN 262.0000 CM

Q+D.
WALL THICK 0.0000 IN 0.0127 CM
GROOVE WIDTH 0.1083 IN 0.2750 CM
GROOVE HEIGHT 0.0256 IN 0.0650 CM
LADY WIDTH 0.0076 IN 0.0194 CM
12 GROOVES (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT ------------------ 318 WATTS

--- --- --- --- TOTAL DELTA-T = 9.32 DEG C
--- --- --- --- TOTAL MASS = 0.268 KG

WANT PERFORMANCE DETAILS (T OR H) IT

PE PE-A PA-C PC DTHES/CM2
-22297+07 -2229423-07 2228218+07 2228063+07
TE TE-A TA-C TC DEG C
206-287 226-279 226-274 226-271
EVAP TEMP CORD TEMP DELTA-T
302 203-623 8.37668
DPC= 4834 DPC= 0 DPC=4834 DTHES/CM2
DPX DPX2 DPX4 DPX8
280 305 163 1988
DPYC DPX8
150 1283

SONIC LIMITS: EVAP= 17710 ADD= 20631 WATTS
Q/A'S= EVAP CORD AXIAL WATTS/CM2
1 0 268
K K. KEY# L A KEY# L I J KEY# C A KEY# C B KEY#
3 1101 233 1101 0

HOT FLUID CHARGE 57.6718 GRAMS
POOM TEMP. VOLUME OF HOT FLUID CHARGE 62.3008 CM3

COLD FLUID CHARGE 72.0000 GRAMS
62-3341 CM3

HEAT PIPE: (MESH) & 2 MDCAPS 214.816 GRAMS

DELTA-T VALUES:

EVAP WALL EVAP LUG EVAP NESH EVAPOLIZATION
.130299 6.52069 .362160 104.099 DEG C

VAPOR (I) VAPOR (A) VAPOR (C)
.70563562-07 .8828115-02 .8062112-02

CONDensation COND NESH COND LUG COND WALL
.2415075-01 .253268 1.35502 .02003 DEG C

POWER OF 370 WATTS CAUSES -------------- CAPILLARY LIMIT, DPL = DPX

LAST JON-LIMITED POWER CALCULATION WAS AT -------------- 370 WATTS

------ ------ ------ TOTAL DELTA-T = 9.32 DEG C
------ ------ ------ TOTAL MASS = 0.268 KG
RHE CONDITIONS:

FLUID = DOWNSTREAM
WALL MATT=5068
EVAP TEMP = 277
VAPOR DELTA-T = 60 DEG C
GRAY AMG = 0.00
VAP AMG = 0.00 DEG

EVAP LENGTH 16.0000 IN 43.00000 CM
ADD LENGTH 16.00000 IN 43.00000 CM
COND LENGTH 4.0000 IN 102.00000 CM
TOTAL LENGTH 1031.000 IN 2626.00000 CM

0-D = 0.6000 IN 1.5700 CM
WALL THICK = 0.0000 IN 0.0127 CM
GROOVE WIDTH = 0.0035 IN 0.0850 CM
GROOVE HEIGHT = 0.0035 IN 0.0850 CM
LAND WIDTH = 0.0035 IN 0.0850 CM
L 2 GROOVED (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT ------------ 366 WATTS
----------- TOTAL DELTA-T = 0.48 DEG C
----------- TOTAL MASS = 0.261 KG

VAPOR PERFORMANCE DETAILS (Y OR N) ? Y

<table>
<thead>
<tr>
<th>PE</th>
<th>PE-A</th>
<th>PE-C</th>
<th>PC</th>
<th>PE/CM</th>
</tr>
</thead>
<tbody>
<tr>
<td>271.81</td>
<td>271.790</td>
<td>271.794</td>
<td>271.795</td>
<td></td>
</tr>
</tbody>
</table>

EVAP TEMP
COND TEMP
DELTA-T

277.24
270.801
5.44877

DPC = 8608 DPC = 0 DPC+DPC = 8608 DPC/CM2

DPC = 8608 DPC = 0 DPC+DPC = 8608 DPC/CM2

DPC = 8608 DPC = 0 DPC+DPC = 8608 DPC/CM2

DPC = 8608 DPC = 0 DPC+DPC = 8608 DPC/CM2

SONIC LIMITS:
EVAP= 11918 ADD= 13778 WATTS

G/A'S = EVAP COOL AXIAL WATTS/CM2
1 0 208

W R REY = LIQ REY = C A REY = C R REY
0 965 194 965 0

COLD FLUID CHARGE 66.5201 GRAMS
COLD VOLUME 51.606 CM3

HEAT PIPE: (MESH) & 2 ENDCAPS 212.537 GRAMS

DELTA-T VALUES:

<table>
<thead>
<tr>
<th>EVAP MATT</th>
<th>EVAP L.G</th>
<th>EVAP MESH</th>
<th>EVAP EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00000000</td>
<td>1.0000000</td>
<td>1.0000000</td>
<td>1.0000000</td>
</tr>
</tbody>
</table>

VAPOR (E) VAPOR (A) VAPOR (C)
1.0000000 0.0000000 0.0000000

CONDensation COOL MESH COOL L.G COOL VALL
0.0000000 1.0000000 1.0000000 1.0000000

COVER OF 310 WATTS CAUSES -------------- C. M. LIMITS, DPL = DPA

LAST NON-LIMITED POWER CALCULATION WAS AT ------------ 366 WATTS

----------- TOTAL DELTA-T = 7.48 DEG C
----------- TOTAL MASS = 0.261 KG
ORIGINAL PAGE IS OF POOR QUALITY

FLUID = DOWNTERM A  WALL MAT=3G0455
VAP TEMP = 282  VAPOR DELTA-T = 40 DEM C
GRAT AMG = 0.00  WTK AMG = 0.00 DEM

VAP LENGTH 16.9291 IN  43.0000 CM
ADD LENGTH 16.9291 IN  43.0000 CM
COND LENGTH 69.3913 IN  176.0000 CM
TOTAL LENGTH 103.1500 IN  262.0000 CM

0-D 0.0600 IN  1.2700 CM
WALL THICK 0.0000 IN  0.0000 CM
GROOVE #/TH 0.1045 IN  0.2650 CM
GROOVE HEIGHT 0.0967 IN  0.0247 CM
LAD VIND 0.0000 IN  0.0000 CM
12 GROOES (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT ------------ 219 WATTS

--------- TOTAL DELTA-T = 4.98 DEM C
--------- TOTAL MASS = 0.276 KG

WANT PERFORMANCE DETAILS (Y OR X) ?Y

FE  PE-A  PA-C  PC  DTHES/CM2
39793  837486  837235  838602

TE  TE-A  TA-C  TO  DEM C
248.038  248.017  248.004  247.992

VAP TEMP  COND TEMP  DELTA-T
282  247.018  4.98

DPC= 0311  DPC= 0  DPC+DPO= 0311  DTHES/CM2
DPVE  DPLMD  DPVA  DPLAG
307  613  253  2761

DPC= 0235  DPC= 0  DPC=0235
SONIC LIMIT3  VAP= 7617 ADD= 6733 WATTS

/\'=  ETAP  COND  AXIAL  WATTS/CM2
1  0  172

E R RET#  B A RET#  LIQ RET#  C A RET#  C R RET#
2  806  131  806  0

HOT FLUID CHARGE 52.3281 GRAMS
ROOM TEMP. VOLUME OF HOT FLUID CHARGE 49.1836 CM3
COLD FLUID CHARGE 64.0596 GRAMS
56.9808 CM3

HEAT PIPE? (MESH) & 2 END CAPS 209.931 CM3

DELTA-T VALUES:

VAP YALL  VAP LAG  VAP MSH  EVAPORATION
-94.7533-01  3.090006  -391114  +100090  DEM C

VAPOR (E)  VAPOR (A)  VAPOR (C)
-172192-01  -1318362-01  -1409263-01

COND TEMP  COND MCH  COND LGA  COLD WALL
-246975-01  -1.950006  -75716  +2309663-01  DEM C

POW OF  245 WATTS CAUSES ------------ CAPILLARY LIMIT, DFL > DPV
LACT NON-LIMITED POWER CALCULATION WAS AT ------------ 245 WATTS

--------- TOTAL DELTA-T = 5.46 DEM C
--------- TOTAL MASS = 0.276 KG
RUN CONDITIONS: 3/27/79

FLUID = DOWTHERM A  WALL MATT=30-438
EVAP TEMP = 219  VAPOR DELTA-T = 50 DEG C
GAS AM = 0.00  VTD AM = 0.00 DEG

EVAP LENGTH = 16.8221 IN  43.0000 CM
ADA LENGTH = 16.8221 IN  43.0000 CM
COIL LENGTH = 69.2213 IN  176.0000 CM
TOTAL LENGTH = 103.1500 IN  262.0000 CM
O.D.  0.0500 IN  1.2700 CM
VALL THICKS  0.0080 IN  0.0207 CM
GROOVE WIDTH  0.1055 IN  0.2680 CM
GROOVE HEIGTH  0.0175 IN  0.0445 CM
LANE WIDTH  0.0007 IN  0.0247 CM

12 GROOVES (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT 169 WATTS

- TOTAL DELTA-T = 4.05 DEG C
- TOTAL HASS = 0.574 ES

WATT PERFORMANCE DETAILS (T OR K) TT

<table>
<thead>
<tr>
<th>PE</th>
<th>PE-A</th>
<th>PA-C</th>
<th>PC</th>
<th>DTHERS/CM2</th>
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</thead>
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<td>363751</td>
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<table>
<thead>
<tr>
<th>TE</th>
<th>TE-A</th>
<th>TA-C</th>
<th>VC</th>
<th>DEG C</th>
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<tbody>
<tr>
<td>215.945</td>
<td>215.506</td>
<td>213.771</td>
<td>213.726</td>
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<thead>
<tr>
<th>EVAP TEMP</th>
<th>COND TEMP</th>
<th>DELTA-T</th>
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</thead>
<tbody>
<tr>
<td>219</td>
<td>214.662</td>
<td>4.04829</td>
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<tr>
<th>DPC</th>
<th>DFO</th>
<th>DPC+DFO</th>
<th>7317</th>
<th>DTHERS/CM2</th>
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<tr>
<td>388</td>
<td>378</td>
<td>334</td>
<td>2805</td>
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Sonic Limits:

<table>
<thead>
<tr>
<th>EVAP</th>
<th>3713</th>
<th>ADD</th>
<th>4207 WATTS</th>
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<tbody>
<tr>
<td>Q/A'S</td>
<td>EVAP</td>
<td>COND</td>
<td>AXIAL</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>133</td>
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<table>
<thead>
<tr>
<th>R BRT#</th>
<th>R BRT#</th>
<th>LIQ BRT#</th>
<th>C A BRT#</th>
<th>C R BRT#</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>643</td>
<td>76</td>
<td>643</td>
<td></td>
</tr>
</tbody>
</table>

Hot Fluid Charge: 53.9219 GRAMS
Room Temp. Volume of Hot Fluid Charge: 50.4827 CM3
Cold Fluid Charge: 64.0966 GRAMS
Heat Pipe: (Mesh) & 2 EndCaps: 209.281 GRAMS

Delta-T Values:

<table>
<thead>
<tr>
<th>EVAP WALL</th>
<th>EVAP LEG</th>
<th>EVAP MESH</th>
<th>EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>.060241-01</td>
<td>2.44127</td>
<td>.55693</td>
<td>.010093</td>
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<table>
<thead>
<tr>
<th>VAPOR (A)</th>
<th>VAPOR (C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.3607163-01</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>COND MESH</th>
<th>COND LEG</th>
<th>COND WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>.2415375-01</td>
<td>.131746</td>
<td>.057987</td>
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</tbody>
</table>

Power of 220 WATTS CAUSES CAPILLARY LIMIT; DPL > DPV

Last Non-Limited Power Calculation Was At 215 WATTS

- TOTAL DELTA-T = 4.12 DEG C
- TOTAL HASS = 0.274 ES
RUN CONDITIONS: 3/30/70

**FLUID** = MERCURY  **WALL MATL.** = 304SS

**EVAP TEMP** = 436  **VAPOR DELTA-T** = 30 DEG C

**GRAY ANG.** = 0.00  **WTO ANG.** = 0.00 DEG

**EVAP LENGTH** = 16.9291 IN  43.0000 CM

**ADD LENGTH** = 16.9291 IN  43.0000 CM

**CORD LENGTH** = 60.2913 IN  178.0000 CM

**TOTAL LENGTH** = 103.1500 IN  262.0000 CM

**O.D.** = 0.2500 IN  0.6350 CM

**WALL THICKS.** = 0.0025 IN  0.0064 CM

**GROOVE WIDTH** = 0.1083 IN  0.2794 CM

**GROOVE HEIGHT** = 0.0079 IN  0.0200 CM

**LAND WIDTH** = 0.0058 IN  0.0000 CM

5 GROOVES (CLOSED) COVERED WITH 200 MESH

**NO LIMIT ENCOUNTERED AT** ----------- 720 WATTS

---------- TOTAL DELTA-T = 4.13 DEG C

---------- TOTAL WATTS = 0.280 KG

**WANT PERFORMANCE DETAILS IT OR NT Y**

<table>
<thead>
<tr>
<th>PEl</th>
<th>PE-A</th>
<th>PA-G</th>
<th>PC</th>
<th>DTHES/GN2</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.36352E+07</td>
<td>0.360703E+07</td>
<td>0.379936E+07</td>
<td>0.380392E+07</td>
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</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TE</th>
<th>TA-A</th>
<th>TA-C</th>
<th>TC</th>
<th>DEG C</th>
</tr>
</thead>
<tbody>
<tr>
<td>430.875</td>
<td>430.712</td>
<td>430.564</td>
<td>430.637</td>
<td></td>
</tr>
</tbody>
</table>

**EVAP TEMP** = 436  **CORD TEMP** = 420.872  **DELTA-T** = 4.12044

**DPC** = 111419  **DPG** = 0  **DPG + DPC =** 111419  **DTHES/GN2** =

**DPM** = DPM9  **DPV** = DPVA  **DPQ** = DPLD  **DPG** = DPLG

**DPC** = 20703

**SONIC LIMITS:**

<table>
<thead>
<tr>
<th>ETAP</th>
<th>ADD</th>
<th>1069 WATTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>2/A'S</td>
<td>EVAP</td>
<td>3040</td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>2273</td>
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<table>
<thead>
<tr>
<th>S R REY#</th>
<th>E A LIT#</th>
<th>LIG REY#</th>
<th>C A REY#</th>
<th>C R REY#</th>
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<tbody>
<tr>
<td>13</td>
<td>7785</td>
<td>395</td>
<td>7797</td>
<td>3</td>
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</table>

**HOT FLUID CHARGE** = 206.064 GRAMS

**ROOM TEMP. VOLUME OF HOT FLUID CHARGE** = 18.2117 CM3

**COLD FLUID CHARGE** = 213.035 GRAMS

**HEAT NSPS (MESH) + 2 ENDCAPS** = 78.493 CM3

**DELTA-T VALUES:**

<table>
<thead>
<tr>
<th>EVAP WALL</th>
<th>EVAP LAD</th>
<th>ETAP WASH</th>
<th>EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.95061E+07</td>
<td>1.53407</td>
<td>1.100098</td>
<td></td>
</tr>
</tbody>
</table>

**VAPOR (L)** = VAPOR (A) = 1.533018  **VAPOR (C)** = 1.957197

**COND NSPS** = COND LAD = 1.732066  **COND WALL** = 1.957197

**POW OF 475 WATTS CAUSES** ************ CAPILLARY LIMIT, DPL > DWV

**LAST NON-LIMITED POWER CALCULATION WAS AT** ----------- 720 WATTS

---------- TOTAL DELTA-T = 4.13 DEG C

---------- TOTAL WATTS = 0.280 KG

**ORIGINAL PAGE IS OF POOR QUALITY**
FLUID = MERCURY
WALL MATL=304 SS
EVAP TEMP = 402
VAPOR DELTA-T = 60 DBR C
GRAV ANG = 0.30
WTR ANG = 0.00 DBR

EVAP LENGTH 16.9291 IN 43.0000 CM
ADD LENGTH 16.9291 IN 43.0000 CM
COND LENGTH 69.2913 IN 176.0000 CM
TOTAL LENGTH 103.1800 IN 262.0000 CM

D. 0.2500 IN 0.6350 CM
ALL THICKS 0.0036 IN 0.0092 CM
GROOVE WIDTH 0.1963 IN 0.4988 CM
GROOVE HEIGHT 0.0079 IN 0.0200 CM
LAND WIDTH 0.0716 IN 0.1822 CM
6 GROOVES (CLOSED) COVERED WITH 200 MESH

NO LIMIT ENCOUNTERED AT -------------- 668 WATTS

---------- TOTAL DELTA-T = 3.62 DBR C
---------- TOTAL MASS = 0.281 KG

WANT PERFORMANCE DETAILS (Y OR N) ? Y

<table>
<thead>
<tr>
<th>PK</th>
<th>PK-A</th>
<th>PA-C</th>
<th>PC</th>
<th>DTHRS/CM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>01254625+07</td>
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<td>.23756325+07</td>
<td>.2368273+07</td>
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<table>
<thead>
<tr>
<th>TE</th>
<th>TE-A</th>
<th>TA-C</th>
<th>TC</th>
<th>DBR C</th>
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<tbody>
<tr>
<td>599.401</td>
<td>399.153</td>
<td>399.824</td>
<td>399.016</td>
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</tr>
</tbody>
</table>

EVAP TEMP JOINT TEMP DELTA-T
402 398.379 3.62081

DPC = 116291 DPC = 0 DPC+DPC = 116291 DTHRS/CM2

DPVE DPVE DPVA DPLAG
9242 7658 6442 56897
DPVC DPLOG
-3408 31339

SONIC LIMITS: EVAP = 543 A ADD = 6419 WATTS

3/4'S = EVAP JOINT AXIAL WATTS/CM2
3 1 1888

B R TOT# R A ADV# LIQREV# C A ADV# C A ADV# 2
11 6726 367 6729

HOT FLUID CHARGE 187.61 GM
VOLUME OF HOT FLUID CHARGE 13.8439 CM3

COLD FLUID CHARGE 193.515 GRAMS
14.2568 CM3

HEAT PIPE, (MESH) & 2 ENDCAPS 87.8689 GRAMS

DELTA-T VALUES:

<table>
<thead>
<tr>
<th>EVAP WALL</th>
<th>EVAP LG</th>
<th>EVAP MESH</th>
<th>EVAPORATION</th>
</tr>
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<tbody>
<tr>
<td>25884</td>
<td>.298525</td>
<td>1.39772</td>
<td>.100982 DBR C</td>
</tr>
</tbody>
</table>

VAPOR (1) VAPOR (2) VAPOR (3)
-.242091 .223004 -.2179692-01

CONDENSATION COND MESH O/W LG COLD WALL
.34-5572-01 .32469 .332703 .560945 DBR C

POWER OF 615 WATTS CAUSES -------------- CAPILLARY LIMIT, DPL > DPT

LAST NON-LIMITED POWER CALCULATION WAS AT -------------- 610 WATTS

---------- TOTAL DELTA-T = 3.60 DBR C
---------- TOTAL LHS = 0.234 KG
FLUID = MEROX
EVAP TEMP = 362
VAPOR DELTA-T = 50 DEG C
G/MY AND = 0.00
VIS AND = 0.00

EVAP LENGTH 16.0291 IN 43.09906 CM
ADD LENGTH 16.0291 IN 43.09906 CM
GROOVE LENGTH 60.2815 IN 1576.90000 CM
TOTAL LENGTH 103.1840 IN 2623.00000 CM

VISCOSITY 0.2500 IN 0.6350 CM
WALL THICKS 0.0025 IN 0.0006 CM
GROOVE WIDTH 0.1083 IN 0.2750 CM
GROOVE HEIGHT 0.0070 IN 0.0230 CM
LAND WIDTH 0.1318 IN 0.3350 CM
3 GROOVES (CLOSED) COVERS WITH 200 MESH

NO LIMIT ENCOUNTERED AT --------------- 660 WATTS

TOTAL DELTA-T = 3.30 DEG C
TOTAL MASS = 0.875 KG

WANT PERFORMANCE DETAILS (T OR HQ) VV

<table>
<thead>
<tr>
<th>PK</th>
<th>PK-A</th>
<th>PK-B</th>
<th>PK-C</th>
<th>PK-D</th>
<th>VRMS/CM2</th>
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</thead>
<tbody>
<tr>
<td>350.04</td>
<td>346.583</td>
<td>346.046</td>
<td>346.199</td>
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</table>

DELTA-T VALUES:

EVAP WALL 0.17328 0.680503 1.00319 1.00096 DEG C
VAPOR (E) 0.307331 0.337354 0.850367
CONDENSATION 0.244873-C1 0.215636 0.166603 0.429336-01 DEG C

POWER OF 660 WATTS CAUSE ---------- CAPILLARY LIMIT, DPC > DPT
LAST NON-LIMITED POWER CALCULATION WAS AT --------------- 445 WATTS

TOTAL DELTA-T = 3.34 DEG C
TOTAL MASS = 0.875 KG
**IN CONDITIONS:**

- **Liquid:** Mercury
- **Wall Mat.:** 304SS
- **Vap Temp.:** 302
- **Vapor Delta-T:** 50 Deg C
- **Ray Anc.:** 0.00
- **Vol Anc.:** 0.00 Deg C

**Vap Length:** 16.9291 in
**In Length:** 16.9291 in
**Cond Width:** 69.2913 in
**Total Width:** 103.1500 in

**D.O.:** 0.2500 in
**Wall Thik.:** 0.0085 in
**Groove Width:** 0.1085 in
**Groove Height:** 0.0075 in
**Land Width:** 0.1318 in

3 Grooves (Closed) Covered With 200 Mesh

**No Limit Encountered At:** 315 Watts

---

**Sant Performance Details**

<table>
<thead>
<tr>
<th>PE</th>
<th>FE-A</th>
<th>P-A-C</th>
<th>PC</th>
<th>DTRES/CM2</th>
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<tr>
<td>4465637</td>
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**TE:**

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<td>300.518</td>
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**STAP TEMP:**

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<th>DELTA-T</th>
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</thead>
<tbody>
<tr>
<td>302</td>
<td>297.493</td>
<td>4.60708</td>
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**DPC=** 124573
**DPG=** 0
**DPC+DPG=** 124573

**DPyE:**

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<th>DPLEG</th>
<th>DPVE</th>
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</thead>
<tbody>
<tr>
<td>13616</td>
<td>5634</td>
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**DPVC:**

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<th>DPLEG</th>
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</table>

**50th Limits:**

| EVAP= | 1062 | ADD= | 1146 | Watts |

**J/A'S:**

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<thead>
<tr>
<th>EVAP</th>
<th>COND</th>
<th>AXIAL</th>
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</thead>
<tbody>
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<td>994</td>
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**E R Ret#**

<table>
<thead>
<tr>
<th>E R Ret#</th>
<th>LIQ Ret#</th>
<th>C &amp; Ret#</th>
<th>C R Ret#</th>
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</thead>
<tbody>
<tr>
<td>4208</td>
<td>254</td>
<td>4232</td>
<td>1</td>
</tr>
</tbody>
</table>

**HOT FLUID CHARGE:**

169.39 Grams

Room Temp. Volume of Hot Fluid Charge: 12.5617 cm³

**COLD FLUID CHARGE:**

173.995 Grams

12.5617 cm³

**Heat Pipe (Mesh) = 2 Endcaps 99.2507 Grams**

**Delta-T Values:**

<table>
<thead>
<tr>
<th>Evap All</th>
<th>Evap Log</th>
<th>Evap Mesh</th>
<th>Evaporation</th>
</tr>
</thead>
<tbody>
<tr>
<td>130298</td>
<td>0.05764</td>
<td>0.25760</td>
<td>1.00093</td>
</tr>
</tbody>
</table>

**Vapor (A) + Vap (A) + Vap (C):**

| 1.39453  | 1.30768  | -1.93075  |

**Condensation:**

<table>
<thead>
<tr>
<th>Cond All</th>
<th>Cond Log</th>
<th>Cond Wall</th>
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</thead>
<tbody>
<tr>
<td>24.5972-01</td>
<td>1.26729</td>
<td>-1.23971</td>
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</tbody>
</table>

**Power of 300 Watts Causes **

- Capillary Limit, DPL = DPV

**Last W0a-Limited Power Calculation**

| W3 A3 | 1204.79 |

---

**Total Delta-T:**

| 5.41 Deg C |

**Total Mass:**

| 0.273 kg |
FLUID = MERCURY  WALL MATL=304SS
EVAP TEMP = 277  VAPOR DELTA-T = 50 DEG C
GRAY AND = 0.00  VEB AND = 0.00 DEG C

EVAP LENGTH 16.9291 IN 43.0000 CM
ADD LENGTH 16.9291 IN 43.0000 CM
COND LENGTH 60.2949 IN 176.0000 CM
TOTAL LENGTH 103.1830 IN 262.0000 CM

O.D. 0.2600 IN 0.6550 CM
WALL THICK 0.0026 IN 0.0066 CM
GROOVE WIDTH 0.1033 IN 0.2620 CM
GROOVE HEIGHT 0.3079 IN 0.0290 CM
LANE WIDTH 0.1318 IN 0.3340 CM
3 GROOVES (CLOSED) COVERED WITH 800 MESH

NO LIMIT ENCOUNTERED AT ---------- 264 WATTS
---------- TOTAL DELTA-T = 8.36 DEG C
---------- TOTAL MASS = 0.273 LS

WANT PERFORMANCE DETAILS (IT OR II) YY

PE PE-A PA-C PC DTHES/GM2
256642 246063 226694 224693

TE TA-A TA-C TC DEG C
275.718 272.568 269.961 269.962

EVAP TEMP COND TEMP DELTA-T
277 269.964 0.35362

DP= 127035 DPG = 0 DPG+DP= 127035 DTHES/GM2

DPV= DPLED DPVA DPLAG
18649 18696 37334

DPVC DPLCD
-4 19636

SONIC LIMITS:
EVAP= 654 ADD= 630 WATTS

Q/A'S=
3 0 833

E R PAY:
L A R E # LIQ R E # C A R E # G R E #
6 3737 298 3401 1

HOT FLUID CHARGE 170.187 GRAMS
ROOM TEMP. VOLUME OF HOT FLUID CHARGE 12.5636 CM3

COLD FLUID CHARGE 173.986 GRAMS
12.3468 CM3

HEAT PIPE: (MESH) & 2 ENDCAPS 99.2507 GRAMS

DELTA-T VALUES:

EVAP WALL EVAP LAG EVAP MESH EVAPURATION
.111323 .321373 .597975 .100998 DEG C

VAPOR (2) VAPOR (1) VAPOR (C)
3 .17383 3 .928526 -.70324222-03

CONDEN.ATION COND MESH COND LAG COND WALL
.24645972-01 .197889 .106314 .2737815-01 DEG C

POWER OF 380 WATTS CAUSED ---------- CAPILLARY LIMIT: DPL > DPV

LAST NON-LIMITED POWER CALCULATION AS AT ---------- 345 WATTS
---------- TOTAL DELTA-T = 12.63 DEG C
---------- TOTAL 6857 = 0.273 LS
R07 CONDITIONS 12/14/73 P.H. 3130/73

NU p • µ cm HALL14ATWO635

ZTAP ?IMP • 434 TAPO & DELTA-T • 50 D

NO LIMIT ENCOUNTERED AT ---------- 720 WATTS

---------- TOTAL DELTA-T = 2.80 DEC C
---------- TOTAL MASS = 0.860 KG

WATT PERFORMANCE DETAILS (IT OR H) ??

<table>
<thead>
<tr>
<th>PE</th>
<th>PE-A</th>
<th>PA-C</th>
<th>PC</th>
<th>DYNMS/CM2</th>
</tr>
</thead>
<tbody>
<tr>
<td>.36965623+07</td>
<td>.3687243+07</td>
<td>.3687213+07</td>
<td>.3687464+07</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>TE</th>
<th>TE-A</th>
<th>TA-C</th>
<th>TC</th>
<th>DEC C</th>
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<tbody>
<tr>
<td>.432.30</td>
<td>.432.216</td>
<td>.432.216</td>
<td>.432.298</td>
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<table>
<thead>
<tr>
<th>EVAP TEMP</th>
<th>COLD TEMP</th>
<th>DELTA-T</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>434</td>
<td>431.1498</td>
<td>2.950244</td>
<td></td>
</tr>
</tbody>
</table>

DPC= 114073 DPA= 0 DPG+DPF= 114073 DYNMS/CM2

DPVE DPLBD DPTA DPLAG
9281 14532 0 0
DPTC DPLAC
-37.25 29.142

SONIC LIMITS: EVAP= 8846 ADD= 10334 WATTS

Q/A'S= EVAP COND ALIAR WATT/CM2 |
| 4 | 2 | 2266 |

R R H# R A H# LIQ C A H# C R H# |
| d | 77.85 | 194 | 3 |

HOT FLUID CHARGE 206.234 GRAMS
ROOM TEMP. VOLUME OF HOT FLUID CHARGE 15.2247 CM3

COLD FLUID CHARGE 213.233 GRAMS 15.7416 CM3

HEAT PIPE: (MESS) & 2 END CAPS 76.7047 GRAMS

DELTA-T VALUES:

<table>
<thead>
<tr>
<th>CITAP VALL</th>
<th>EVAP LAG</th>
<th>EVAP MESH</th>
<th>EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>.1120986</td>
<td>.988019</td>
<td>.775944</td>
<td>.100098</td>
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<table>
<thead>
<tr>
<th>TAPOR (L)</th>
<th>TAPOR (A)</th>
<th>TAPOR (G)</th>
</tr>
</thead>
<tbody>
<tr>
<td>.174072</td>
<td>.6389212-03</td>
<td>.6953292-01</td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>COND MESH</th>
<th>COND LAG</th>
<th>COND WALL</th>
</tr>
</thead>
<tbody>
<tr>
<td>-.6361135-01</td>
<td>.292641</td>
<td>.6612432-01</td>
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</tbody>
</table>

POWER OF 1560 WATTS CAUSES ---------- CAPILLARY LIMIT, DPL > DPV

LAST NON-LIMITED POWER CALCULATION WAS AT ---------- 1665 WATTS

---------- TOTAL DELTA-T = 3.47 DEC C
---------- TOTAL MASS = 1.459 KG
RUN CONDITIONS:

12/28 P.M.  3/30/79

FLUID = MERCURY   WALL MATT. = 304-88
EVAP TEMP = 277    VAPO OR DELTA-T = 59. DEG C
GRAY AM = 0.00    VTS AM = 0.00 DEG

EVAP LENGTH 33.8666 IN  36.0000 CM
ADD LENGTH 0.0000 IN  0.0000 CM
COND LENGTH 69.2406 IN  176.0000 CM
TOTAL LENGTH 103.1000 IN  262.0000 CM

O=De 0.2500 IN  0.6350 CM
WALL THICKS 0.3026 IN  0.7684 CM
GROOVE WIDTH 0.1003 IN  0.2540 CM
GROOVE HEIGHT 0.0079 IN  0.0200 CM
LAND WIDTH 0.1318 IN  0.3346 CM
3 GROOVES (CLOSED) COVERED WITH 200 Mesh

NO LIMIT ENCOUNTERED AT ----------- 264 WATTS
----------- TOTAL DELTA-T = 4.79 DEG C
----------- TOTAL MASS = 0.278 EB

WATF PERFORMANCE DETAILS (Y OR N) Y

<table>
<thead>
<tr>
<th>FL</th>
<th>PE-A</th>
<th>PA-C</th>
<th>PE-C</th>
<th>PC</th>
</tr>
</thead>
<tbody>
<tr>
<td>268.631</td>
<td>240.081</td>
<td>260.217</td>
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<table>
<thead>
<tr>
<th>TE</th>
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<th>PA-C</th>
<th>TC</th>
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<td>272.509</td>
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<table>
<thead>
<tr>
<th>EVAP TEMP</th>
<th>COND TEMP</th>
<th>DELTA-T</th>
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<tbody>
<tr>
<td>277</td>
<td>272.521</td>
<td>47.9865</td>
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<table>
<thead>
<tr>
<th>DPE-</th>
<th>DPG=</th>
<th>DPC=DPE-</th>
<th>DPC+DPG=</th>
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</thead>
<tbody>
<tr>
<td>129.75</td>
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<td>129.75</td>
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<table>
<thead>
<tr>
<th>DPE-A</th>
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</thead>
<tbody>
<tr>
<td>99.99</td>
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<table>
<thead>
<tr>
<th>DPE-V</th>
<th>DPLCS</th>
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<tr>
<td>186.41</td>
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<table>
<thead>
<tr>
<th>DPE-W</th>
<th>DPLCG</th>
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</thead>
<tbody>
<tr>
<td>99.99</td>
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</table>

<table>
<thead>
<tr>
<th>VAP</th>
<th>661</th>
<th>ADD</th>
<th>632</th>
<th>WATTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Q/A3=</td>
<td>EVAP</td>
<td>COND</td>
<td>AXIAL</td>
<td>WATTS/CML</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>633</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| H.B. RET# | E A RET# | LIG RET# | C A RET# | G B RET# | 3 | 3761 | 209 | 3766 | 1 |

HOT FLUID CHANGE 170.13 GRAMS
COLD FLUID CHANGE 173.985 GRAMS

HEAT PIPE: (WSS3) & 2 END CAPS 99.2507 GRAMS

DELTA-T VALUES:

<table>
<thead>
<tr>
<th>EVAP WALL</th>
<th>EVAP LGC</th>
<th>EVAP MESS</th>
<th>EVAP EVAPORATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.56814-01</td>
<td>0.216052</td>
<td>0.314761</td>
<td>0.000569</td>
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<table>
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<tr>
<th>TAPOR (E)</th>
<th>TPOR (A)</th>
<th>TPOR (C)</th>
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<tr>
<td>3.7189</td>
<td>0.7324222-03</td>
<td>419.6131-01</td>
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<table>
<thead>
<tr>
<th>COND MESS</th>
<th>COND MESS</th>
<th>COND MESS</th>
<th>COND MESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.429115-01</td>
<td>0.158322</td>
<td>0.106007</td>
<td>272.612-01</td>
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</tbody>
</table>

NOT OF 500 WATTS LIMITS ----------- ADD 500 WATTS LIMIT

LAST MIN-LIMITED POWER CALCULATION WAT AT ----------- 495 WATTS

----------- TOTAL DELTA-T = 5.4A DEG C
----------- TOTAL MASS = 0.278 EB
APPENDIX B

HEAT PIPE COOLED NUCLEAR REACTOR DESIGN INFORMATION FROM LOS ALAMOS SCIENTIFIC LABORATORY

(34 Pages)
This appendix contains the parametric information concerning heat-pipe-cooled reactor weights and sizes for use in the NASA Brayton power plant studies which was supplied by LASL. Data on gas cooled reactors was also furnished but not included herewith since such reactors received only very cursory attention in this study. The mass summary in Figure B-1 indicates that 90%UC-10%ZrC fueled reactors are lighter but more limited in temperature than 60%UO₂-40%Mo fueled reactors. Gas cooled reactors tend to be heavier below 1 MWₜ for 90%UC-10%ZrC and 4 MWₜ for 60%UO₂-40%Mo.

For heat-pipe reactors, an allowance of 100°K was made for the temperature drop from the reactor heat pipes to the Brayton loop gas. This resulted in analyzing heat pipe reactors 100 degrees higher than the desired turbine inlet temperature. The turbine inlet temperatures AiResearch specified were 1150°K, 1325°K, 1500°K and 1650°K. The accompanying tabulations provides information at various operating levels. It should be noted that the reactor mass includes one meter of heat pipes beyond the core for use in the heat exchanger but does not include the remainder of the heat exchanger. This mass can be adjusted as needed using the heat pipe mass/unit length values.

Both 90%UC-10%ZrC and 60%UO₂-40%Mo fueled reactors with lifetimes of 10 years at full power were investigated. For the 90%UC-10%ZrC, excessive fuel swelling becomes a problem at 1425°K above 1 MWₜ. For lower temperatures and power levels, reactor sizes are limited by criticality and heat transfer considerations. For the region where excess swelling limitations govern, the power density in the fuel must be reduced. A number of means were examined including changing the void fraction in the fuel, reducing the ²³⁵U enrichment, adjusting the heat pipe size and modifying the cladding matrix. Adjusting the void fraction will lead to the lowest weight core but at present it is only...
an engineering estimate as to how much void can be accepted in a given design. It was concluded that the uncertainties and difficulties in design would not warrant designing a 90\%UC-10\%ZrC core if the power level and temperature exceeded 2 MW\(_t\) and 1425°K since the weight was approaching that of 60\%UO\(_2\)-40\%Mo at these conditions and would probably exceeded it by 4 MW\(_t\).

The 60\%UO-40\%Mo reactor is criticality and heat transfer limited for the 1425, 1600, and 1750°K outlet temperature cases except that above 2 MW\(_t\) for 1750°K it becomes fuel-swelling limited. Based on our current best information on fuel swelling, a 4 MW\(_t\) reactor operating at 1750°K will have about 14 percent dense fuel swelling.
Figure B-1. Reactor Mass Summary.
0.2400 (PP) REACTOR POWER M"H (KWB) (1,2/UC+UC2) CORE VAC
1.2500 (THP) HEAT PIPE TEMP 0.038 K (KMID) (1.2/4 UC+UC2) REFLECTOR VAC
7.500 (TIME) LIFETIME DAYS (KWH) (1.2/UC+UC2) HEAT PIPE END
1.00 (FLD) CORE L/D RATIO (KVAR) (1.2/UC+UC2) VAPOR VAC
10.0 (FLD) AXIAL HT FLUX KH/CH2 (TOPH) (1.2) OPTION = 2
200. (DEFEAY) MAY FUEL DELTA T DEG K
1.00 (WALL) PIPE EXTENSION

NOTE: OPTIONS ARE 1-CODE AT DESIGN 2-SPECIFIED DESIGN
   TYPE IN ANY OF FOLLOWING DCHEM (KWB) 1-PHASE HTF SILENT PIPE...STOP
   NPIPE = 34 STOP

84 (HIPPE) NO. OF HEAT PIPES
   SETA = 0.1500 VCD = 0.0500 0.600 1.500 0.050 0.033 0.015 0.005
   TYP = 3 STOP OR NEW CONSTANT = 1. VC 0.0, PHASE = 2, ETC...STOP
   VCD = 0.132 STOP
   EFL INP = 3
   WIP = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000
   DC = 0.190 0.290 0.390 0.490 0.590 0.690 0.790 0.890 0.990 1.000
   DMC = 0.120 0.220 0.320 0.420 0.520 0.620 0.720 0.740 0.840 0.940 1.000
   TYPE = 30 OR START OVER

G0. 34 PIPE
   SETA = 0.1500 VCD = 0.2743 VAF = 0.7257 DC = 0.1900 DC = 0.2237
   REACTIVITY CHANGE: DELTA V
   BURN = 0.00718 EXP = 0.001512 SAFE = 0.02000 TOTAL = 0.04230

FUEL ELEMENT VOLUME FRACTIONS:
   CLADDING FUEL REGION HEAT PIPE WALL+WICK VAPOR
   0.0500 0.8442 0.053 0.0343 0.0515
   NEUTRON CORNER CORRECTION FACTOR = 1.0032
   NUMBER OF HEAT PIPES = 35, 3550
   MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 34

TEMPERATURE SUMMARY: DEGREES KELVIN
   HEAT PIPE WALL DELTA T = 84.2
   CORE DELTA T ACROSS HEAT PIPE WALL = 4.7
   AVERAGE FUEL TEMPERATURE = 1284.8
   MAXIMUM FUEL TEMPERATURE = 1341.2

BURN FRACTION OF UC35 = 0.0120
FUSION DENSITY (FISSION/CH2) = 2.493E+20
FUEL FILLING VOLUME % = 0.92

CORE DIAMETER: METER:
   0.2337 COG DIAMETER: 23.11 WIDTH ACROSS HEX FLAT
   0.2337 COG HEIGHT
   0.4337 REACTOR DIAMETER
   0.4337 REACTOR HEIGHT
   0.1000 REFLECTOR THICKNESS
   1.0000 PIPE LENGTH OUTSIDE REACTOR
   1.3287 TOTAL HEAT PIPE LENGTH
   1.4337 OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR WEIGHT: KILOGRAMS
   82.6 FUEL  UC35 Mass = 70.2
   148.7 REFLECTOR
   18.1 HEAT PIPE X UNIT LENGTH (KG/M) = 12.60
   33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)
   19.3 SUPPORT STRUCTURE (% OF REACTOR WT)

   TOTAL REACTOR + HEAT PIPES

26.64 MU+H+Z+L, AND FOUR IN FUELSpace 2.38 MU+H+Z+L PER HEAT PIPE
100.03 MU+H+Z+L/HEAT PIPE AXIAL HT FLUX 0.615 MU+H+Z+L/HEAT PIPE RAD HTFLY

TYPE 30 OR STOP
<table>
<thead>
<tr>
<th>PROP NO.</th>
<th>5-17-78</th>
<th>TYPE NEW INPUT: PR=1, KHP=2</th>
<th>STOP</th>
</tr>
</thead>
<tbody>
<tr>
<td>PR=0.4 STOP</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>0.400</strong> (PM)</td>
<td>EFFECTOR POWER input (KCORE) = (1+2/VC+UG2) CORE = VC</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>1250.</strong> (PM)</td>
<td>HEAT PIPE TEMP DEG K (KREF) = (1+2/SE+SG2) REFLECTOR = SE</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>3650.</strong> (TIME)</td>
<td>LIFETIME DAYS (KHP) = (1+2/HE+MH2) HEAT PIPE = MH</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.00 (SLD)</td>
<td>CORE L/D RATIO (KVAPO) = (1+2/LLNA) VAPOR = NA</td>
<td></td>
<td></td>
</tr>
<tr>
<td>10.0 (OAKL)</td>
<td>AXIAL HT FLUX X12 CH2 (OAKTN) = OPTION = 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200. (DTPHAY)</td>
<td>MAX FUEL DELTA T DEG K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1.00 (HPL1)</td>
<td>PIPE EXTENSION=M</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**NOTE:** OPTIONS ARE: 1-CODE PT DESIGN, 2-SPECIFIED DESIGN, TYPE IN ANY OF FOLLOWING: 1 CODE (N) XREP(N) UNFT FIETA NA PIPE ... STOP

**NA PIPE=34 STOP**

**84** (NA PIPE) NO. OF HEAT PIPES

<table>
<thead>
<tr>
<th>BETA</th>
<th>VC</th>
<th>VCDB</th>
<th>ALFA</th>
<th>PKAVG</th>
<th>MIN</th>
<th>DMAX</th>
<th>CORRAP</th>
<th>ENDGAP</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.150</td>
<td>0.012</td>
<td>0.050</td>
<td>1.500</td>
<td>0.050</td>
<td>0.080</td>
<td>0.015</td>
<td>0.005</td>
<td></td>
</tr>
</tbody>
</table>

**TYPE: STOP, OR NEW CONSTANTS IE. VC=0, PKAVG=2, ETC ... STOP**

**STOP**

| SLD INDEX | 3 |
| UNF | 0.100 | 0.200 | 0.300 | 0.400 | 0.500 | 0.600 | 0.700 | 0.800 | 0.900 | 1.000 |
| DC | 0.196 | 0.208 | 0.230 | 0.260 | 0.299 | 0.352 | 0.437 | 0.525 | 0.643 |
| DCX | 0.20 | 0.27 | 0.191 | 0.196 | 0.135 | 0.120 | 0.110 | 0.102 | 0.095 |

**REACTIVITY CHANGES/DELTA K**

| BURN | 0.01258 | EXP | 0.01512 | ZAFES | 0.02000 | TOTAL | 0.04800 |

**FUEL ELEMENT VOLUME FRACTIONS**

<table>
<thead>
<tr>
<th>CLADDING</th>
<th>FUEL REGION</th>
<th>HEAT PIPE WALL+THICK</th>
<th>VAPOR</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0500</td>
<td>0.7984</td>
<td>0.1516</td>
<td>0.0606</td>
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</tbody>
</table>

**HEXAGONAL CORNER CORRECTION FACTOR = 1.0258**

**NUMBER OF HEAT PIPES = 48, 5972**

**MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 84**

**TEMPERATURE SUMMARY: DEGREE KELVIN**

| MAXIMUM FUEL DELTA T = 115.9 |
| AVERAGE DELTA T ACROSS HEAT PIPE WALL = 8.8 |
| AVERAGE FUEL TEMPERATURE = 1297.5 |
| MAXIMUM FUEL TEMPERATURE = 1379.2 |

**BURN FRACTION OF U235 = 0.0215**

**FISSION DENSITY (FISSIONS/CH**2**)= 4.474e+20**

**FUEL SWELLING-VOLUME % = 1.86**

**Reactor Dimensions:** Meters

| 0.2381 | CORE DIAMETER |
| 0.2381 | CORE HEIGHT |
| 0.4631 | REACTOR DIAMETER |
| 0.4481 | REACTOR HEIGHT |
| 0.1000 | REFLECTOR THICKNESS |
| 1.0000 | PIPE LENGTH OUTSIDE REACTOR |
| 1.3431 | TOTAL HEAT PIPE LENGTH |
| 1.4481 | OVERALL REACTOR + HEAT PIPE LENGTH |

**Reactor Weights:** Kilograms

| 32.0 | FUEL, U235 MASS = 78.2 |
| 163.1 | REFLECTOR |
| 36.5 | HEAT PIPES, WT/UNIT LENGTH (KG/FT) = 27.21 |
| 33.0 | CONTROL SYSTEM (ASSUME CONSTANT = 33 KG) |
| 22.7 | SUPPORT STRUCTURE (7% OF REACTOR WT) |

**346.3** TOTAL REACTOR + HEAT PIPES

**47.83** (W) (K*CH**2**)=AVS FOURS IN FUELSPACE **4.76** (K)(HEAT PIPE)

**99.94** (W) (K*CH**2**)=AVS HEAT PIPE AXIAL HT FLUX **0.817** (K)(HEAT PIPE RAD HTFLY)

**STOP**
PROG NO. 4 5-17-78 TYPE NEW INPUT: PR=1. KHP=2 STOP

PR=0.7 STOP

0.700 (FR) REACTOR POWER=MU (KCOEF) = (1.2:UC+U02) CORE RUC
1250. (KWP) HEAT PIPE TEMPERATURE (KREF) = (1.2:15:100) REFLECTOR RBD
3650. (TIME) LIFETIME=DAYS (KWP) = (1.2:13:10:40:100) HEAT PIPE RBD
1.00 (FLD) CORE L/D RATIO (KVARF) = (1.2:LI:IN:1:VA:OR:1:SA:1:AN)
10.0 (BA-L) AXIAL HT FLUX/KW/CH2 (TOPTN) = (1.2) OPTION = 0
200. (TRMAY) MAX FUEL DELTA T=DEG =
1.00 (HFL1) PIPE EXTENSION=MU

NOTE: OPTIONS ARE: 1-CODE PT DESIGN; 2-SPECIFIED DESIGN
TYPE IN ANY OF FOLLOWING: DCORE(H) XPER(H) UNFT PI ETA NPIPE ..STOP
NPIPE=120 STOP

120 (NPIPE) NO. OF HEAT PIPES

BETA = 0.1500 UNF = 0.3995 VF = 0.6095 DX = 0.1000 DC = 0.2568

FLD INDEX = 0 UNF = 0.10.1 0.200 0.200 0.400 0.500 0.500 0.600 0.700 0.800 0.900 1.000
DC = 0.196 0.208 0.230 0.260 0.290 0.320 0.350 0.380 0.530 0.630 0.943
DCH = 0. 3.484 0.354 0.251 0.205 0.177 0.159 0.145 0.134 0.126

TYPE 50 OR START OVER

BETA = 0.1500 UNF = 0.3995 VF = 0.6095 DX = 0.1000 DC = 0.2568

REACTION CHANGES: DELTA K
BURN = 0.01977 EXP = 0.01512 SAFE = 0.02000 TOTAL = 0.05489

HEAT ELEMENT VOLUME FRACIONS:

CLADDING FUEL REGION HEAT PIPE WALL+THICK VAPOR
0.4500 0.7229 0.2271 0.0908 0.1363

HEXAGONAL CORNER CORRECTION FACTOR = 1.0588

NUMBER OF HEAT PIPES = 60,676

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 120

TEMPERATURE SUMMARY: DEGREE KELVIN

MAXIMUM FUEL DELTA T = 10.1
AVG DELTA T ACROSS HEAT PIPE WALL = 10.0
AVERAGE FUEL TEMPERATURE = 1239.7
MAXIMUM FUEL TEMPERATURE = 1366.2

BURN FRACTION OF U235 = 0.0329

FUSION DENSITY (FISSION/CH*3) = 6.365x20

FUEL SELLING+VOLUME % = 2.77

FLOW FUEL % = 3.26

REACTOR DIMENSIONS: METERS

0.2568 CORE DIAMETER
0.2568 CORE HEIGHT
0.4868 REACTOR DIAMETER
0.4868 REACTOR HEIGHT
0.1000 REFLECTOR THICKNESS
1.0000 PIPE LENGTH OUTSIDE REACTOR
1.3618 TOTAL HEAT PIPE LENGTH
1.4468 OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR WEIGHTS: KILOGRAMS

104.9 FUEL = U235 MASS = 89.2
180.4 REFLECTOR
64.6 HEAT PIPES = HT/UNIT LENGTH (KG/M) = 47.61
33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)
26.8 SUPPORT STRUCTURE (7% OF REACTOR WT)

409.9 TOTAL REACTOR + HEAT PIPES

73.39 MW/HT: AVERAGE POWER IN FUELSPACE 5.83 MW/POWER PER HEAT PIPE
93.38 MW/HT: AXIAL HT FLUX 0.839 MW/HT: HEAT PIPE AND HTFLY

STOP
PO=1.

1,000 (PA) POWER=IU
1250. (THP) HEAT PIPE TEMP DEG K
3650. (TLP) LIFETIME DAYS
1.00 (FLD) CORE L/D RATIO
10.0 (DAP) AXIAL HT FLUX/M/C2 (IOPTH) (1/2)
200. (DFMH) MAX FUEL DELTA T DEG K
1.00 (WPL!) PIPE EXTENSION

NOTE: OPTIONS ARE: 1-CODE PT DESIGN; 2-SPECIFIED DESIGN

TYP IN ANY OF FOLLOWING: D CORE(H) X REF(H) UNFI BIETA N PIPE ... STOP

NPipe=162 STOP

162 (NPipe) NO. OF HEAT PIPES

BETA VCD ALFA PAWS EMN DCMN CORAP ENDCAP END GAP
0.150 0.008 0.050 0.600 1.500 0.050 0.080 0.015 0.005

VCD=0.006 STOP

CLD INDEX = 3
VNP = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000
DC = 0.196 0.238 0.260 0.260 0.290 0.315 0.325 0.347 0.385 0.434
DCM = 0.220 0.245 0.268 0.290 0.313 0.335 0.352 0.377 0.403 0.434

** STOP OR NEW CONSTANTS IE. VCD=0. PAWS=2. ETC ... STOP**

BETA =0.1500 VNP =0.4333 VF =0.5617 DX =0.1000 DC =0.2737

FOR REACTIVITY CHANGES: DELTA K

POW = 0.02533 EXP = 0.01512 SAFE = 0.0200 TOTAL = 0.06045

FUEL ELEMENT VOLUME FRACTIONS

CLADDING FUEL REGION HEAT PIPE WALL+NICK VAPOR
0.0500 0.6648 0.2852 0.1141 0.1711

WEX=SOLAR CORNER CORRECTION FACTOR =1.0943

NUMBER OF HEAT PIPES = 68.6911

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 162

TEMPERATURE SUMMARY: DEGREE KELVIN

MAXIMUM FUEL DELTA T = 84.8
AVERAGE DELTA T ACROSS HEAT PIPE WALL = 9.9
AVERAGE FUEL TEMPERATURE =1238.2
MAXIMUM FUEL TEMPERATURE =1349.7
BURN FRACTION OF U235 =0.0422

PISITON DENSITY (PISSIONS/CM*3) = 8.796E+20

FUEZ SHELLING VOLUME % = 3.39

\( \frac{1}{2} \text{FUEL AREA} = 41.1^2 \times 3.99 \)

REACTOR DIMENSIONS: METERS

CORE DIAMETER = 20.42 WIDTH ACROSS HEAT FLATS
CORE HEIGHT = 21.44 EQUIV. FUEL ELEMENT Dia
PRACTOR DIAMETER = 20.89 EQUIV. FUEL REGION D.D.
REACTOR HEIGHT =11.45 HEAT PIPE D.D.
REFLECTOR THICKNESS = 8.37 VAPOR DIAMETER

1.0000 PIPE LENGTH OUTSIDE REACTOR = 61.75 VAPOR AREA: MM*2

1.3788 TOTAL HEAT PIPE LENGTH

1.4337 OVERALL REACTOR HEAT PIPE LENGTH

REACTOR HeIGHTS: METERS

117.0 FUEL U235 MASS = 99.4
197.8 REFLECTOR
93.8 HEAT PIPE: HT/UNIT LENGTH (KG/M) = 68.02
33.0 CONTROL SYSTEM (ASSUME CONSTANT = 32 KG)
30.9 SUPPORT STRUCTURE (7% OF REACTOR HT)

472.5 TOTAL REACTOR + HEAT PIPES

94.02 MU/MM*3 AVG DENS IN FUELSPACE 6.17 KW=POWER PER HEAT PIPE
93.97 MU/MM*2 HTPIPE AXIAL HT FLUX 0.810 MU/MM*2 HTPIPE RAD HTFLX

STOP
2,000 (PR) REACTOR POWER MH  
1250. (TPH) HEAT PIPE TEMP DEG K  
3650. (TIME) LIFETIME DAYS  
1.00 (SLD) CORE L/D RATIO  
10.0 (DAX) AXIAL HT FLUX KW/CH2 (100TH)  
200. (DTPHAX) MAX FUEL DETA T DEG K  
1.00 (MLP) PIPE EXTENSION M

NOTE: OPTIONS ARE 1-CODE PT DESIGN; 2-SPECIFIED DESIGN

TYPE IN ANY OF FOLLOWING: 
D CORE (H) X REF (H) WPFT PIETA NPIPE ...STOP

NPipe = 210 STOP

210 (NPipe) NO. OF HEAT PIPES

BETA VR VCD ALFA PKAVG SHIN DXGIN COPGAP ENDPAR

0.150 0.006 0.050 0.600 1.500 0.050 0.030 0.015 0.005

TYPE: STOP OR NEW CONSTANTS IE. VR=0. PKAVG=2. ETC ...STOP

VC=0.005 STOP

SND INDEX = 3

VNF = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000

DC = 0.196 0.203 0.230 0.260 0.299 0.352 0.437 0.535 0.645 +.

DCW = 0. 3.228 0.590 0.421 0.345 0.299 0.268 0.244 0.226 0.212

++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ ++ +

BETA = 0.1500  

0.5467  VF = 0.4533  

DC = 0.1000  DC = 0.3210

REACTIVITY CHANGES: DELTA K  

BURN = 0.0600  EXP = 0.0152  SIZE = 0.0200  TOTAL = 0.0750

FUEL ELEMENT VOLUME FRACTIONS

CLADDING FUEL REGION HEAT PIPE WALL+VICK VAPOUR

0.0500  0.5360  0.4140  0.1656  0.2384

HEXAGONAL CORNER CORRECTION FACTOR = 1.2092

NUMBER OF HEAT PIPES = 84.9168

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 210

TEMPERATURE SUMMARY: DEGREE KELVIN

MAXIMUM FUEL DELTA T = 80.9

AVERAGE FUEL TEMPERATURE = 1290.0

MINIMUM FUEL TEMPERATURE = 1350.5

BURN FRACTION OF U235 = 0.0648

FUSION DENSITY (FISSIONS/CH**2) = 1.351E+21

FUEL SHELLING VOLUME % = 5.29

FUEL CEMENT % = 6.22

REACTOR DIMENSIONS: METERS  

0.3210  CORE DIAMETER

0.3210  CORE HEIGHT

0.5100  REACTOR DIAMETER

0.5100  REACTOR HEIGHT

0.1000  REFLECTOR THICKNESS

1.0000  PIPE LENGTH OUTSIDE REACTOR

1.4260  TOTAL HEAT PIPE LENGTH

1.5310  OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR HEIGHTS: KILOGRAMS

152.4  FUEL: U235 MASS = 129.5

251.5  REFLECTOR

193.9  HEAT PIPES: HT/UNIT LENGTH (KG/M) = 136.00

33.0  CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)

44.0  SUPPORT STRUCTURE (7% OF REACTOR HT)

474.9  TOTAL REACTOR + HEAT PIPES

144.39 MW**= AVG POWER IN FUELSPACE  

9.02 MW+POWER FPR HEAT PIPE

100.00 MW**=2+HTPIPE AXIAL HT FLUX  

0.858 MW**=2+HTPIPE RAD HTFLX

TYPE 'END' TO STOP
PROG NO. 7 5-17-78 TYPE NEW INPUT! P=1, H=2 ...STOP

1.000 (M) REACTOR POWER=411 (kcore) (1.2-UC+H2) CORE FUEL
1500. (THP) HEAT PIPE TEMP=94 K (kref) (1.2-TCP) REFLECTOR FUEL
3650. (TIME) LIFETIME=19 DAYS (khp) (1.2-NS+H2) HEAT PIPE FUEL
1.00 (SILD) CORE L/D RATIO (kphar) (1.2/L1)N1A VAPOR FUEL
10.0 (DPA) AXIAL HT FLUX=1W/CM2 (OPTN) (1.2) OPTION 2
200. (OPTN) MAX FUEL DELTA T=100
1.00 (HPI) PIPE EXTENSION=M

NOTE: OPTIONS ARE: 1-CODE PT DESIGN, 2-SPECIFIED DESIGN
TYPE IN ANY OF FOLLOWING: DCORE(H) XREF(H) VAPF FITZ FUEL HPIPE ...STOP

HP=264 STOP

264 (NP=1) NO. OF HEAT PIPES

BETA UC=0.1500 0.050 0.150 0.150 0.150 0.150 0.150 0.150
VCD=0.100 0.100 0.100 0.100 0.100 0.100 0.100 0.100
VNF=0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
DC=0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000
DCH=0.000 0.000 0.000 0.000 0.000 0.000 0.000 0.000

DELTA K
BURN = 0.05500 EXP = 0.01512 SAFE = 0.02000 TOTAL = 0.09012

FUEL ELEMENT VOLUME FRACTIONS

CLADDING FUEL REGION HEAT PIPE WALL+THICK VAPOR
0.0500 0.4051 0.5449 0.2180 0.3269

HEMDRICAL CORNER CORRECTION FACTOR = 1.3995

NUMBER OF HEAT PIPES = 101,9710

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 264

TEMPERATURE SUMMARY-DEGREE KELVIN

MAXIMUM FUEL DELTA T = 77.2
AVG DELTA T ACROSS HEAT PIPE WALL = 16.9
AVERAGE FUEL TEMPERATURE=1292.6
MAXIMUM FUEL TEMPERATURE = 1352.5
BURN FRACTION OF U235 = 0.0917
FISSION DENSITY (FISSIONS/CM**3) = 1.910E+21

FUEL SHELLING VOLUME % = 7.64

" " \n\nFUEL ELEMENT DIMENSIONS: MM

0.3954 CORE DIAMETER 23.13 WIDTH ACROSS HEX FLATS
0.3954 CORE HEIGHT 24.29 EQUIV. FUEL ELEMENT DI
0.6254 REACTOR DIAMETER 23.67 EQUIV. FUEL REGION O.D.
0.6054 REACTOR HEIGHT 17.93 HEAT PIPE O.D.
0.1000 REFLECTOR THICKNESS 13.89 VAPOR DIAMETER
1.0000 PIPE LENGTH OUTSIDE REACTOR 151.46 VAPOR AREA+NM**2
1.5004 TOTAL HEAT PIPE LENGTH
1.6054 OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR HEIGHTS: KILOGRAMS

215.5 FUEL  U235 MASS = 183.2
350.0 REFLECTOR
408.0 HEAT PIPES+ HT/UNIT LENGTH (KG/M) = 271.90
33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)
70.5 SUPPORT STRUCTURE (7% OF REACTOR HT)

-----
1076.9 TOTAL REACTOR + HEAT PIPES

204.17 H=H**3, AVS POWER IN FUELSPACE 15.15 KW-POWER PER HEAT PIPE
100.04 H=H**2, HT PIPE AXIAL HT FLUX = 0.873 HU/H**2, HT PIPE RAD HTFLX

TYPE NO OP STOP
**Type 50 or stop**

### Reactor Parameters

- **Type** = 50
- **KHP** = 2
- **STOP**

#### Reactor Power

- **Plant Power: 266,650 MW**
- **Reactor Power: 266,650 MW**
- **Type** = 50
- **STOP**

#### Heat Pipe Data

- **Heat Pipe Type**: 1
- **Heat Pipe Length**: 1,433m
- **Heat Pipe Diameter**: 0.127m

#### Reactor Core Data

- **Core Diameter**: 0.2337m
- **Core Height**: 0.2337m

#### Fuel Data

- **Fuel Type**: U235
- **Fuel Mass**: 70.2 kg

#### Reflectors

- **Reflector Mass**: 143.7 kg

#### Control System

- **Control System**: 3
- **Other Control System**: 19.8

#### Heat Pipes

- **Heat Pipe Power**: 25.1 MW
- **Heat Pipe Type**: 1

#### Summary

- **Total Reactor + Heat Pipes**: 302.1 MW
0.400 (HP) REACTOR POWER = MH (KORE) (1.2/VC+U02) CORE = VC
1425. (HTP) HEAT PIPE TEMP DEG K (KREA) (1.2/BE+160) REFLECTOR = 160
3650. (TIME) LIFETIME DAYS (WNP) (1.2/13/HE10K) HEAT PIPE = 10
1.00 (SLD) CORE L/D RATIO (KHAP) (1.2/LINHA) VAPOR = 1
10.0 (DAIL) AXIAL HT FLUX KM/CH2 (TOPTH) (1.2) OPTION = 2
200. (DFTHAN) MAX FUEL DELTA T DEG K
1.00 (HPL1) PIPE EXTENSION

NOTE: OPTIONS ARE 1 1-CODE PT DESIGN 2-SPECIFIED DESIGN
TYPE IN ANY OF FOLLOWING 1 DCODE(H) WNP(H) WHT PENTA PIPE ... STOP
HPipe=34 STOP 84 (HPipe) NO. OF HEAT PIPES

BETA = 0.150 0.012 0.050 0.600 1.500 0.050 0.080 0.015 0.005

STOP OR NEW CONSTANTS IE. VC=0, PKAVS=2, ETC ... STOP

SLD INDEX = 3

BETA = 0.150 0.01295 0.6705 0.1000 0.2381

REACTIVITY CHANGES: DELTA K
BURN = 0.01288 EXP = 0.01764 SAFE = 0.02000 TOTAL = 0.05052

FUEL ELEMENT VOLUME FRACTIONS
CLADDING FUEL REGION HEAT PIPE WALL+HICK VAPOR

0.0500 0.7984 0.1516 0.0606 0.0910

HEXAGONAL CORNER CORRECTION FACTOR = 1.0258

NUMBER OF HEAT PIPES = 48,6978

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 84

TEMPERATURE SUMMARY: DEGREE KELVIN
MAX FUEL DELTA T = 115.9
AVG DELTA T ACROSS HEAT PIPE WALL = 8.8
AVG FUEL TEMPERATURE = 1472.5
MAX FUEL TEMPERATURE = 1554.2

BURN FRACTION OF U235 = 0.0215

FISSION DENSITY (F ISSIONS/CH+2) = 4.474+20

FUEL SWELLING VOLUME % = 6.44

FUEL ELEMENT DIMENSIONS: MN
2.382 CORE DIAMETER 24.59 Width across hex flats

2.382 CORE HEIGHT 25.82 EQUIV. FUEL ELEMENT DI

4.681 REACTOR DIAMETER 25.17 EQUIV. FUEL REGION O.D.

4.481 REACTOR HEIGHT 10.05 HEAT PIPE O.D.

1.000 REFLECTOR THICKNESS 7.79 VAPOR DIAMETER

1.000 PIPE LENGTH OUTSIDE REACTOR 47.64 VAPOR AREA: MN+2

1.3411 TOTAL HEAT PIPE LENGTH

1.4481 OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR HEIGHTS: KILOGRAMS
92.0 FUEL, U235 MASS = 78.2
162.1 REFLECTOR
36.5 HEAT PIPES, HT/UNIT LENGTH (KG/H) = 27.21
33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)
22.7 SUPPORT STRUCTURE (7% OF REACTOR HT)

346.3 TOTAL REACTOR + HEAT PIPES

47.83 MN/H+2, AVG POWER IN FUELSPACE 4.76 KW/POWER PER HEAT PIPE
99.3A MN/H+2, HT PIPE AXIAL HT FLUX 0.817 MN/H+2, HT PIPE RAD HTFLX

TYPE go OR STOP
**PROB NO. 10  5-17-73  **TYPE NEW INPUT?  PIP=P1, KWP=2...STOP  
**START=0.7 STOP**

0.700 (PR) REACTIVITY CHANGE
1485, (KMP) HEAT PIPE TRIP DEG K
3630, (TIME) LIFE IN DAYS
1.00 (SLD) CORE L/D RATIO
10.0 (PHEL) AxIAL HT FLUX=1kW/CM² (OPTN) (1-2) OPTION #2
200, (STFHE): MAX FUEL DELTA T=40 K
1.00 (PHEL) PIPE EXTENSION

**NOTE: OPTIONS ARE: 1-CODE PT DESIGN 2-SPECIFIED DESIGN**

**TYPE IN ANY OF FOLLOWING DORE (H): KWP (H) UNIT FUEL [ETA] NP [PIPE] ...STOP**

**NP=120 STOP**

120 (NP) NO. OF HEAT PIPES
BETA VC VCD ALFA PK/WA BMIN DXMIN CORP+ ENDGAP
0.150 0.012 0.050 1.500 0.050 0.050 0.015 0.055
**TYPE=0.008 STOP**

SLD INDEX = 3
UN = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000
DC = 0.196 0.208 0.230 0.260 0.299 0.325 0.352 0.385 0.429 0.443 |
DCH = 0.4384 0.354 0.251 0.205 0.177 0.159 0.145 0.134 0.126

**STOP**

**BETA = 0.500  UN = 0.3505  DC = 0.500  DC = 0.2568**

**REACTION CHANGEx DELTA K**

**BURN = 0.01977  EXP = 0.01764  SAFE = 0.00200  TOTAL = 0.05741**

**FUEL ELEMENT VOLUME FRACTIONS**

**CLADDING FUEL REGION HEAT PIPE WALL+VAPOR**

**0.0500 0.7229 0.2271 0.0908 0.1363**

**HEXAGONAL CORNER CORRECTION FACTOR =1.0583**

**NUMBER OF HEAT PIPES = 60.6776**

**MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 120**

**TEMPERATURE SUMMARY: DEGREE KELVIN**

**MAXIMUM FUEL DELTA T = 101.1**

**AVG DELTA T ACROSS HEAT PIPE WALL = 10.0**

**AVERAGE FUEL TEMPERATURE =1468.7**

**MAXIMUM FUEL TEMPERATURE =1541.2**

**BURN FRACTION OF U235 = 0.0328**

**FUEL DENSITY (FUSSONS/CM²) = 6.865E+20**

**FUEL SWELLING: VOLUME % = 9.65**

**DENSE FUEL 4% = 11.35**

**REACTION DIMENSIONS: METER**

**FUEL ELEMENT DIMENSIONS: MM**

**0.2568 CORE DIAMETER  22.24 WIDTH ACROSS HEX FLATS**

**0.2568 CORE DIAMETER  23.35 EQUIV. FUEL ELEMENT DIAM**

**0.4368 REACTOR DIAMETER  **

**0.4668 REACTOR HEIGHT  **

**0.1000 REFLECTOR THICKNESS  8.62 VAPOR DIAMETER**

**1.0000 PIPE LENGTH OUTSIDE REACTOR  58.34 VAPOR AREA; MM²**

**1.4668 TOTAL HEAT PIPE LENGTH**

**1.4668 OVERALL REACTOR+HEAT PIPE LENGTH**

**REACTION HEIGHTS: KILOGRAMS**

**104.9 FUEL: U235 MASS = 89.2**

**180.4 REFLECTOR**

**64.8 HEAT PIPE: HT UNIT LENGTH (KG/MM) = 47.61**

**33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)**

**36.8 SUPPORT STRUCTURE (7% OF REACTOR HT)**

**409.9 TOTAL REACTOR + HEAT PIPES**

**73.29 MW/UNIT-49% OF TOTAL IN FUELSPACE  5.83 KW/POWER PER HEAT PIPE**

**99.95 MW/UNIT: HT PIPE AXIAL HT FLUX  0.833 MW/MM²: HT PIPE RAD HT FLUX**

**STOP**
**TOPIC:** OPTIONS ARE 1-CODE PT DESIGN; 2-SPECIFIED DESIGN

**TYPE IN ANY OF FOLLOWING:**

1. 

**DETAILED OPTIONS:**

1. SETA = 0.25 STOP

**NOTES:**

1. TOTAL HEAT PIPE LENGTH = 162

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<th>VEF =</th>
<th>BURN =</th>
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**FUEL ELEMENT VOLUME FRACTIONS:**

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<th>HEAT PIPE WALL+WICK</th>
<th>VAPOR</th>
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**FACTOR SUMMARY DEGREE KELVIN:**

* MAXIMUM FUEL DELTA T = 87.5
* AVERAGE FUEL TEMPERATURE = 1463.5
* MAXIMUM FUEL TEMPERATURE = 1526.6

**BURN FRACTION OF U235 = 0.0382

**FUSION DENSITY (FUSIONS/CM**3**) = 7.017E+20

**FUEL SWELLING VOLUME % = 9.54

**REACTOR DIMENSIONS Meter**

| CORE DIAMETER | 0.2904 |
| CORE HEIGHT   | 0.2904 |
| REACTOR DIAMETER | 0.5204 |
| REACTOR HEIGHT | 0.5004 |
| REFLECTOR THICKNESS | 0.1000 |
| PIPE LENGTH OUTSIDE REACTOR | 1.0000 |
| TOTAL HEAT PIPE LENGTH | 1.394 |

**REACTOR DIMENSIONS Kilograms**

| FUEL U235 Mass | 110.0 |
| REFLECTOR      | 215.1 |
| HEAT PIPES WT/UNIT LENGTH (KG/M) | 67.98 |
| CONTROL SYSTEM (ASSUME CONSTANT = 33 KG) |

**TOTAL REACTOR + HEAT PIPES**

| MW/H*8*3 + ASU POWER IN FUELSpace | 6.17 |
| MW/HPHEAT PIPE AXIAL HT FLUX | 0.783 |
| MW/HPHEAT PIPE RAD HTFLX |

**TYPE NEW INIPT PA-1, WP=2...STOP**
**PROP NO. 16 5-17-78 TYPE NEW INPUTS PIP=1, KHP=2 ... STOP**

2,000 (ER) REACTOR POWER MW 
1425. (THP) HEAT PIPE TEMPERATURE K 
3500. (TIME) LIFETIME DAYS

1.00 (ILD) CORE L/D RATIO

1.00 (HLI) PIPE EXTENSION PERCENT

**NOTE:** OPTIONS ARE 1: CODE PT DESIGN; 2: SPECIFIED DESIGN

**TYPE IN ANY OF FOLLOWING**

1. CORE (M) XREF (M) VAP FLUX/HTR FLUX

2. (DTHMA) MAX FUEL DELTA T DEGREES K

1.00 (NPIPE) NO. OF HEAT PIPES

STOP

**NPIPE** = 210 STOP

**BETA** = ?

**VC** = ?

**VCD** = ?

**ALFA** = ?

**PKA** = ?

**PKV** = ?

**SMIN** = ?

**DXMIN** = ?

**CORRAP** = ?

**END** = ?

**STOP**

**BETA** = 0.4 STOP

**EFD INDEX** = 3

**UNF** = 0.100

0.200

0.300

0.400

0.500

0.600

0.700

0.800

0.900

1.000

**DC** = 0.196

0.203

0.230

0.250

0.300

0.350

0.390

0.400

0.430

0.470

0.500

**DTH** = 0.1

0.0

0.0

0.0

0.0

0.0

0.0

0.0

0.0

0.0

0.0

0.0

**TYPE** = 00 OR START OVER

**STOP**

**Beta** = 0.4000

**UNF** = 0.6217

**VF** = 0.3783

**DV** = 0.1000

**DC** = 0.3672

**Fuel Element Volume Fractions**

**CLADDING**

**FUEL REGION**

**HEAT PIPE WALL**

**VAPOR**

0.0500

0.6336

0.3164

0.1265

0.1898

**Hexagonal Corner Correction Factor** = 1.1173

**Number of Heat Pipes** = 94.2127

**Minimum Practical (or Specified) Number of Heat Pipes** = 210

**Temperature Summary: Degree Kelvin**

**Maximum Fuel Delta T** = 39.7

**Average Delta T Across Heat Pipe Wall** = 11.4

**Average Fuel Temperature** = 1466.3

**Maximum Fuel Temperature** = 1531.9

**Burn Fraction of U235** = 0.0519

**Fission Density (Fissions/CH3)** = 7.6308 x 10^20

**Fuel Swelling + Volume %** = 10.56

**dure fuel** = 17.60

**Reactor Dimensions:** Meters

**FUEL ELEMENT DIMENSIONS:** MM

0.3672

0.3672

0.5772

0.1000

1.0000

1.4722

1.5772

**Core Diameter**

**Core Height**

**Reactor Diameter**

**Reactor Height**

**Reflector Thickness**

**PIPER LENGTH OUTSIDE REACTOR**

**TOTAL HEAT PIPE LENGTH**

**OVERALL REACTOR+HEAT PIPE LENGTH**

**Reactor Weights:** Kilograms

190.4

310.7

200.3

33.0

51.4

**FUEL**

**REFLECTOR**

**HEAT PIPE: WT/UNIT LENGTH (KG/M) = 136.03**

**Control System (Assume Constant = 33 KG)**

**Support Structure (7% of Reactor HT)**

**TOTAL REACTOR + HEAT PIPES**

81.56 MW/HH\***3 AVG FORD IN FUELSPACE 9.52 MW/POWER PER HEAT PIPE

99.83 MW/HH\***2 HTPIPE AXIAL HT FLUX 0.750 MW/HH\***2 HTPIPE AXIAL HT FLUX

**********

STOP

**Type** = 00 OR STOP
<table>
<thead>
<tr>
<th>Column 1</th>
<th>Column 2</th>
<th>Column 3</th>
<th>Column 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>123.45</td>
<td>67.89</td>
<td>0.123</td>
<td>4.56</td>
</tr>
<tr>
<td>78.90</td>
<td>23.45</td>
<td>0.567</td>
<td>6.78</td>
</tr>
<tr>
<td>34.56</td>
<td>56.78</td>
<td>0.789</td>
<td>8.90</td>
</tr>
<tr>
<td>45.67</td>
<td>67.89</td>
<td>0.901</td>
<td>1.23</td>
</tr>
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</table>
#### Reactor Dimensions: Meters

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Diameter</td>
<td>0.3115</td>
</tr>
<tr>
<td>Core Height</td>
<td>0.3115</td>
</tr>
<tr>
<td>Reactor Diameter</td>
<td>0.5415</td>
</tr>
<tr>
<td>Reactor Height</td>
<td>0.5215</td>
</tr>
<tr>
<td>Reflector Thickness</td>
<td>0.1000</td>
</tr>
<tr>
<td>Pipe Length</td>
<td>1.0000</td>
</tr>
<tr>
<td>Total Heat Pipe Length</td>
<td>1.4165</td>
</tr>
</tbody>
</table>

#### Fuel Element Dimensions: Meters

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width Across Hex Flats</td>
<td>32.18</td>
</tr>
<tr>
<td>Equiv. Fuel Element Dia</td>
<td>33.79</td>
</tr>
<tr>
<td>Equiv. Fuel Region O.D.</td>
<td>33.79</td>
</tr>
</tbody>
</table>

#### Reactor Dimension: Kilograms

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel U235 Mass</td>
<td>108.7</td>
</tr>
<tr>
<td>Reflector</td>
<td>240.2</td>
</tr>
<tr>
<td>Heat Pipes</td>
<td>19.3</td>
</tr>
<tr>
<td>Control System</td>
<td>33.0</td>
</tr>
<tr>
<td>Support Structure</td>
<td>35.5</td>
</tr>
</tbody>
</table>

#### Reactor Heatsup: Meters

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Reactor + Heat Pipes</td>
<td>1.5215</td>
</tr>
</tbody>
</table>

#### Summary: Temperature

- Maximum Fuel Delta T: 75.2°K
- Average Delta T Across Heat Pipe Wall: 3.4°K
- Average Fuel Temperature: 1455.4°K
- Maximum Fuel Temperature: 1505.3°K
- Burn Fraction of U235: 0.0077
- Fission Density (Fissions/CH2): 8.345E+19
- Fuel Filling Volume %: 0.
PROJ NO. 2 5-18-78  TYPE NEW INPUT: PA=1, KH=2 ...STOP
PA=1.4 STOP

0.400 (PR) REACTOR POWER = MH

1425, (THP) HEAT PIPE TEMP = °K

3510, (TIME) LIFETIME = days

1.00 (SLD) CORE L/D RATIO

10.0 (DAXL) A:IAL HT FLUX = W/CH2

200, (DTPHAX) MAX FUEL DELTA T = °K

NOTE: OPTION 1: 1-CODE PT DESIGN; 2-SPECIFIED DESIGN

TYPE IN ANY OF FOLLOWING 1) CORE (H) X,REF (H) XUNIT FEITA NPIPE ...STOP

NPIPE = 24 STOP

84 (NPIPE) NO. OF HEAT PIPES

BETA VC VCD ALFA PK0K PH/0K KHMIN DNXMIN CORR/P RNDEP

0.100 0.012 0. 0.600 1.500 0.050 0.080 0.015 0.005 STOP

STOP

INDEX = 3

UTC = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000

DC = 0.299 0.326 0.363 0.412 0.475 0.562 0.694 0.961 1.754 °

DC = 0.299 0.326 0.363 0.412 0.475 0.562 0.694 0.961 1.754 °

STOP

BETA = 0.1000 UTC = 0.1848 UTC = 0.8152 DC = 0.1000 DC = 0.2214

REACTIVITY CHAN/DELTA X

BURN = 0.00274 BAFF = 0.02000 TOTAL = 0.04155

FUEL ELEMENT VOLUME FRACIONS

CLADDING FUEL PENION HEAT PIPE WALL+VICK VAPOUR

0. 0.9167 0.0333 0.0333 0.0500

HEXAGONAL CORNER CONNECTION FACTOR = 1.0070

FUEL ELEMENT VOLUME = 46.5370

MIMIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 84

TEMPERATURE SUMMARY: DEGREE KELVIN

MAXIMUM FUEL DELTA T = 110.8

AVG DELTA T ACCUM. HEAT PIPE WALL = 6.5

AVERAGE FUEL TEMPERATURE = 1468.5

MAXIMUM FUEL TEMPERATURE = 1545.7

BURN FRACTION OF U235 = 0.0147

FUSION DENSITY (FUSIONS/CH3) = 1.585E+20

FUEL SWELLING VOLUME % = 0.

REACTOR DIMENSIONS: METERS

0.3214 CORE DIAMETER

0.3214 CORE HEIGHT

0.5514 REACTOR DIAMETER

0.5714 REACTOR HEIGHT

0.1000 REFLECTOR THICKNESS

1.0000 PIPE LENGTH OUTSIDE REACTOR

1.4264 TOTAL HEAT PIPE LENGTH

1.5014 OVERALL REACTOR+HEAT PIPE LENGTH

FUEL ELEMENT DIMENSIONS: MH

33.19 WIDTH ACROSS HEX FLAT

34.85 EQUIV. FUEL ELEMENT DIAM.

34.85 EQUIV. FUEL REGION D.0.

10.06 HEAT PIPE D.0.

7.79 VAPOUR DIAMETER

47.66 VAPOUR AREA+ MN+2

547.9 TOTAL REACTOR + HEAT PIPES

16.94 MH/HE+3: AX. PINS IN FUELSILACE

4.76 KW/POWER PER HEAT PIPE

99.32 MH/H+2+HTPIPE A:IAL HT FLUX

1.605 MH/H+2+HTPIPE RAD HTFLX

STOP
0.700 (PR) REACTOR POWER = HH
0.700 (KOE) (1/2 UC: UO2) COPE = NO5.0UO2
1425. (THP) HEAT PIPE TEMP = 1200 °C
3650. (TIME) LIFETIME = DAYS
1.00 (FF) CORE L/D RATIO
10.0 (CAYL) AERIAL HT FLUX MW/CH4 (IDPHT) (1/2)
200. (RTHPA) MAX FUEL DELTA T DEG K

NOTE: OPT: ONS ARE 1 - CODE PT DESIGN: 2 - SPECIFIED DESIGN
TYPE IN ANY OF FOLLOWING (H) XREF (H) UNF PT ETA PIPE ... STOP
PIPE=120 STOP

120 (NPipe) NO. OF HEAT PIPES

TYPE=0.003 STOP

INDEX = 3

UNF = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000
DC = 0.299 0.336 0.363 0.412 0.425 0.475 0.542 0.694 0.961 1.754 *
DCH = 0.280 0.263 0.214 0.184 0.154 0.125 0.10 0.130 0.122

SELA = 0.1000 UNF = 0.2264 UF = 0.7736 DX = 0.1000 DC = 0.3343

REACTIVITY CHANGER: DELTA K
BURN = 0.01425 EXP = 0.01274 SAFE = 0.02000 TOTAL = 0.04709

FUEL ELEMENT VOLUME FRACTION:
CLADDING FUEL REGION HEAT PIPE WALL+HICK VAPOR
0.3665 0.1335 0.0534 0.0801

HEXAGONAL CORNER CORRECTION FACTOR = 1.0180

NUMBER OF HEAT PIPES = 61.1476

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 120

TEMPERATURE SUMMARY: DEGREE KELVIN
MAXIMUM FUEL DELTA T = 101.9
AVER DELTA T ACROSS HEAT PIPE WALL = 7.7
AVERAGE FUEL TEMPERATURE = 1466.7
MAXIMUM FUEL TEMPERATURE = 1538.4
BURN FRACTION OF U235 = 0.0239

FUSION DENSITY (FUSIONS/CH4) = 2.584E+20

FUEL FUELING VOLUME % = 0.

REACTOR DIMENSIONS: METERS
0.1348 CORE DIAMETER
0.3348 CORE HEIGHT
0.5448 REACTOR DIAMETER
0.5448 REACTOR HEIGHT
0.1000 REFLECTOR THICKNESS
1.0000 PIPE LENGTH OUTSIDE REACTOR
1.4393 TOTAL HEAT PIPE LENGTH
1.5448 OVERALL REACTOR + HEAT PIPE LENGTH

REACTOR WEIGHTS: KILOGRAMS
249.3 FUEL: U235 Mass = 122.8
263.5 REFLECTOR
68.5 HEAT PIPES: HT/UNIT LENGTH (CH4) = 47.53
33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)
42.9 SUPPORT STRUCTURE (7% OF REACTOR HT)

655.2 TOTAL REACTOR + HEAT PIPES

27.62 KW/CH4 AVG POWER IN FUELSPACE 5.83 KW/POWER PER HEAT PIPE
100.05 KW/CH4+HTPIPE AXIAL HT FLUX 0.644 KW/CH4+HTPIPE A AXIAL HT FLUX

STOP
### PROBLEM NO. 4  \(5-18-78\)

**TYPE NEW INPUT: PR=1, KHP=2 ... STOP**

**PR=1, STOP**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reactor Power (MW)</td>
<td>(1,000)</td>
</tr>
<tr>
<td>Core Power ((f_{\text{core}})) ((1:2))</td>
<td>(U^0)</td>
</tr>
<tr>
<td>Heat Pipe Temp. ((K))</td>
<td>(1425)</td>
</tr>
<tr>
<td>Lifetime (Days)</td>
<td>(3650)</td>
</tr>
<tr>
<td>FL/D Ratio</td>
<td>(1.00)</td>
</tr>
<tr>
<td>Axial HT Flux ((\text{KWh} \cdot \text{cm}^2))</td>
<td>(10.0)</td>
</tr>
<tr>
<td>Heat Pipe Axial HT Flux ((\text{KWh} \cdot \text{cm}^2))</td>
<td>(200)</td>
</tr>
<tr>
<td>No. of Heat Pipes</td>
<td>(62)</td>
</tr>
<tr>
<td>No. of Heat Piping ((\text{No. of pipes}))</td>
<td>(162)</td>
</tr>
<tr>
<td>Beta ((\text{beta}))</td>
<td>(0.006)</td>
</tr>
<tr>
<td>VE</td>
<td>0.006</td>
</tr>
<tr>
<td>VE</td>
<td>0.008</td>
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<tr>
<td>VE</td>
<td>0.000</td>
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<tr>
<td>VE</td>
<td>0.000</td>
</tr>
<tr>
<td>DC</td>
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<td>DC</td>
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<td>DC</td>
<td>0.363</td>
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<td>DC</td>
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<td>DC</td>
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<tr>
<td>DC</td>
<td>0.562</td>
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<tr>
<td>DC</td>
<td>0.694</td>
</tr>
<tr>
<td>DC</td>
<td>0.961</td>
</tr>
<tr>
<td>DC</td>
<td>1.754</td>
</tr>
<tr>
<td>DCH</td>
<td>0.25</td>
</tr>
<tr>
<td>DCH</td>
<td>0.31</td>
</tr>
<tr>
<td>DCH</td>
<td>0.45</td>
</tr>
<tr>
<td>DCH</td>
<td>0.72</td>
</tr>
</tbody>
</table>

**NOTE:** OPTIONS ARE: 1-CODE PT DESIGN; 2-SPECIFIED DESIGN

**TYPE IN ANY OF FOLLOWING:** DCORE \((f\text{core})\) \(K\text{REP}(f\text{rep})\) UHFT \(f\text{beta} \text{pipe} \ldots \text{STOP}

**NPipe=162 STOP**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>BETA</td>
<td>(0.100)</td>
</tr>
<tr>
<td>VNF</td>
<td>(0.26)</td>
</tr>
<tr>
<td>VF</td>
<td>(0.7370)</td>
</tr>
<tr>
<td>DC</td>
<td>(0.100)</td>
</tr>
<tr>
<td>DC</td>
<td>(0.3482)</td>
</tr>
<tr>
<td>Burn</td>
<td>(0.01915)</td>
</tr>
<tr>
<td>EXP</td>
<td>(0.01274)</td>
</tr>
<tr>
<td>IAFE</td>
<td>(0.0200)</td>
</tr>
<tr>
<td>TOTAL</td>
<td>(0.05139)</td>
</tr>
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</table>

**FUEL ELEMENT VOLUME FRACTIONS**

<table>
<thead>
<tr>
<th>Region</th>
<th>Factor</th>
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<tbody>
<tr>
<td>Cladding</td>
<td>(0.0)</td>
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<tr>
<td>Fuel Region</td>
<td>(0.8238)</td>
</tr>
<tr>
<td>Heat Pipe Wall</td>
<td>(0.1762)</td>
</tr>
<tr>
<td>Vapour</td>
<td>(0.0705)</td>
</tr>
<tr>
<td>Vapour</td>
<td>(0.1057)</td>
</tr>
</tbody>
</table>

**HEAT PIPE CORNER CORRECTION FACTOR** | \(1.0315\)

**Number of Heat Pipes** | \(712\)

**Minimum Practical (or Specified) Number of Heat Pipes** | \(162\)

**Temperature Summary:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Fuel Delta T</td>
<td>(87.9)</td>
</tr>
<tr>
<td>Average Fuel Temperature</td>
<td>(1462.1)</td>
</tr>
<tr>
<td>Maximum Fuel Temperature</td>
<td>(1524.7)</td>
</tr>
<tr>
<td>Burn Fraction of U235</td>
<td>(0.0019)</td>
</tr>
<tr>
<td>Fission Density</td>
<td>(3.447 \times 10^2)</td>
</tr>
<tr>
<td>Fuel Swelling, Volume %</td>
<td>(0)</td>
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**Reactor Dimensions:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core Diameter</td>
<td>(0.3482)</td>
</tr>
<tr>
<td>Core Height</td>
<td>(0.3482)</td>
</tr>
<tr>
<td>Reactor Diameter</td>
<td>(0.5782)</td>
</tr>
<tr>
<td>Reactor Height</td>
<td>(0.5582)</td>
</tr>
<tr>
<td>Reflector Thickness</td>
<td>(0.1000)</td>
</tr>
<tr>
<td>Pipe Length Outside Reactor</td>
<td>(1.0000)</td>
</tr>
<tr>
<td>Total Heat Pipe Length</td>
<td>(1.4582)</td>
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</table>

**Fuel Element Dimensions:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Width Across Hex Flats</td>
<td>(25.37)</td>
</tr>
<tr>
<td>Equiv. Fuel Element Dia</td>
<td>(27.27)</td>
</tr>
<tr>
<td>Equiv. Fuel Region O.D.</td>
<td>(27.27)</td>
</tr>
<tr>
<td>Heat Pipe O.D.</td>
<td>(11.45)</td>
</tr>
<tr>
<td>Vapour Diameter</td>
<td>(8.87)</td>
</tr>
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</table>

**Heat Pipe Dimensions:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Reactor + Heat Pipe Length</td>
<td>(1.5582)</td>
</tr>
</tbody>
</table>

**Reactor Weights:**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>(359.4)</td>
</tr>
<tr>
<td>Reflector</td>
<td>(285.5)</td>
</tr>
<tr>
<td>Heat Pipes</td>
<td>(98.8)</td>
</tr>
<tr>
<td>Control System</td>
<td>(33.0)</td>
</tr>
<tr>
<td>Support Structure</td>
<td>(47.4)</td>
</tr>
</tbody>
</table>

**Total Reactor + Heat Pipes** | \(724.1\)

**Fuels:**

<table>
<thead>
<tr>
<th>Type</th>
<th>Power</th>
<th>Heat Pipe</th>
</tr>
</thead>
<tbody>
<tr>
<td>MW</td>
<td>(35.84)</td>
<td>(6.17)</td>
</tr>
<tr>
<td>MW</td>
<td>(99.98)</td>
<td>(0.537)</td>
</tr>
</tbody>
</table>

**Type go or stop**
PNOB NO. 5  5-18-78  TYPE NEW INPUT: PPA1, KNP=2 ...STOP

PPA2, STOP

2.000 (PP) REACTOR POWER (MW) (kCORE) (1.2/V CORE UO2) CORE = MO64UO2
1425. (TPAP) HEAT PIPE TEMPERATURE K (kREP) (1.2/SI-E) REACTOR FLOE
3650. (TIME) LIFETIME (DAYS) (kHP) (1.2/3N) HEAT PIPE = HP
1.00 (SLED) CORE L/D RATIO (kRAPF) (1.2/LI) VAPOUR FRA
10.0 (OXYL) AXIAL HT FLUX (K/M2) (OPTN) (1.2) OPTION =
200. (DFMAX) MAX. FUEL DELTA T (DEG K)

1.00 (HFL) PIPE EXTENSION = HP

NOTE: OPTIONS ARE: 1-CODE PT DESIGN; 2-SPECIFIED DESIGN
TYPE IN ANY OF FOLLOWING: DCORE(M) VRAPF(M) HEAT PIPE PT HEAT PIPE ...STOP

NPipe=210 STOP

210 (NPipe) NO. OF HEAT PIPES

BETA VC UCD ALPA PFAV3 BMIN DXMIN COMPAR END GAP
0.100 0.006 0. 0.600 1.500 0.050 0.080 0.015 0.005

TYPE: STOP; OR NEW CONSTANTS IE. VC=0, PFAV=2, ETC ...STOP

VC=0.005 STOP

SLED INDEX =

0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 1.000
0.299 0.366 0.363 0.412 0.475 0.562 0.694 0.961 1.754 *
0.632 0.448 0.360 0.311 0.278 0.252 0.234 0.219 0.207

* + + + + + + + + TYPE 50 OR START OVER + + + + + + + + + + + +

BETA = 0.1000 0.3566 0.6434 0.1000 DC = 0.3893

FUEL ELEMENT VOLUME RATIO:

CLADDING FUEL REGION HEAT PIPE WALL+HICK VAPOUR

0.0.7185 0.2815 0.1126 0.1689

HEXAGONAL CORNER CORRECTION FACTOR = 1.0825

NUMBER OF HEAT PIPES = 92.2398

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 210

TEMPERATURE SUMMARY: DEGREE KELVIN

MAXIMUM FUEL DELTA T = 87.8

AW'S DELTA T ACROSS HEAT PIPE WALL = 10.8

MAXIMUM FUEL TEMPERATURE = 1529.0

BURN FRACTION G = 0.0358 0.0823

FISSION DENSITY (FISSIONS/CM**3) = 5,648+20

FUEL SWELLING: VOLUME % = 0.

REACTOR DIMENSIONS: METERS

0.3823 CORE DIAMETER

0.3823 CORE HEIGHT

0.6193 REFLECTOR DIAMETER

0.5993 REFLECTOR HEIGHT

0.1000 REFLECTOR THICKNESS

1.0000 PIPE LENGTH OUTSIDE REACTOR

1.4343 TOTAL HEAT PIPE LENGTH

1.5293 OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR HEIGHTS: KILOGRAMS

314.6 FUEL; U233 Mass = 160.5
341.3 REFLCTOR
203.3 HEAT PIPES; HT/UNIT LENGTH (KG/H) = 136.03
33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)
62.6 SUPPORT STRUCTURE (7% OF REACTOR WT)

---------
956.7 TOTAL REACTOR + HEAT PIPES

KAP 97 MW/H**3-AVG FOW IN FUELSPACE = 9.52 MW/POW PER HEAT PIPE
99.93 MW/H**2-HTPIPE AXIAL HT FLUX = 0.707 MW/H**2-HTPIPE RAD HTFLX

---------

STOP
**ERROR: PAGE IS OF POOR QUALITY**

**PROF NO.** 6 5-18-78 **TYPE NEW INPUT: PA=1, KW=2 ... STOP**

**STOP**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.000 (PP) REACTOR POWER [MW]</td>
<td>(kcore) (1.2/vo1) core = 0050vo2</td>
</tr>
<tr>
<td>1425.4 (TPR) HEAT PIPE TEMP DEG K (kref) (1.2/vo1)</td>
<td>REFLECTOR = 650</td>
</tr>
<tr>
<td>3650.0 LIFETIME DAYS (kref) (1.2/vo1)</td>
<td>HEAT PIPE = 60</td>
</tr>
<tr>
<td>1.00 (SLD) CORE L/D RATIO (kvar) (1.2/vo1)</td>
<td>VAPOR = 0</td>
</tr>
<tr>
<td>10.0 (PCLY) AXIAL HT FLUX [KW/CM2] (OPTN)</td>
<td>(1.2) OPTION =</td>
</tr>
<tr>
<td>200. (APEN) MAX FUEL DELTA T DEG K</td>
<td></td>
</tr>
<tr>
<td>1.00 (HPI) PIPE EXTENSION</td>
<td></td>
</tr>
</tbody>
</table>

**NOTE: OPTIONS ARE: 1-CODE FOR DESIGN, 2-SPECIFIED DESIGN**

**TYPE IN ANY OF FOLLOWING: D (CORE) (M) (REF) (H) (HTPIPE) VAPOR PIPE ... STOP**

**NPipe=266 STOP**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>266 (NPipe) NO. OF HEAT PIPES</td>
<td></td>
</tr>
<tr>
<td>BETA</td>
<td>VC</td>
</tr>
<tr>
<td>VCD ALPHA PHA'S EMIN DMIN CORSAF ENDS</td>
<td></td>
</tr>
<tr>
<td>0.100</td>
<td>0.004</td>
</tr>
</tbody>
</table>

**STOP**

**SLD INDEX = 3**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.100</td>
<td>0.200</td>
</tr>
</tbody>
</table>

**DC = 0.295 | 0.325 | 0.363 | 0.412 | 0.475 | 0.562 | 0.694 | 0.961 | 1.754 |

**DCH = 0.897 | 0.884 | 0.853 | 0.833 | 0.813 | 0.340 | 0.230 | 0.200 | 0.190 | 0.190 |

**BETA = 0.1000 | UNF = 0.4720 | VF = 0.5280 | DX = 0.1000 | DC = 0.4554**

**REACTIVITY CHANGES [DELTA K]**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>ENU = 0.04777</td>
<td>EXP = 0.1274</td>
</tr>
</tbody>
</table>

**FUEL ELEMENT VOLUME FRACTIONS**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLADDING</td>
<td>FUEL REGION</td>
</tr>
<tr>
<td>0.589</td>
<td>0.411</td>
</tr>
</tbody>
</table>

**MATERIAL CORNER CORRECTION FACTOR = 1.1840**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>115.0234</td>
<td>NUMBER OF HEAT PIPES =</td>
</tr>
</tbody>
</table>

**MINIMUM PRACTICAL (OP SPECIFIED) NUMBER OF HEAT PIPES = 266**

**TEMPERATURE SUMMARY [DEGREE KELVIN]**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MAX FUEL DELTA T = 386.5</td>
<td></td>
</tr>
<tr>
<td>MAX'S DELTA T ACROSS HEAT PIPE WALL = 14.6</td>
<td></td>
</tr>
<tr>
<td>AVERAGE HT TEMPERATURE = 1468.4</td>
<td></td>
</tr>
<tr>
<td>MAX FUEL TEMPERATURE = 1533.3</td>
<td></td>
</tr>
</tbody>
</table>

**BURN FRACTION OF U235 = 0.0796**

**FUSION DENSITY (FISSIONS/CM3) = 8.59% + 20**

**FUEL SHELLING VOLUME % = 0.**

**FUEL ELEMENT DIMENSIONS [MM]**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4554</td>
<td>CORE DIAMETER</td>
</tr>
<tr>
<td>0.4554</td>
<td>CORE HEIGHT</td>
</tr>
<tr>
<td>0.6854</td>
<td>REACTOR DIAMETER</td>
</tr>
<tr>
<td>0.6854</td>
<td>REACTOR HEIGHT</td>
</tr>
<tr>
<td>0.1000</td>
<td>REFLECTOR THICKNESS</td>
</tr>
<tr>
<td>1.0000</td>
<td>PIPE LENGTH OUTSIDE REACTOR</td>
</tr>
<tr>
<td>1.5604</td>
<td>TOTAL HT PIPE LENGTH</td>
</tr>
<tr>
<td>1.6554</td>
<td>OVERALL REACTOR+HEAT PIPE LENGTH</td>
</tr>
</tbody>
</table>

**FUEL ELEMENT VOLUME [MM]**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>26.54</td>
<td>WIDTH ACROSS HEX FLAT</td>
</tr>
<tr>
<td>27.87</td>
<td>EQUIV. FUEL ELEMENT DIA</td>
</tr>
<tr>
<td>27.87</td>
<td>EQUIV. FUEL REGION O.D.</td>
</tr>
<tr>
<td>17.87</td>
<td>HEAT PIPE O.D.</td>
</tr>
<tr>
<td>13.84</td>
<td>VAPOR DIAMETER</td>
</tr>
<tr>
<td>150.41</td>
<td>VAPOR AREA - MH**2</td>
</tr>
</tbody>
</table>

**REACTOR WEIGHT: KILOGRAMS**

<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>416.0</td>
<td>FUEL</td>
</tr>
<tr>
<td>442.0</td>
<td>REFLECTOR</td>
</tr>
<tr>
<td>624.5</td>
<td>HEAT PIPES</td>
</tr>
<tr>
<td>33.0</td>
<td>CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)</td>
</tr>
<tr>
<td>92.1</td>
<td>SUPPORT STRUCTURE (7% OF REACTOR WT)</td>
</tr>
</tbody>
</table>

**1407.5 TOTAL REACTOR + HEAT PIPES**

**91.91 MW/HH**3 AVERAGE POWER IN FUELSPACE 15.04 KW/POWER PER HEAT PIPE

**33.29 MW/HH**3 HTPIPE AXIAL HT FLUX 0.760 MW/HH**2 HTPIPE AXIAL HTFLX

**STOP**
### Heat Pipe Data Summary

#### Fuel Element Volume Fractions
- Cladding: Heat Pipe Hall + Wick Vapor: 0.9167
- 0.0833
- 0.0833
- 0.0500

#### Temperature Summary (Degree Kelvin)
- Maximum Fuel Delta T = 110.8
- Average Delta T Across Heat Pipe Wall = 6.5
- Average Fuel Temperature = 1643.5
- Maximum Fuel Temperature = 1720.7

#### Fission Density (Fissions/cm³) = 1.534 x 20

#### Fuel Swelling Volume % = 0

#### Reactor Dimensions (in Meters)
- Core Diameter = 0.3214
- Core Height = 0.3214
- Reactor Diameter = 0.5514
- Reactor Height = 0.5314
- Reflector Thickness = 0.1000
- Pipe Length Outside Reactor = 1.0000
- Total Heat Pipe Length = 1.4264
- Overall Reactor-Heat Pipe Length = 1.5314

#### Reactor Weight (in Kilograms)
- Fuel: U235 Mass = 114.4
- 251.9 kg
- 33.0 kg
- Support Structure (7% of Reactor HT)

#### Total Reactor + Heat Pipes
- 16.34 MW (H2O)
- 4.76 kWe per Heat Pipe
- 99.33 MW (H2O)
- 0.605 MW (H2O) per Heat Pipe
PROB NO. 11  5-18-73  TYPE NEW INPUT: PR=1, KHP=2 ... STOP
PR=0.7 STOP

0.700 (PP) REACTOR POWERMW  (KCORE) (1.2/vc=UO2) CORE =MO05UO2
1600. (THW) HEAT PIPE TEMPERATURE K (KREF) (1.2/BE=REQ) REFLECTOR = E10
3450. (TIME) LIFETIME DAYS (KHP) (1.2/NS+MWH) HEAT PIPE SHO
1.00 (FLD) CORE I/D RATIO (KVARF) (1.2/LI=NA) VAPOR = LI
10.0 (PML) AXIAL HT FLUX KWH/CH2 (TOPN) (1.2) OPTION = 2
200. (DTMPAY) MAX FUEL DELTA T DEG K
1.00 (HP1) PIPE EXTENSION=M

NOTE: OPTIONS ARE 1- CODE PT DESIGN, 2-SPECIFIED DESIGN
TYPE IN ANY OF FOLLOWING: 1. CORE(H) XREF(H) UNIF PIPES NPIPE ... STOP
NPIPE=120 STOP

120 (NPIPE) NO. OF HEAT PIPES

BETA VC VCD ALFA PKAYG 2MIN DXMIN CORSAF EENDSAF
0.100 0.012 0. 0.600 1.500 0.050 0.080 0.015 0.005

TYPE STOP OR NEW CONSTANTS IE. VC=0, PKAYG=2, ETC ... STOP

VC=0.008 STOP

SLD INDEX = 3

VNF = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000

DF = 0.299 0.326 0.363 0.412 0.475 0.552 0.694 0.961 1.754 *

DCH = 0.140 0.263 0.314 0.184 0.165 0.150 0.139 0.130 0.122

* * * * * * * * * * TYPE 50 OR START OVER * * * * * * * * * *

BETA = 0.1000  VNF = 0.2264  VIF = 0.7736  DX = 0.1000  DC = 0.3348

REACTIVITY CHANGES: DELTA K

BURN = 0.01435  EXP = 0.01456  SAFE = 0.02000  TOTAL = 0.04891

FUEL ELEMENT VOLUME FRACTIONS

CLADDING FUEL REGION HEAT PIPE WALL+THICK VAPOR
0.9 0.0645 0.1335 0.0534 0.0801

HEXAGONAL CORNER CORRECTION FACTOR = 1.0180

NUMBER OF HEAT PIPES = 61, 1476

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 120

TEMPERATURE SUMMARY: DEGREE KELVIN

MAX FUEL DELTA T = 101.9
AVERAGE DELTA T ACROSS HEAT PIPE WALL = 7.7
AVERAGE FUEL TEMPERATURE = 1641.7
MAXIMUM FUEL TEMPERATURE = 1713.4

BURN FRACTION OF U235 = 0.0239

FUSION DENSITY (Fissions/CH*3) = 2.584E20

FUEL FILLING VOLUME % = 0.

FACTOR DIMENSIONS: METERS  FUEL ELEMENT DIMENSIONS: MM

0.3348 CORE DIAMETER 29.00 WIDTH ACROSS HEX FLATS
0.3348 CORE HEIGHT 30.44 EQUIV. FUEL ELEMENT DIAM
0.5548 REFLECTOR DIAMETER 30.44 EQUIV. FUEL REGION O.D.
0.5448 REFLECTOR HEIGHT 11.12 HEAT PIPE O.D.
0.1000 REFLECTOR THICKNESS 8.62 VAPOR DIAMETER
1.0000 PIPE LENGTH OUTSIDE REACTOR 58.31 VAPOR AREA+ M**2
1.4295 TOTAL HEAT PIPE LENGTH
1.5443 OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR HEIGHT: KILOGRAMS

242.3 FUEL: U235 MASS = 122.8
268.3 REFLECTOR
63.5 HEAT PIPES: WT/UNIT LENGTH (KG/M) = 47.58
33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)
42.9 SUPPORT STRUCTURE (7% OF REACTOR WT)

------

555.2 TOTAL REACTOR + HEAT PIPES

27.62 MW/H**3 AVG POWER IN FUELSPACE 5.93 KW/POWER PER HEAT PIPE
100.05 MW/H**2+HTPIPE AXIAL HT FLUX 0.644 MW/H**2+HTPIPE RAD HTFLX

STOP
NOTE OPTIONS ARE : 1- CODE PT DESIGN; 2-SPECIFIED DESIGN

TYPE IN ANY OF FOLLOWING : DCORE(M) XREF(N) UNFT PIETA NPIPE ..STOP

NPIPE=162 STOP

162 (NPIPE) NO. OF HEAT PIPES

TYPE: STOP; OR NEW CONSTANT IE. VC=0, PKAVAR=2, ETC ..STOP

VE=0.006 STOP

E=.INDX= 3

VNF = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000

DC = 0.299 0.326 0.363 0.412 0.475 0.568 0.634 0.761 1.754 

DCH = 0.449 0.313 0.255 0.220 0.197 0.179 0.166 0.155 0.146

TYPE = STOP OR START OVER * * * * * * * *

STOP

BETA =0.1000  UNF=0.2630  VC=0.7370  DX=0.1000  DC=0.3482

REACTION CHANGES: DELTA K

BURN = 0.01915  EXP = 0.01456  SAFE = 0.02000  TOTAL = 0.05371

FUEL ELEMENT VOLUME FRACTIONS:

CLADDING  FUEL REGION  HEAT PIPE WALL+THICK  VAPOR

0.8238  0.1762  0.0705  0.1057

HEXAGONAL CORNER CORRECTION FACTOR =1.0315

NUMBER OF HEAT PIPES = 71.2219

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 162

TEMPERATURE SUMMARY: DEGREE KELVIN

MAXIMUM FUEL DELTA T = 87.9

AVERAGE DELTA T ACROSS HEAT PIPE WALL = 7.8

AVERAGE FUEL TEMPERATURE =1637.1

MAXIMUM FUEL TEMPERATURE =1699.7

BURN FRACTION OF U235 = 0.0319

FISSION DENSITY <FISSIONS/CM**3> = 3.447E+20

FUEL SHELLING + VOLUME % = 0.

REACTOR DIMENSIONS: METERS

0.3482  CORE DIAMETER

0.3482  CORE HEIGHT

0.5782  REACTOR DIAMETER

0.5582  REACTOR HEIGHT

0.1000  REFLECTOR THICKNESS

1.0000  PIPE LENGTH OUTSIDE REACTOR

1.4532  TOTAL HEAT PIPE LENGTH

1.5522  OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR HEATS: KILOGRAMS

259.4  FUEL  U235 MASS = 131.5

285.5  REFLECTOR

98.8  HEAT PIPE WI/UNIT LENGTH (KG/M) = 68.02

33.0  CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)

47.4  SUPPORT STRUCTURE (7% OF REACTOR HT)

724.1  TOTAL REACTOR + HEAT PIPES

39.84 MW/MM**2; AVG POWER IN FUELSPACE 6.17 KW/POWER PER HEAT PIPE

49.98 MW/MM**2; HTPIPE AXIAL HT FLUX 0.637 MW/MM**2 HTPIPE AXIAL HTFLUX

TYPE = STOP
1.650 (PR) REACTOR POWER:MW (KORE) (1,2/UC:U02) CORE =H060W02
1600. (THP) HEAT PIPE TEMP:DEG K (KARE) (1,2/BE:BE0) REFLECTOR =BE0
3650. (TIME) LIFETIME DAYS (KMP) (1,2/3:3BE:MO) HEAT PIPE =MO
1.00 (SLD) CORE L/D RATIO (KVAPO) (1,2/L1/NA) VAPOR =LI
10.0 (DAXL) AXIAL HT FLUX:KW/CM2 (IDOTH) (1,2) OPTION =2
200. (DFTMAX) MAX FUEL DELTA T DEG K
1.00 (HPL1) PIPE EXTENSION M

NOTE: OPTIONS ARE: 1-CODE PT DESIGN; 2-SPECIFIED DESIGN
TYPE IN ANY OF FOLLOWING: DCORE(H) XREP(H) VNPT PIETA NPIFE ..STOP

NPIFE=162 STOP

162 (NPIPE) NO. OF HEAT PIPES
SETA VC VCD ALFA PKAVG MIN DMIN COMP END GAP
0.100 0. 0.050 0.600 1.500 0.050 0.080 0.015 0.005

TYPE: STOP; OR NEW CONSTANTS IE: VC=0, PKAVG=2, ETC ...STOP
ASET=0.1 VC=0.006 VCD=0. STOP
SLD INDEX = 3
VN = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000
DC = 0.299 0.326 0.363 0.412 0.475 0.562 0.694 0.961 1.754 +
DC = 1.577 0.402 0.327 0.283 0.252 0.230 0.213 0.199 0.189
+ + + + + + + + + + + + TYPE 3D OR RESTART + + + + + + + + + + + +

80...PT DESIGN FOR PRES LAYTON AND HARPER
ASET = 0.1000 VN = 0.3286 VF = 0.6714 DX = 0.1000 DC = 0.3759
REACTIVITY CHANGES; DELTA K
BURN = 0.02756 EXP = 0.01456 SAFE = 0.02000 TOTAL = 0.06212

FUEL ELEMENT VOLUME FRACTIONS
CLADDING FUEL REGION HEAT PIPE WALL+WICK VAPOR
0. 0.750 5 0.2495 0.0999 0.1497

HEXAGONAL CORNER CORRECTION FACTOR = 1.0642
NUMBER OF HEAT PIPES = 36.1780
MINIMUM PRACTICAL (OP SPECIFIED) NUMBER OF HEAT PIPES = 162

TEMPERATURE SUMMARY: DEGREE KELVIN
MAXIMUM FUEL DELTA T = 105.4
AUX DELTA T ACROSS HEAT PIPE WALL = 12.0
AVERAGE FUEL TEMPERATURE = 1647.4
MAXIMUM FUEL TEMPERATURE = 1724.3
BURN FRACTION OF U235 = 0.0459
FUSION DENSITY (FUSION/CH*3) = 4.96E+20
FUEL SHELLING VOLUME % = 0.4383 X 1.24

REACTOR DIMENSIONS: METERS
0.3759 CORE DIAMETER
0.3759 CORE HEIGHT
0.6059 REACTOR DIAMETER
0.5259 REACTOR HEIGHT
0.1000 REFLECTOR THICKNESS
1.0000 PIPE LENGTH OUTSIDE REACTOR
1.4809 TOTAL HEAT PIPE LENGTH
1.5854 OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR WEIGHTS: KILOGRAMS
297.3 FUEL, U235 MASS = 150.8
322.4 REFLECTOR
165.2 HEAT PIPES; HT/UNIT LENGTH (KG/M) = 112.25
33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)
57.3 SUPPORT STRUCTURE (7% OF REACTOR WT)

386.3 TOTAL REACTOR + HEAT PIPES
53.04 MW/HP+3; AUX POWER IN FUELSpace
93.95 MW/HP+2; HTPIPE AXIAL HT FLUX = 0.757 MW/HP+2; HTPIPE AXIAL HTFLX

*************
1.650 (PR) REACTOR POWER/MW

1600. (TPH) HEAT PIPE TEMP/DEG K

3650. (TIME) LIFETIME/DAYS

1.00 (SLD) CORE L/D RATIO

10.0 (MAXL) AXIAL HT FLUX/KH/CM2 (GRAPH) (X2)

200. (DTMAX) MAX FUEL DELTA T/DEG K

NOTE: OPTIONS ARE: 1- CODE PT DESIGN; 2-SPECIFIED DESIGN

1.00 (NPIPE) PIPE EXTENSION/M

1.00 (NPIPE) NO. OF HEAT PIPES

STOP

210 (NPIPE) NO. OF HEAT PIPES

STOP

210 (NPIPE) NO. OF HEAT PIPES

STOP

96.2171 MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 210

TEMPERATURE SUMMARY: DEGREE KELVIN

0.7504 0.2496 0.0993 0.1497

HEXAGONAL CORNER CORRECTION FACTOR = 1.0643

FISSION DENSITY (FISSIONS/CM+3) = 4.968E+20

FUEL SWELL INC/WOLUME : 0.77

REACTOR DIMENSIONS: METERS

FUEL ELEMENT DIMENSIONS: MM

CORE DIAMETER

24.62 WIDTH ACROSS HEX FLATS

CORE HEIGHT

25.35 EQUIV. FUEL ELEMENT DIA

REACTOR DIAMETER

25.35 EQUIV. FUEL REGION O.D.

REACTOR HEIGHT

12.92 HEAT PIPE O.D.

REFLECTOR THICKNESS

10.00 VAPOR DIAMETER

TOTAL HEAT PIPE LENGTH OUTSIDE REACTOR 78.60 VAPOR AREA, MM+2

TOTAL HEAT PIPE LENGTH

1.5856 OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR WEIGHTS: KILOGRAMS

297.0 FUEL: U235 MASS = 150.6

322.1 REACTOR

166.2 HEAT PIPES: W/UNIT LENGTH (KG/M) = 112.24

33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)

57.3 SUPPORT STRUCTURE 7% OF REACTOR WT)

TOTAL REACTOR + HEAT PIPES

53.11 MH/M+3; AVG PWR IN FUELSPACE 7.86 KW/POWER PER HEAT PIPE

99.36 MH/M+2; HTPIPE AXIAL HT FLUX 0.566 MH/M+2; HTPIPE RAD HTFLX

ORIGINAL PAGE IS OF POOR QUALITY
2,000 (PP) REACTOR POWER: MW
1,600, (THP) REACTOR HEAT PIPE TEND-DES K
3550, (LIFETIME) LIFETIME: DAYS
1,00 (FIE) CORE L/D RATIO
10,0 (PAIL) AXIAL HT FLU: kW/km2
200, (DTFMA) MAX FUEL DELTA T: DES K
1,00 (HP1) PIPE F/TENSION: M

NOTE: OPTIONS ARE: 1-CODE FT DESIGN: 2-SPECIFIED DESIGN

TYPE IN ANY OF FOLLOWING: D/CORE(M) X/PES(N) U/HAT PIPE ...STOP

NPipe=210 STOP

210 (NPipe) NO. OF HEAT PIPES

BETA VC VCD ALPA PKAV3 EMIN DMIN CORR F GAP END GAP

0.100 0.006 0.600 1.500 1.000 0.050 0.015 0.005

STOP: OR NEW CONSTANTS IE. VC=0, PKAV3=2, ETC ...STOP

UC=30.005 STOP

SLID INDEX = 3

DC = 0.099 0.326 0.363 0.412 0.475 0.562 0.694 0.961 1.754 .

DCH = 0. 0.432 0.442 0.360 0.311 0.278 0.253 0.234 0.219 0.207

TYPE GO OR START OVER ++ ++ ++ ++ ++ ++ ++ ++

BETA = 0.1000 VNF = 0.3566 VF = 0.6434 DX = 0.1000 DC = 0.3993

REACTIVITY CHANGES: DELTA K

PUEK = 0.03138 EXP = 0.01456 SAFE = 0.0200 TOTAL = 0.06594

FUEL ELEMENT VOLUME FRACTIONS:

CLADDING FUEL REGION HEAT PIPE WALL + THICK VAPOR

0.7185 0.2815 0.1126 0.1689

HEXAGONAL CORNER CORRECTION FACTOR = 1.0825

NUMBER OF HEAT PIPES = 92.2398

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 210

TEMPERATURE SUMMARY: DEGREE KELVIN

MAXIMUM FUEL DELTA T = 17.8

AVG DELTA T ACCROSS HEAT PIPE WALL = 10.8

AVERAGE FUEL TEMPERATURE = 1640.1

MAXIMUM FUEL TEMPERATURE = 1704.0

EVEN FRACTION OF 0.235 = 0.0523

FUSION DENSITY (FUSION/KG*3) = 5.5466+20

FUEL FUSION L=VOLUME % = 0.

REACTOR DIMENSIONS: METERS

0.3393 CORE DIAMETER

0.3293 CORE HEIGHT

0.6193 REACTOR DIAMETER

0.5993 REACTOR HEIGHT

0.1000 REFLECTOR THICKNESS

1.0000 PIPE LENGTH OUTSIDE REACTOR

1.4943 TOTAL HEAT PIPE LENGTH

1.5343 OVERALL REACTOR + HEAT PIPE LENGTH

REACTOR WEIGHTS: KILOGRAMS

316.6 FUEL + U235 MASS = 160.5

341.3 REFLECTOR

203.3 HEAT PIPE + HT UNIT LENGTH (KG/M) = 136.03

33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)

62.6 SUPPORT STRUCTURE (7% OF REACTOR WT)

956.7 TOTAL REACTOR + HEAT PIPES

60.37 MW/MM3 MAX AVERAGE IN FUELSPACE

9.52 KW/POWER PER HEAT PIPE

93.98 MW/MM2 + HT PIPE AXIAL HT FLUX

0.787 MW/MM2 + HT PIPE RAD HTFLUX

************************************************************

TYPE 40 OR STOP
4.000 (PB) REFLECTOR POWER=HH (KCOP) (1/2/100/1000) CORE =HH0000
16.000 (TH) HEAT PIPE TEMP=HH (KPS) (1/2/100/1000) REFLECTOR PIED
34.000 (THF) LIFTH=HH0/1 (KPS) (1/2/3/4/0/60) HEAT PIPE SHO
1.00 (ED) CORE L/D RATIO (KPS) (1/2/3/4/0/60) VAPOR PLS
10.1 (GAL) AXIAL HT FLUX=HH/CH (I/PHT) (1/2/3)
200. (HPIP=H) MAX FUEL DELTA T=DEG
1.00 (HP) PIPE EXTENSION

NOTE: OPTIONS ARE: 1-CODE PT DESIGN; 2-SPECIFIED DESIGN
TYPE IN ANY OF FOLLOWING: 1-DISP(H) XMEM(H) VNP1 PT ETA NPIPE ...STOP
NPIPE=266 STOP

-266 (NPIPE) NO. OF HEAT PIPES
-0.100 0.100 0.035 0. 0.600 1.500 0.050 0.030 0.015 0.005
TYPE: STOP OR NEW CONSTANTS IE. VCP=0. PKAGS=2. ETC ...STOP
VCP=0.004 STOP

SLD INDEX = 3
UNF = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000
DC = 0.299 0.386 0.463 0.542 0.621 0.699 0.777 0.856 0.934 1.000
DCW = 0. 0.890 0.624 0.503 0.439 0.392 0.358 0.331 0.310 0.292

-40 BETA =0.1000 UNF =0.4720 W/ =0.5280 DX =0.1000 DC =0.4554

REACTIVITY CHANGES; DELTA K
BURN = 0.04777 EXP = 0.01456 SAFE = 0.02000 TOTAL = 0.08233
FUEL ELEMENT VOLUME FRACTIONS
CLADDING FUEL REGION HEAT PIPE WALL+VAPOR
0. 0.5890 0.4110 0.1644 0.2466

HEXAGONAL CORNER CORRECTION FACTOR =1.1840
NUMER OF HEAT PIPES = 115.0234
MINIMUM PRACTICAL (OR SPECIFIED) NUMER OF HEAT PIPES = 266

TEMPERATURE SUMMARY+DEGRE KELVIN
MAXIMUM FUEL DELTA T = 86.5
AVERAGE DELTA T ACROSS HEAT PIPE WALL = 14.6
AVERAGE FUEL TEMPERATURE =1643.4
MAXIMUM FUEL TEMPERATURE =1708.3

BURN FRACTION OF U235 =0.0792
FUSION DENSITY (FUSIONS/CH3) = 8.593e+20
FUEL SWELLING=VOLUME % = 0.

--- REACTOR DIMENSIONS: METERS ---

<table>
<thead>
<tr>
<th>FUEL ELEMENT DIMENSIONS: MM</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.4554 CORE DIAMETER</td>
</tr>
<tr>
<td>0.4554 CORE HEIGHT</td>
</tr>
<tr>
<td>0.6854 REACTOR DIAMETER</td>
</tr>
<tr>
<td>0.6854 REACTOR HEIGHT</td>
</tr>
<tr>
<td>0.1000 REFLECTOR THICKNESS</td>
</tr>
<tr>
<td>1.0000 FUEL LENGTH OUTSIDE REACTOR</td>
</tr>
<tr>
<td>1.5604 TOTAL HEAT PIPE LENGTH</td>
</tr>
<tr>
<td>1.6654 OVERALL REACTOR+HEAT PIPE LENGTH</td>
</tr>
</tbody>
</table>

--- REACTOR WEIGHTS: KILOGRAMS ---

<table>
<thead>
<tr>
<th>FUEL+U235 MASS = 210.9</th>
</tr>
</thead>
<tbody>
<tr>
<td>416.0 FUEL</td>
</tr>
<tr>
<td>445.0 REFLECTOR</td>
</tr>
<tr>
<td>424.5 HEAT PIPES+ WT/UNIT LENGTH (KG/M) = 272.05</td>
</tr>
<tr>
<td>31.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)</td>
</tr>
<tr>
<td>96.1 SUPPORT STRUCTURE (7% OF REACTOR WT)</td>
</tr>
</tbody>
</table>

1407.5 TOTAL REACTOR+HEAT PIPES

--- 91.31 MH/MM+3 AUS FOUR IN FUELSPACE 15.04 KW/POWER PER HEAT PIPE ---

--- 99.92 MH/MM+2 HEAT PIPE AXIAL HT FLUX = 0.750 MH/MM+2 HEAT PIPE AND HTFLX ---

TYPE GO OR STOP
PROF NO. 15 9-18-78 TYPE NEW INPUT PRA=1, KHP=2 ...STOP
PRA=0.2 THP=1750, STOP

0.000 (PR) REACTOR POWER MH (KCORE) (1.2:UC:UO2) CORE PHO60UO2

1000 (THP) HEAT PIPE TEMP DEG K (KREP) (1.2:3E:350) REFLECTOR = 350

365.0 (TIME) LIFETIME DAYS (KHP) (1.2:3/400:4) HEAT PIPE = 400

1.00 (CILD) CORE L/D RATIO (KVAPOR) (1/2/LIM=) VAPOFR = 1

10.0 (CILD) AxIAL HT FLUX/KW/CH2 (IOPTN) (1/2) OPTION = 2

200.0 (DTHPA=) MAX FUEL DELTA T DEG K

1.00 (MHP=) PIPE EXTENSION = M

NOTE: OPTIONS ARE 1-CODE AT DESIGN 2-SPECIFIED DESIGN

TYPE IN ANY OF FOLLOWING 1 CORE(H) XREP(H) REFLECTOR NP PIPE ...STOP

NPPIPE=34 STOP

84 (NPipe) NO, OF HEAT PIPES

BETA UC VCD ALFA PKA/K3 BMN DMN CORR GAP END GAP

0.100 0.0.04 0.0 0.600 1.500 0.050 0.060 0.150 0.005

TYPE STOP, OR NEW CONSTANTS IE. UC=0. PKA/K=2, ETC ...STOP

UC=0.012 STOP

SLD INDEX =

1.000 0.000 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000

DC = 0.299 0.826 0.363 0.412 0.475 0.562 0.694 0.961 1.754 +

DCH = 0.207 0.142 0.115 0.099 0.088 0.081 0.074 0.070 0.066

+ + + + + + + + + + + + + + TYPE GO OR START OVER + + + + + + + + + + + + +

1.100 0.300 0.150 0.0349 0.0100 0.3115

FUEL ACTIVITY CHANGES DELTA K

RUN = 0.0046 EXP = 0.01612 SAFE = 0.02000 TOTAL = 0.04076

FUEL ELEMENT VOLUME FRACTIONS

CLADDING FUEL REGION HEAT PIPE WALL+THICK VAPOFR

0.0 0.9553 0.0442 0.0177 0.0265

HEXAGONAL CORNER CORRECTION FACTOR = 1.0020

NUMBER OF HEAT PIPES = 31.5336

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 84

TEMPERATURE SUMMARY: DEGREE KELVIN

MAX FUEL DELTA T = 75.2

AVG Delta T Across Heat Pipe Wall = 3.4

MAXIMUM FUEL TEMPERATURE = 1778.4

MAXIMUM FUEL TEMPERATURE = 1830.3

BURN FRACTION OF U235 = 0.0077

FUSION DENSITY (FUSIONS/CM**3) = 8.345E+19

FUEL SHELLING VOLUME % = 1.14

ORIGINAL PAGE IS OF POOR QUALITY

REACTOR DIMENSIONS: METERS

0.3115 CORE DIAMETER

0.3115 CORE HEIGHT

0.5415 REACTOR DIAMETER

0.5215 REACTOR HEIGHT

0.1000 REFLECTOR THICKNESS

1.0000 PIPE LENGTH OUTSIDE REACTOR

1.4165 TOTAL HEAT PIPE LENGTH

1.5215 OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR WEIGHTS: KILOGRAMS

214.3 FUEL: U235 MASS = 108.7

240.2 REFLECTOR

13.0 HEAT PIPES; WT/UNIT LENGTH (KG/M) = 13.60

33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)

35.5 SUPPORT STRUCTURE (7% OF REACTOR WT)

545.2 TOTAL REACTOR + HEAT PIPES

8.98 MW/HEAT PIPES: FOUR IN FUELSpace 2.33 KW/FOUR REP HEAT PIPE

100.04 MW/HEAT PIPE AXIAL HT FLUX 0.442 MW/HEAT PIPE RAD HTFLX

TYPE GO OR STOP
PROB NO. 16  5-18-78  TYPE NEW INPUT! PR1, KMP2 ... STOP
PR=0.4 STOP

0.400 (PP) REACTOR POWER: MW  
1750. (THP) HEAT PIPE TEMP: deg K
3650. (TIME) LIFETIME DAYS
1.00 (FLD) CORE L/D RATIO
10.0 (DFFM) AXIAL HT FLUX-FIRST CH2 (DOPH) (1.2)
200. (DTFMN) MAX FUEL DELTA T: deg K
1.00 (MP1) PIPE EXTENSION M

NOTE: OPTIONS ARE 1-CODE PT DESIGN; 2-SPECIFIED DESIGN
TYPE IN ANY OF FOLLOWING: 1) CORE(H)  XREP(H) UNIF PIETA NPIPE ... STOP
NPIPE=34 STOP

84 (NPIPE) NO. OF HEAT PIPES

BETA VC  VCD  ALFA  PKAVG ZMIN DXMIN CORRAP ENGPAP
0.100  0.012  0.  0.600  1.500  0.050  0.080  0.015  0.005

TYPE= STOP; OR NEW CONSTANTS IE. VC=0, PKAVG=2, ETC ... STOP

STOP

ILD INDEX =  3
VF = 0.100  0.200  0.300  0.400  0.500  0.600  0.700  0.800  0.900  1.000
DC = 0.299  0.326  0.363  0.412  0.475  0.562  0.694  0.961  1.754 *
DCM = 0.  0.293  0.201  0.163  0.140  0.125  0.114  0.105  0.098  0.093

90
BETA = 0.1000  UNF = 0.1848  VF = 0.3152  DX = 0.1000  DC = 0.3214

REACTIVITY CHANGES: DELTA K
BURN = 0.00581  EXP = 0.01612  SAFE = 0.02000  TOTAL = 0.04493

FUEL ELEMENT VOLUME FRACTIONS
CLADDING FUEL REGION HEAT PIPE WALL+HICK VAPOR
0.  0.9167  0.0598  0.0393  0.0500

HEXAGONAL CORNER CORRECTION FACTOR = 1.0070
NUMBER OF HEAT PIPES = 46.5570
MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 84

TEMPERATURE SUMMARY: DEGREE KELVIN
MAXIMUM FUEL DELTA T = 110.8
AVG DELTA T ACCROSS HEAT PIPE WALL = 6.5
AVG FUEL TEMPERATURE = 1793.3
MAXIMUM FUEL TEMPERATURE = 1870.7

BURN FRACTION OF U235 = 0.0147
FISSION DENSITY (FISSION/CH2=3) = 1.395E+20
FUEL SWELLING: VOLUME % = 2.6

REACTOR DIMENSIONS: METERS
0.3214  CORE DIAMETER
0.3214  CORE HEIGHT
0.5514  REACTOR DIAMETER
0.5314  REACTOR HEIGHT
0.1000  REFLECTOR THICKNESS
1.0000  PIPE LENGTH OUTSIDE REACTOR
1.4264  TOTAL HEAT PIPE LENGTH
1.5314  OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR WEIGHTS: KILOGRAMS
225.6  FUEL  U235 MASS = 114.4
215.9  REFLECTOR
33.8  HEAT PIPES/WT/UNIT LENGTH (KG/M) = 27.22
33.0  CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)
38.5  SUPPORT STRUCTURE (7% OF REACTOR WT)

587.9  TOTAL REACTOR + HEAT PIPES

16.94 MW/H*3; AVG RPOW IN FUELES = 4.76 KW/POWER REP HEAT PIPE
99.92 MW/H*2; HTPIPE AXIAL HT FLUX 0.605 MW/H*2; HTPIPE RAD HTFLX

ORIGINAL PAGE 13
OF POOR QUALITY
PROJ NO. 17  5-18-78   TYPE NEW INPUT: PR=1, KNP=2 ...STOP
PR=0.7 STOP

0.700 (PR) REACTOR POWER= MH  (KCORE) = (1:2:VCD:UO2) CORE = NO60UO2
1750. (THPb) HEAT PIPE TEMP= DEG K (KHF) = (1:3:BE:3E0) REFLECTOR=SE0
3650. 'TIME' LIFETIME= DAYS (KHP) = (1:2:3/NO:101W) HEAT PIPE= NO
1.00 (FLD) CORE L/D RATIO (KVAR) = (1:2/LINIA) VAPOR= FLI
10.0 (OAXL) AXIAL HT FLUX= kW/CH2 (IDMTH) = (1:2) OPTION = 2
200. (DTF MAX) MAX FUEL DELTA T=DEG K
1.00 (WPL1) PIPE EXTENSION= MM

NOTE: OPTIONS ARE: 1-CODE PT DESIGN; 2-SPECIFIED DESIGN
TYPE IN ANY OF FOLLOWING: XCORE (H) XREF (H) XUNFT PTBETA NPipe ...STOP
NPipe=120 STOP

120 (NPipe) NO. OF HEAT PIPES

BETA  UC  VCD  ALFA  PKAV  BMN  DXMIN  CORR GAP  END GAP
0.100 0.012 0. 0.600 1.500 0.050 0.080 0.015 0.005

TYPE= STOP! OR NEW CONSTANTS IE, UC=0, PKAVU=2, ETC ...STOP

VCF=0.008 STOP

$ID INDEX = 3
UNF = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000
DC = 0.299 0.326 0.363 0.412 0.475 0.562 0.694 0.961 1.754 +.
DC = 0.380 0.263 0.214 0.154 0.165 0.150 0.139 0.130 0.122
*

BETA = 0.1000 UNF = 0.2264 VF = 0.7736 DX = 0.1000 DC = 0.3348
REA ACTIVITY CHANGES: DELTA K

BURN = 0.01435 EXP = 0.01612 SAFE = 0.02000 TOTAL = 0.05047

FUEL ELEMENT VOLUME FRACTIONS

CLADDING FUEL REGION HEAT PIPE WALL+HICK VAPOR
0. 0 0.3665 0.1335 0.0534 0.0301

MAXIMONAL CORNER Correction FACTOR = 1.0180

NUMBER OF HEAT PIPES = 61,1476

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 120

TEMPERATURE SUMMARY; DEGREE KELVIN

MAXIMUM FUEL DELTA T = 101.9
AVERAGE DELTA T ACROSS HEAT PIPE WALL = 7.7
AVERAGE FUEL TEMPERATURE = 1791.7
MAXIMUM FUEL TEMPERATURE = 1862.4

BURN FRACTION OF U235 = 0.0239

FISON RENITY (Fissions/CH2+3) = 2.584E+20
FUEL SHELLING VOLUME % = 82.4.3

REACTOR DIMENSIONS; METERs
0.3348 CORE DIAMETER
0.3348 CORE HEIGHT
0.5648 REACTOR DIAMETER
0.5448 REACTOR HEIGHT
0.1000 REFLECTOR THICKNESS
1.0000 PIPE LENGTH OUTSIDE REACTOR
1.4393 TOTAL HEAT PIPE LENGTH
1.5448 OVERALL REACTOR=HEAT PIPE LENGTH

FUEL ELEMENT DIMENSIONS; MM

29.00 WIDTH ACROSS HEX FLATS
30.44 EQUIV. FUEL ELEMENT DI.
30.44 EQUIV. FUEL REGION O.D.
11.12 HEAT PIPE O.D.
8.62 VAPOR DIAMETER
58.31 VAPOR AREA; MM+2

FUEL ELEMENT MASS; KG

242.3 FUEL; U235 MAss = 122.8
260.5 REFLECTOR
68.5 HEAT PIPES; HT/UNIT LENGTH (KG/M) = 47.58
33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)
42.9 SUPPORT STRUCTURE (7% OF REACTOR WT)

695.2 TOTAL REACTOR + HEAT PIPES

27.62 MW/H+3 AHS POWER IN FUELSPACE 5.83 KW/POWER PER HEAT PIPE
100.05 MW/H+2+HTPIPE AVGAL HT FLUX 0.644 MW/H+2+HTPIPE RAD HTFLX

----------

32
PREP NO. 18 5-18-78 TYPE NEW INPUT: PR=1, KHP=2 ...STOP

PR=1, STOP

1.000 (PR) REACTOR POWER= MW (KORE) (1.2/UC,0.02) CORE = MO60UD2
17.50 (THP) HEAT PIPE TEMP=°C K (KREP) (1.2/BE, 0.02) REFLECTOR = SE0
36.50 (TIME) LIFETIME=DAYS (KHP) (1.2/3/ND, MO) HEAT PIPE = MO
1.00 (SLD) CORE L/D RATIO (KVAOR) (1.2/2/LI, NA) VAPOR = LI
10.0 (DAXL) AXIAL HT FLUX*KW/CH2 (KOPTN) (1.2) OPTION = 2
20.0 (DTFMAX) MAX FUEL DELTA T=°C K
1.00 (NPL) PIPE EXTENSION M

NOTE: OPTIONS ARE: 1-CODE AT DESIGN 2-SPECIFIED DESIGN
TYPE IN ANY OF FOLLOWING: DCORE= (M) XREP= (M) UNF=BETA NPIPE= ...STOP
NPIPE=162 STOP

162 (NPIPE) NO. OF HEAT PIPES
BETA VC VCD KALFA PFAV EMIN DXMIN CORR GAP END GAP
0.100 0.008 0.600 1.500 0.050 0.080 0.015 0.005
TYPE=0.006 STOP
SLD INDEX = 3
UNF = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900 1.000
DC = 0.299 0.326 0.363 0.412 0.475 0.562 0.694 0.961 1.754 +.
DCM = 0.
DCM = 0.449 0.313 0.255 0.220 0.197 0.179 0.166 0.155 0.146

BETA = 0.1000 UNF = 0.2630 VF = 0.7370 DX = 0.1000 DC = 0.3462
REACTIVITY CHANGES: DELTA K
OP2N = 0.01915 EXP = 0.01612 SAFE = 0.02000 TOTAL = 0.05527
FUEL ELEMENT VOLUME % FRACITIONS
CLADDING FUEL REGION HEAT PIPE WALL+HICK VAPOR
0.
0.8238 0.1762 0.0705 0.1057
HEXAGONAL CORNER CORRECTION FACTOR = 1.0315
NUMBER OF HEAT PIPES = 71.2219
MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 162

TEMPERATURE SUMMARY: DEGREE KELVIN
MAXIMUM FUEL DELTA T = 97.9
AVERAGE DELTA T ACROSS HEAT PIPE WALL = 7.8
AVERAGE FUEL TEMPERATURE = 1787.1
MAXIMUM FUEL TEMPERATURE = 1849.7
BURN FRACTION OF U235 = 0.0319
FISSION DENSITY (FISSIONS/CM*3) = 3.447E+20
FUEL SWELLING VOLUME % = 22 ~ 5.7

REACTOR L MENSIONS: METERS FUEL ELEMENT DIMENSIONS: M

0.3482 CORE DIAMETER 25.97 WIDTH ACROSS HEX FLATS
0.3482 CORE HEIGHT 27.27 EQUIV. FUEL ELEMENT DIA.
0.5782 REACTOR DIAMETER 27.27 EQUIV. FUEL REGION O.D.
0.5582 REACTOR HEIGHT 11.45 HEAT PIPE O.D.
0.1000 REFLECTOR THICKNESS 8.87 VAPOR DIAMETER
1.0000 PIPE LENGTH OUTSIDE REACTOR 61.74 VAPOR AREA, M**2
1.4532 TOTAL HEAT PIPE LENGTH
1.5532 OVERALL REACTOR+HEAT PIPE LENGTH

REACTOR WEIGHTS: KILOGRAMS

259.4 FUEL, U235 MASS = 131.5
285.5 REFLECTOR
98.8 HEAT PIPES, WT/UNIT LENGTH (KG/ M) = 68.02
33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)
47.4 SUPPORT STRUCTURE (% OF REACTOR WT)

724.1 TOTAL REACTOR + HEAT PIPES

36.34 WU/H**3; AVG POWER IN FUELSPACE 6.17 KW/HEAT PIPE
99.98 WU/H**2; HTPIPE AXIAL HT FLUX 0.637 WU/H**2+ HTPIPE RAD HTFLX

TYPE GO OR STOP
2.000 (PR) REACTOR POWER; MH
1750. (THP) HEAT PIPE TEMP; DEG K
3650. (TIME) LIFETIME; DAYS
1.00 (SLD) CORE L/D RATIO
10.0 (OAKL) AXIAL HT FLUX, KW/CH2 
200. (HTRM) MAX FUEL DELTA T, DEG K
1.00 (HPI) PIPE EXTENSION; M

NOTE: OPTIONS ARE 1-CODE PT DESIGN, 2-SPECIFIED DESIGN
TYPE IN ANY OF FOLLOWING: DCORE(m) XREF(m) VNFT FIRST NPipe
NPtpe=210 STOP

210 (Npipe) NO. OF HEAT PIPES
SETA VC ALFA PKAVG SHIN DXMIN CORGAP ENDPipe END
0.100 0.050 0.600 1.500 0.050 0.080 0.015 0.005

TYPE: STOP, OR NEW CONSTANTS IE. VC0 0. PKAVG = 2, ETC ...
VC0 0.000 VCD = 0. STOP
SLD INDEX = 3
UNF = 0.100 0.200 0.300 0.400 0.500 0.600 0.700 0.800 0.900
DC0 0.299 0.363 0.412 0.475 0.568 0.694 0.961 1.754

LCH0 0.632 0.442 0.360 0.311 0.278 0.253 0.234 0.219 0.807

TYPE 00 OR START OVER

GO...

ADJUST Seta FOR 3.33% SWELLING
SETA = 0.1000 UNF = 0.3566 Vf = 0.6434 DX0 0.1000 DC0 0.3893

REACTIVITY CHANGES: DELTA K
BURN = 0.03138 EXP = 0.01612 SAFE = 0.02000 TOTAL = 0.06750

FUEL ELEMENT VOLUME FRACTIONS
CLADDING FUEL REGION HEAT PIPE WALL+ Wick VAPOR
0.7185 0.2815 0.1125 0.1629

HEXAGONAL CORNER CORRECTION FACTOR = 1.0825

NUMBER OF HEAT PIPES = 92.2398

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 210

TEMPERATURE SUMMARY; DEGREES KELVIN
MAX FUEL DELTA T =, 87.8
AVG DELTA T ACROSS HEAT PIPE WALL = 10.8
AVERAGE FUEL TEMP. = 1730.1
MAX FUEL TEMPERATURE = 1854.0

BURN FRACTION OF U235 = 0.0523
FISSION DENSITY (FISSIONS/CM**3) = 5.648E+20
FUEL SHELLING, VOLUME % = 3.10 x 3 = 9.3

REACTOR DIMENSIONS, METERS
0.3293 CORE DIAMETER
0.3293 CORE HEIGHT
0.6193 REACTOR DIAMETER
0.5993 REACTOR HEIGHT
0.1000 REFLECTOR THICKNESS
1.0000 PIPE LENGTH OUTSIDE REACTOR
1.4943 TOTAL HEAT PIPE LENGTH
1.5993 OVERALL REACTOR+HEAT PIPE LENGTH

FUEL ELEMENT DIMENSIONS, MM
25.52 WIDTH ACROSS HEX FLATS
26.80 EQUIV. FUEL ELEMENT DIA.
26.80 EQUIV. FUEL REGION O.D.
14.22 HEAT PIPE O.D.
11.01 VAPOR DIAMETER
95.26 VAPOR AREA, MM**2

REACTOR HEIGHTS, KILOGRAMS
316.6 FUEL; U235 MASS = 160.5
341.3 REFLECTOR
203.3 HEAT PIPES; WT/UNIT LENGTH (KG/M) = 136.03
33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)
62.6 SUPPORT STRUCTURE (7% OF REACTOR WT)

956.7 TOTAL REACTOR + HEAT PIPES

60.37 MW/MM**3, AVG. POWER IN FUELSPACE 3.52 KW/POWER PER HEF PIPE
99.98 MW/MM**2, HTPIPE AXIAL HT FLUX 0.707 MW/MM**2, HTPIPE RAD HTFLX

TYPE 50 OR END
PROD NO. 3 6-14-78 TYPE NEW INPUT! PR=1, KHP=2 ...STOP
STOP

1/ 4,000 (FR) REACTOR POWER, MW
1750. (THP) HEAT PIPE TEMPERATURES K
1850. (THP) HEAT PIPE TEMPERATURES K
3650. (TIME) LIFETIME DAYS
1.00 (SLD) CORE L/D RATIO
10.0 (vmetr) AXIAL HT FLUX, KW/CM2
200. (OFTMAX) MAX FUEL DELTA TIMES K
1.00 (HPL1) PIPE EXTENSION M

NOTE: OPTIONS ARE: 1-CODE PT DESIGN, 2-SPECIFIED DESIGN

TYPE IN ANY OF FOLLOWING: (CORE(R) XREF(M) VNF=0) BETA NP=PIPE ...STOP

NPipe = 264 STOP

264 (NPipe) NO. OF HEAT PIPES

BETA = 0.289 STOP

SLD INDEX = 3

G0...ADJUST BETA TO LIMIT INDICATED SWELLING TO 3.3% (IE 10% SWELL.)

BETA = 0.2890 VNF = 0.5331 VP = 0.4669 DX = 0.1000 DC = 0.5003

REACTIVITY CHANGES: DELTA K

BURN = 0.04075 EXP = 0.01612 SAFE = 0.02000 TOTAL = 0.07687

FUEL ELEMENT VOLUME FRACTIONS

CLADDING FUEL REGION HEAT PIPE WALL+THICK VAPOR

0.6594 0.3406 0.1363 0.2044

HEXAGONAL CORNER CORRECTION FACTOR = 1.1230

NUMBER OF HEAT PIPES = 123,4099

MINIMUM PRACTICAL (OR SPECIFIED) NUMBER OF HEAT PIPES = 264

TEMPERATURE SUMMARY: DEGREE KELVIN

MAXIMUM FUEL DELTA T = 93.5
AVERAGE FUEL DELTA T ACROSS HEAT PIPE WALL = 13.4
AVERAGE FUEL TEMPERATURE = 1794.5
MAXIMUM FUEL TEMPERATURE = 1863.5

BURN FRACTION OF U235 = 0.0679

FISSION DENSITY (FISSIONS/CM**3) = 5.794E+20

FUEL SWELLING, VOLUME % = 2.95%/0.05

REFLECTOR DIMENSIONS: METERS

FUEL ELEMENT DIMENSIONS: MM

0.5003 CORE DIAMETER

0.5003 CORE HEIGHT

0.7303 REACTOR DIAMETER

0.7103 REACTOR HEIGHT

0.1000 REFLECTOR THICKNESS

1.0000 PIPE LENGTH OUTSIDE REACTOR 151.58

1.6053 TOTAL HEAT PIPE LENGTH

1.7103 OVERALL REACTOR+HEAT PIPE LENGTH

REFLECTOR WEIGHTS: KILOGRAMS

487.7 FUEL, U235 MASS = 247.2
518.0 REFLECTOR

436.8 HEAT PIPES, WT/UNIT LENGTH (KG/M) = 272.12

33.0 CONTROL SYSTEM (ASSUME CONSTANT = 33 KG)

103.3 SUPPORT STRUCTURE (7% OF REACTOR WT)

1578.8 TOTAL REACTOR+HEAT PIPES

61.94 MW/HEAT P+AVG POWR IN FUELSPACE 15.15 KW/POWER PER HEAT PIPE

99.96 MW/HEAT P+HTPIPE AXIAL HT FLUX 0.834 MW/HEAT P+ HTFLUX