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The Scalability of OTR Space Nuclear Power Systems

Donald R. Gallup

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Sandia National Laboratories
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THE SCALABILITY OF OTR SPACE NUCLEAR POWER SYSTEMS

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ABSTRACT

Masses of the STAR-C power system and an optimized OTR power system versus power level are investigated. The impacts of key system parameters on system performance are also addressed. The STAR-C is mass competitive below about 15 kWe, but at higher power levels the scalability is relatively poor. An optimized OTR is the least massive space nuclear power system below 25 kWe, and scales well to 50 kWe. The system parameters that have a significant impact on the scalability of the STAR-C are core thermal flux, thermionic converter efficiency, and core length to diameter ratio. The emissivity of the core surface is shown to be a relatively unimportant parameter. For an optimized OTR power system, the most significant system parameter is the maximum allowable fuel temperature. It is also shown that if advanced radiation-hardened electronics are used in the satellite payload, a very large mass savings is realized.

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1.0 Introduction

For the past several years, the Air Force has been expressing an interest in space nuclear reactor power supplies for use with future satellites. The power range of interest to the Air Force is 5 to 40 kWe. As a result, there have been new power system concepts proposed by industry that provide viable alternatives to the SP-100 power system, which was originally intended for use at higher power levels, e.g., 100 kWe. One of the concepts that has received considerable attention is the STAR-C power system, which is being proposed by GA Technologies (GA). Due to the attention received by STAR-C, the Air Force Space Technology Center (AFSTC) requested Sandia National Laboratories to investigate the viability of out-of-core thermionic reactor (OTR) power systems. OTR is a generic term for a STAR-C type power system.

This report presents the results of a study on the optimization of OTR power systems. The three primary objectives of the study were (1) to determine how well an OTR can scale with power level, (2) to determine the impact of key system parameters on OTR system performance, and (3) to compare the system performance of an optimized OTR power system with that of the STAR-C power system on a consistent basis.

A general description of the STAR-C and OTR power systems is given in Sections 1.1 and 1.2, and Section 1.3 briefly discusses the system model used in this study. Chapter 2 discusses the scalability of the STAR-C power system and the impact of key system parameters on STAR-C. In Chapter 3 the scalability and key system parameters of an optimized OTR are discussed. Chapter 4 presents the conclusions of this study.

1.1 The STAR-C Power System

The STAR-C power system, which is a specific version of an OTR power system, is described in detail in References 1 and 2. The STAR-C power system (Figure 1.1) is unique in that it is a totally static power system. The power that is generated in the reactor core is radiated radially across a small vacuum gap to the hot shoes of the thermionic (TI) converters. The TI converters, which are integrated into the reflector, produce electrical power by emitting electrons from the converter emitter to the converter collector, which are separated by a voltage potential. The waste heat is removed from the converter collector by a heat pipe, and is carried to the waste heat radiator, which surrounds the reactor. The satellite payload is protected from radiation emitted from the reactor by a radiation shield comprised of ZrH_2 and LiH. Key system parameters for a 6 kWe STAR-C are given in Table 1.1.

The STAR-C reactor uses monolithic blocks of UC_2 fuel that sit in graphite trays (Figure 1.2). The thickness of the UC_2 is 1.6 cm and the ratio of the inner to outer fuel radius is 0.333. The diameter of the reactor core is either 26 or 42 cm; the diameter selected depends on the reactor power level. The core is built by stacking these trays on top of one another. Desired power and temperature profiles are obtained by varying the thickness of the graphite trays. The graphite trays are coated with NbC to prevent sublimation of the graphite and to retain the volatile fission products. The maximum temperature in the fuel is approximately 2300 K, and the temperature at the radial core surface is 2000 K. The thermal emissivity of the core surface is assumed to be 0.85.

The TI converter used in the STAR-C power system is based on the SET converter, which was developed in a solar power program in the 1960s (Figure 1.3). The approximate emitter and collector temperatures of the converter are 1850 and 1000K, respectively. The efficiency at the electrical leads of the converter is 14.1%. The waste heat produced by the converter is removed from the back side of the collector by an integral heat pipe. The heat is carried to the waste heat radiator, which surrounds the reactor, and radiated to space. The TI converters are integrated into the radial Be reflector, which surrounds the reactor core (Figure 1.1).

The satellite payload is protected from radiation emitted from the reactor by a radiation shield and a separation boom. The radiation shield is comprised of ZrH_2 and LiH. The ZrH_2 is used for shielding against gamma rays, and the LiH is for shielding against neutrons. For a given allowable total dose to the payload, the shield thickness and diameter, and thus mass, depend on the length of the separation boom. Power produced in the power system is carried down the boom by a transmission line, and then converted into the voltages required by the satellite by a power conversion system. (Note: The GA power system description stops at the back side of the shield; thus, the separation boom, transmission line, and power conditioning equipment are not included in their system description. It is included here to provide consistency with other power systems, e.g., the SP-100.)

1.2 The OTR Power System

Out-of-core thermionic reactor is a general name that can be given to the STAR-C power system. It comes from the fact that the power is generated by TI converters that are external to the reactor core. By using the more general name, design changes can be made to investigate the use of different technologies and to optimize the power system without confusing the reader concerning the GA design. The two primary changes that have been made for the studies presented later in this report are (1) the reactor core

dimensions are allowed to vary to obtain a minimum system mass, and (2) the thermionic converter used is based on data obtained from a ThermoElectron test converter (Figure 1.4) [3]. The system characteristics that are similar to the STAR-C include (1) the same fuel form, UC_2 in graphite trays, is used, (2) the same shield materials, LiH and ZrH_2 , are used, and (3) the same reflector material, Be, is used. The key system parameters for a 30 kWe OTR power system are given in Table 1.2. (In future work, other system features, e.g., fuel form, will be varied.)

1.3 OTR System Model

The results presented in this study were obtained using an OTR system model developed at Sandia [4,5,6]. This model can be used to represent either the STAR-C power system or an OTR power system. When an OTR power system is modeled, key system parameters are varied to obtain the optimal system design based on total power system mass. When the STAR-C is modeled, the system parameters defined by GA are used, e.g., a ratio of the inner to outer fuel radius of 0.333 is used.

Although the entire Sandia OTR model has not yet been fully documented, the reactor and shield portion of the model are well documented in Reference 4 and 5. A further indication of the level of detail the model contains can be obtained from the following considerations (1) the model contains over 2200 lines of FORTRAN coding and (2) almost 100 input parameters must be specified (Appendices A and B). An example output from the system model is given in Appendix C.

One note of caution about the mass values obtained using the Sandia OTR model is needed. Specifically, at the higher power levels, i.e., above about 30 kWe, the waste heat radiator becomes so large that it cannot be located above the radiation shield without making design changes, e.g., increasing the diameter of the shield. The impact of these design changes is not included in the system mass.

Table 1.1
Key System Parameters For A 6 kWe STAR-C
Power System (As Defined By Sandia)

System Parameter	Value
<hr/>	
<u>General</u>	
Net Electrical Power (kWe)	6
TI Converter Efficiency (%)	14.1
Net Electrical Efficiency (%)	12.2
<u>Temperatures (K)</u>	
Maximum Fuel	2290
Effective Core Surface	2000
TI Emitter	1863
TI Collector	1016
<u>Dimensions (cm)</u>	
Core Length	35.9
Core Diameter	26.0
Inner Fuel Diameter	8.0
Outer Fuel Diameter	24.0
<u>Masses (kg)</u>	
Reactor	455
Shield	389
Total System	1067

Table 1.2
Key System Parameters For A 30 kWe OTR Power System

System Parameter	Value
<hr/>	
<u>General</u>	
Net Electrical Power (kWe)	30
TI Converter Efficiency (%)	15.1
Net Electrical Efficiency (%)	13.1
<u>Temperatures (K)</u>	
Maximum Fuel	2300
Effective Core Surface	2112
TI Emitter	1900
TI Collector	1000
<u>Dimensions (cm)</u>	
Core Length	77.6
Core Diameter	33.7
Inner Fuel Diameter	25.3
Outer Fuel Diameter	31.4
<u>Masses (kg)</u>	
Reactor	1052
Shield	394
Total System	1867

Figure 1.1
The STAR-C Power System

Figure 1.2
The Fuel Form For STAR-C -- Monolithic
UC₂ In Graphite Trays

Figure 1.3
Schematic Diagram of a STAR-C Thermionic Converter

Figure 1.4
Theoretical Efficiency of a ThermoElectron
Converter -- No Lead Losses

2.0 Scalability of the STAR-C Power System

The Sandia OTR system model has been used to estimate the mass and impact of key system parameters on mass for the STAR-C power system. The mass estimates for the base case power systems are discussed in Section 2.1. A comparison of the Sandia mass estimates with the mass estimates that have been made by GA Technologies is made in Section 2.2. In Section 2.3 the significance of the assumed parameter values for the base case power systems discussed in Section 2.1 is addressed. This is done by varying the parameter values over a wide range and assessing the change in the power system mass estimate.

2.1 Sandia Mass Estimates for STAR-C

The Sandia OTR system model has been used to calculate the mass and other system parameters of the STAR-C concept as described by GA Technologies in References 1 and 2. The results of these mass calculations are given in Table 2.1 and plotted in Figure 2.1 as a function of power. Two sets of Sandia derived mass estimates are included. The first set is for reactor core dimensions as described by GA Technologies [1,2], i.e., the core diameter is either 26 cm or 42 cm and the ratio of the inner to outer fuel radius is 0.333, and this data is plotted as discrete points. The appropriate core diameter was selected based on two criteria (1) minimum system mass and (2) a maximum allowable core aspect ratio, i.e., core length to diameter ratio, of 3.0. The second set of data is for an optimal core geometry, i.e., the core diameter is sized to minimize shield mass and the ratio of the inner to outer fuel radius is minimized to reduce the mass of fuel required, and this data is plotted as a solid line. For this set of data, the core length to diameter ratio was not allowed to exceed 2.5. (Note: All of the mass estimates for radiation shields presented in this report assume that the diameter of the payload is 4 meters and that the permissible radiation dose to the payload is 0.5 Mrad and 10^{13} nvt over a 10 year period. Boom length is optimized based on mass.) The solid line in Figure 2.1 does not represent a fully optimized system, primarily because the core thermal flux is held at 15.3 W/cm^2 , which is the value derived from Reference 1. In Chapter 3, we will present Sandia's results for an OTR that is fully optimized to reduce power system mass.

As can be seen in Figure 2.1, it is important that the core dimensions be selected so as to minimize the power system mass as was done by Sandia. The power system mass can be reduced by as much as 20% by selecting the optimal core dimensions. The reason for the difference in mass between the two cases varies with power level. At 6 kWe, the reduction in mass is brought about primarily by a reduction in the mass of the radiation shield. This results from a

reduction in the diameter, and thus volume, of the shield--the optimized reactor core has a smaller diameter than the GA specified diameter. A comparison of the mass breakdowns for 6 kWe power systems calculated using each of the methods described above is given in Table 2.2. At 15 kWe, the largest contributor to mass reduction for the optimized core geometry is the mass of the reactor itself. The reduction in reactor mass is a result of two factors. First, the optimized reactor has a larger aspect ratio: 2.5 as compared to 1.3. Since both systems require the same amount of surface area to convert the heat produced in the core to electricity via the thermionic converters, the volume of the optimized core is smaller. Second the ratio of the inner to outer fuel radius is larger for the optimized core configuration: 0.72 as compared to 0.33. This results in a lower fraction of the core volume comprised of fuel, which has a much higher density than carbon, and so the average density of the core is smaller. The reduction in the radiation shield for the 15 kWe system with the optimal core dimensions is also significant. As was the case for the 6 kWe system, this is brought about by a reduction in the diameter, and thus volume, of the shield. A comparison of the mass breakdowns for the 15 kWe systems with an optimized core geometry and a 42 cm diameter are presented in Table 2.3.

2.2 Comparison of Sandia and GA Mass Estimates for STAR-C

The mass estimates for the STAR-C power system discussed above are higher than the mass estimates that have been made by GA Technologies [1,2]. A comparison of the Sandia and GA mass estimates for a 6 kWe power system is given in Table 2.4. (The Sandia mass estimate is for a reactor with a 26 cm diameter core. Also, the mass breakdown is different than that given in Tables 2.2 and 2.3, because GA has a different mass breakdown than Sandia.) The major differences in the two mass estimates are explained below.

The Sandia estimate for the reactor and thermionic converters is 25% higher than the GA estimate. This is brought about by the fact that GA does not include power losses in the transmission line and power conditioning system. As a result, GA uses a system efficiency of 13.5%, whereas Sandia calculates an efficiency of 12.2%. Another way of looking at this is that by the GA definition, the Sandia power system is actually a 6.8 kWe system. In either case, the Sandia reactor requires a larger length to produce the necessary power. This additional length results in additional mass. The GA mass estimate for the instrumentation and control (I&C) is about 100 kg lower than the Sandia estimate. This is a result of two factors. First, the GA mass estimate does not include instrumentation. Second, in the control system GA assumes the use of innovative control rod drives and Sandia assumes drives based on the technology being

developed in the SP-100 program. Sandia estimates the mass of the safety systems to be 59 kg. The safety systems include a re-entry heat shield and safety rods and drives. GA has no mass allocation for safety systems. The mass of the Sandia radiation shield is 28 kg less than the GA shield. This is due in part to the fact that the GA shield was for a payload diameter of 4.5 meters and the Sandia shield assumed a 4.0 meter diameter payload. Different shield thicknesses could also contribute to the mass difference. The mass estimates for the electrical subsystems is different, because the GA and Sandia definitions for this subsystem are different. GA only has one component in their estimate: a dc-dc amplifier that boosts the voltage before the power is transmitted down the boom. The Sandia electrical subsystem consists of electrical straps that connect the thermionic converters, a transmission line for carrying the power down the boom, a power conditioning system to convert the power to the proper voltages for a prototypic payload, and a radiator for the power conditioning equipment. The final reason for the large difference between the GA and Sandia mass estimates is that the Sandia estimate includes the mass of the boom that separates the reactor from the payload.

A calculation was made using the Sandia OTR model for a 6 kWe STAR-C and assuming an overall system efficiency of 13.5%, which corresponds to the value used by GA. When the masses of the power conditioning system and separation boom are ignored as was done by GA, the system mass is estimated to be 845 kg compared to 714 kg calculated by GA. In this very comparable situation, almost the entire difference can be attributed to the difference in the mass estimates for the I&C system. This discrepancy needs to be resolved.

2.3 Key System Parameters

There are several key system parameters that can have a significant impact on the masses of the STAR-C power systems that were presented in Section 2.1. Four of these parameters and their impact on the base case system masses are discussed below. The masses presented below are for optimal core dimensions as calculated by Sandia, i.e., they are variations of the mass estimates that produced the solid line in Figure 2.1.

2.3.1 Core Thermal Flux

One of the most important parameters in the design of the STAR-C power system is the core thermal flux, ϕ_{th} . This is particularly true for power levels above 8 to 10 kWe. The basis for the significance of the core thermal flux is as follows. Once the size of the reactor core is large enough to be above the criticality limit, its size becomes limited by thermal considerations. Specifically, the useful power

produced in the core must be radiated across a small gap to the hot shoe of the thermionic converter. If the electrical power flux across the TI converter is less than the core thermal flux, which will always be the case for a reasonable design, it can be shown that the required surface area of the core, A_{CS} is given by:

$$A_{CS} = \frac{P_e}{\eta_{TI} \phi_{th} \eta_e} \quad 2.1$$

where

ϕ_{th} = Core Thermal Flux (W/cm^2)

P_e = Electrical Power (W)

η_{TI} = Efficiency of the Thermionic Converters

η_e = Efficiency of the Electrical Subsystem

This equation shows that as the electrical power of the system increases, the core surface area increases. If the aspect ratio of the core, i.e., the ratio of the core length to diameter, is limited to a reasonable value, then the volume and mass of the core will increase with the core surface area. (The aspect ratio was limited to 2.5 for the calculations presented in this report.)

Figures 2.2 and 2.3 show how the mass of the STAR-C power system varies with core thermal flux for 10 and 30 kWe power levels, respectively. It should be noted that the value used for the base case is $15.3 W/cm^2$ and is noted on the figures by a solid dot. This value was calculated from data presented in Reference 1. For a 10 kWe STAR-C, the mass will significantly increase if the thermal flux falls below $15.3 W/cm^2$; the system mass increases by almost 15% if the flux drops to $12 W/cm^2$. Doubling the thermal flux to $30 W/cm^2$ decreases the total system mass by 15%. For a 30 kWe STAR-C, the system mass increases by 20% if the flux drops to $12 W/cm^2$; and if the flux is doubled to $30 W/cm^2$, the system mass drops by 32%. So at the higher power levels, it is more important to optimize this thermal flux.

2.3.2 Thermionic Converter Efficiency

The efficiency of the thermionic converter is another very important parameter for the STAR-C power system. As can be seen from Equation 2.1, it has the same relationship to the required core surface area as does the core thermal flux.

Figures 2.4 and 2.5 show how total system mass varies with converter efficiency for 10 and 30 kWe power systems, respectively. The base case efficiency is 14.1% [1,2], and is indicated on the figures by a solid dot. If the converter efficiency for a 10 kWe system drops to 12%, the system mass goes up by 11%. If the efficiency goes up to 16%, the system mass drops by 7%. For a 30 kWe STAR-C, the system mass goes up by 14% if the converter efficiency goes down to 12%, and the mass goes down by 10% if the converter efficiency increases to 16%. Again the effect is greater at higher power levels, but the mass decrease permitted by higher thermionic device efficiency is moderate.

2.3.3 Emissivity of the Core Surface

The emissivity of the core surface is another system parameter that can impact the mass of a STAR-C power system. It has inappropriately received a lot of attention as being a weak link in the STAR-C design. The core surface emissivity is an important parameter, because it impacts the core thermal flux:

$$\phi_{th} = \frac{\epsilon_{cs} \epsilon_{hs} \sigma (T_{cs}^4 - T_{hs}^4)}{\epsilon_{cs} + \epsilon_{hs} - \epsilon_{cs} \epsilon_{hs}} \quad 2.2$$

where

ϵ_{cs} = Emissivity of the Core Surface

ϵ_{hs} = Emissivity of the Hot Shoe of the TI Converter

T_{cs} = Temperature of the Core Surface (K)

T_{hs} = Temperature of the Hot Shoe of the TI Converter (K)

σ = Stefan-Boltzman Constant ($5.67 \times 10^{-12} \text{ W/cm}^2 \text{ K}^4$)

It should be noted from the above equation that the impact of hot shoe emissivity and core surface emissivity on thermal flux are identical. Figure 2.6 shows the significance of core surface emissivity on a 20 kWe STAR-C. The solid dot shows the base case: $\epsilon_{cs} = \epsilon_{hs} = 0.85$. The important point to be made from Figure 2.6 is that the core surface emissivity does not have a major impact on the mass of STAR-C; if the core surface and hot shoe emissivities both drop to 0.7, the mass of the power system will increase by only 6%.

Figure 2.6 was obtained using Equation 2.2 to calculate the core thermal flux, and the following (one-dimensional) equation to calculate the core surface temperature, T_{cs} :

$$T_{cs} = T_{fm} - \frac{q_v r_i^2}{4k_f} \left[\left(\frac{r_o}{r_i} \right)^2 - 2 \ln \left(\frac{r_o}{r_i} \right) - 1 \right] - \frac{q_v r_i^2}{2k_g} \left[\left(\frac{r_o}{r_i} \right)^2 - 1 \right] \ln \left(\frac{r_o + t_g}{r_o} \right) \quad 2.3$$

where

- T_{fm} = Maximum Fuel Temperature (K)
- q_v = Volumetric Heat Source in Fuel (W/cm^3)
- k_f = Thermal Conductivity of the Fuel Region (W/cmK)
- k_g = Thermal Conductivity of the Graphite (W/cmK)
- r_o = Outer Radius of the Fuel Ring (cm)
- r_i = Inner Radius of the Fuel Ring (cm)
- t_g = Thickness of the Graphite Ring Around the Fuel (cm)

The Sandia OTR system model uses Equations 2.2 and 2.3 to obtain the values of T_{cs} and ϕ_{th} that are used to size the reactor.

The key point to note about Equations 2.2 and 2.3 is that the thermal calculations for the STAR-C are based on a maximum fuel temperature of 2300 K (and a ratio of inner to outer fuel radius of 0.333). The significance of basing the thermal calculations on constant fuel dimensions and a maximum fuel temperature while allowing all other parameter to vary can be explained in the following simplistic manner. If there is a drop in the core surface emissivity, which will result in a drop in the core thermal flux (the thermal flux radiated from the core surface to the thermionic diode hot shoes), the reactor thermal power, i.e., the volumetric heat source, q_v , must be lowered to prevent over-heating because less heat is leaving the core. However, a smaller volumetric heat source results in an increase in the core surface temperature (Equation 2.3), and this increase in core surface temperature results in a higher core thermal flux (Equation 2.2). Thus, a drop in core emissivity will be compensated for by re-designing with an increase in the core surface temperature while keeping the maximum fuel temperature constant. For example, the base case 20 kWe STAR-C has the following operating parameters: $\epsilon_{cs} = \epsilon_{hs} = 0.85$, $\phi_{th} = 15.3 W/cm^2$, $q_v = 1.00$, $T_{cs} = 2000 K$, $T_{fm} = 2300 K$. If the core surface and hot shoe emissivities were both reduced to 0.70, then the system would

be redesigned with the following operating parameters: $\phi_{th}=13.8 \text{ W/cm}^2$, $q_v=0.90$, $T_{cs}=2032 \text{ K}$, $T_{fm}=2300 \text{ K}$. This 10% drop in the core thermal flux (and volumetric heat source) means that the core length must be increased by 11% to keep the output power constant at 20 kWe. This increase in reactor size and the concomitant increase in shield size result in a larger system mass; the mass increases from 1918 kg to 2038 kg. So the system can be designed to utilize lower core or hot shoe emissivities without severe mass penalties, and degradation of surface emissivity during operation only produces a minimal decrease in output power.

It should be noted that the reason the STAR-C power system was thought to be very sensitive to core surface emissivity is that previous calculations were performed assuming the core surface temperature was held at 2000 K rather than being calculated using Equation 2.3. Figure 2.7 shows the sensitivity of system mass for this case. If the core surface and hot shoe emissivities both drop to 0.7, the mass of the system increases by 22%.

2.3.4 Core Aspect Ratio

The core aspect ratio is a fourth parameter that can have a significant impact on the mass of a STAR-C power system. As was discussed in Section 2.2.1, the core aspect ratio has an impact on the core mass required to obtain the necessary core surface area. In addition, the aspect ratio also has an impact on the mass of the radiation shield--a small aspect ratio tends to increase the diameter of the shield. Figures 2.8 and 2.9 show the impact of aspect ratio on system mass for 10 and 30 kWe systems, respectively. (Unless otherwise stated, the maximum aspect ratio allowed in the calculations presented elsewhere in this report is 2.5, and this value is indicated in the figures by a solid dot. The value 2.5, although somewhat arbitrary, was selected as a maximum value based on the potential difficulties that could be encountered with core retention and the need to maintain a gap between the core and TI hot shoe surface. Figure 2.10 visually represents various aspect ratios.)

If the assumption that the aspect ratio can be 2.5 is optimistic and the actual maximum value is 2.0, then the mass of the 10 kWe system increases by 5% and the mass of the 30 kWe system increases by 7%. On the other hand, if the aspect ratio can be increased to 3.0, the masses of the 10 and 30 kWe systems decrease by 3% and 5%, respectively. A unique characteristic of Figure 2.8 is that as the aspect ratio of the 10 kWe system increases above 4.0, the mass of the power system increases. This can be attributed to the fact that the large aspect ratio causes the reactor mass to be driven by criticality concerns rather than by the core surface area.

Table 2.1
Sandia Mass Estimates For The STAR-C Power System

Power (kWe)	Mass (kg)	
	26 or 42 cm Core Diameter	Optimal Core Diameter
5	1013	904
6	1067	945
8	---	1077
10	1260	1203
15	1997	1590
20	2313	1918
30	2975	2639
40	(1)	3431
50	(1)	4245

(1) Core Aspect Ratio Exceeds 3.0 For A 42 cm Diameter Core

Table 2.2
Comparison Of Sandia Mass Estimates For A 6 kWe STAR-C
Power System For Various Core Diameters

Component	Mass (kg)	
	26 cm Core Diameter	19.9 cm Core Diameter
<u>Reactor</u>		
Fuel	88	76
Moderator	22	16
Structure	23	17
Reflector	108	103
Total	241	211
<u>Inst & Control</u>	138	131
<u>Safety Systems</u>		
Re-entry Shield	18	14
Rods & Drives	41	38
Total	59	52
<u>Shield</u>		
Neutron	134	105
Gamma	255	207
Total	389	312
<u>Thermionics</u>	35	35
<u>Electrical Subsystem</u>		
Power Cond	11	11
PC Radiator	3	3
PC Rad Shield	4	4
TI Straps	22	22
Trans Line	55	55
Total	96	96
<u>Radiator</u>	18	18
<u>Boom</u>	90	90
<u>Total System</u>	1067	945

Table 2.3
Comparison Of Sandia Mass Estimates For A 15 kWe STAR-C
Power System For Various Core Diameters

Component	Mass (kg)	
	42 cm Core Diameter	30.6 cm Core Diameter
<u>Reactor</u>		
Fuel	318	124
Moderator	104	84
Structure	98	66
Reflector	222	202
Total	743	478
<u>Inst & Control</u>	223	199
<u>Safety Systems</u>		
Re-entry Shield	33	22
Rods & Drives	65	59
Total	99	81
<u>Shield</u>		
Neutron	168	137
Gamma	304	191
Total	471	328
<u>Thermionics</u>	88	87
<u>Electrical Subsystem</u>		
Power Cond	23	25
PC Radiator	8	8
PC Rad Shield	4	4
TI Straps	55	36
Trans Line	76	136
Total	166	210
<u>Radiator</u>	46	46
<u>Boom</u>	<u>162</u>	<u>162</u>
<u>Total System</u>	1997	1590

Table 2.4
Comparison Of The Sandia And GA Mass Estimates
For A 6 kWe STAR-C Power System

Subsystem	Mass Estimate (kg)	
	Sandia	GA
Reactor and TI's	276	221
Instrumentation & Control	138	38
Safety	59	---
Radiation Shield	389	417
Electrical	96	5
Waste Heat Rejection	18	33
Separation Boom	90	---
Total	1067	714

Figure 2.1
Scalability of the STAR-C Power System With Power

Figure 2.2
Impact of Core Thermal Flux on the
Mass of a 10 kWe STAR-C

Figure 2.3
Impact of Core Thermal Flux on the
Mass of a 30 kWe STAR-C

Figure 2.4
Impact of TI Converter Efficiency on the
Mass of a 10 kWe STAR-C

Figure 2.5
Impact of TI Converter Efficiency on the
Mass of a 30 kWe STAR-C

Figure 2.6
Impact of Core Surface Emissivity on the
Mass of a 20 kWe STAR-C

Figure 2.7
Impact of Core Surface Emissivity on the Mass of a
20 kWe STAR-C Using the Wrong Approach,
i.e., $T_{cs} = 2000$ K

Figure 2.8
Impact of Core Aspect Ratio on the
Mass of a 10 kWe STAR-C

Figure 2.9
Impact of Core Aspect Ratio on the
Mass of a 30 kWe STAR-C

Figure 2.10
Comparison of Aspect Ratios

3.0 Scalability of the OTR Power System

The Sandia OTR system model was used to estimate the mass of a fully optimized OTR power system; one not restricted to a core thermal flux of 15.3 W/cm^2 as in Chapter 2. As stated in Section 1.2, the two major differences between STAR-C and OTR are (1) the reactor core dimensions are allowed to vary to obtain a minimum mass, and (2) the thermionic converter used is based on data obtained from a ThermoElectron test converter [3]. The fully optimized OTR mass estimates are discussed in Section 3.1. In Section 3.2, the significance of the assumed parameter values for the base case OTR power systems discussed in Section 3.1 is addressed. This is done by varying the parameter values over a wide range and assessing the change in the power system mass estimate. The impact of system design changes is discussed in Section 3.3.

3.1 Mass Estimates for OTR Power Systems

The Sandia OTR system model has been used to calculate the mass of a fully optimized OTR power system. The results of these calculations are given in Table 3.1 and plotted in Figure 3.1 as a function of power. Figure 3.1 also includes the Sandia mass estimates for the STAR-C power system for comparison. As this figure shows, optimization of an OTR power system with respect to mass can result in significant improvements over STAR-C as power levels increase. At 30 kWe, the STAR-C power system mass is 41% higher than the mass of the OTR power system.

It should be noted that the reactor core geometry, i.e., fuel tray dimensions, is optimized for each power level in Figure 3.1. This approach is appropriate since no OTR power system has been built. However, when the second OTR system is designed, the minimal cost approach may be to use the same core diameter as was used for the first power system. This could be the case when there is a small, i.e., <20%, change in system power, and would result in a power system mass higher than that indicated in Figure 3.1.

The primary reason that the system mass is improved by such a large amount at the higher power levels is that the thermal flux can be increased significantly with the proper core design. A second reason the mass decreases is that the use of the ThermoElectron TI converter increases system efficiency somewhat. Both of these factors reduce the required core surface area (Equation 2.1) and thus the power system mass. For the 30 kWe OTR power system, the core thermal flux is 25 W/cm^2 . The core thermal flux for the STAR-C is 15.3 W/cm^2 . The TI converter efficiency for the OTR is 15.1%, compared to 14.1% for STAR-C.

The large increase in the core thermal flux that is obtained for the OTR power system results from improvements in the reactor core dimensions. Specifically, as the ratio of the inner to outer fuel radius increases, the temperature drop across the core decreases (Equation 2.3). Therefore, with a given maximum fuel temperature, the core surface temperature increases as the ratio of the inner to outer fuel radius increases. (Note: The derivative of Equation 2.3 with respect to the ratio of the fuel inner to outer radius, i.e., r_i/r_o , is positive, and so as r_i/r_o increases the core surface temperature, T_{cs} , increases.) This higher core surface temperature results in a higher core thermal flux (Equation 2.2).

3.2 Key System Parameters for OTRs

There are several key system parameters that can have a significant impact on the mass of the OTR power system. Five of these parameters and their impact on the base case system masses are discussed below. The first four are parameters that impact system mass through their impact on core thermal flux and TI converter efficiency. The fifth parameter investigated is core aspect ratio.

3.2.1 Emissivity of the Core Surface

The emissivity of the core surface (and TI converter hot shoe) is important to the performance of an OTR, because it impacts the core thermal flux (Equation 2.2) and core thermal flux impacts the reactor core surface area (Equation 2.1). However, if the core surface temperature is calculated based on a maximum fuel temperature (Equation 2.3), then if the design value for emissivity is decreased, the core design can be changed as described in Section 2.3.3 to keep the design output power constant. Figure 3.2 shows how the OTR system mass varies as a function of core surface emissivity for a 20 kWe power system. This figure shows that a drop in the emissivities of the core surface and TI converter hot shoe do not have a large impact on system mass. If these emissivities drop from 0.85 to 0.70, the system mass increases by only 6%.

3.2.2 Maximum Fuel Temperature

The maximum fuel temperature has a significant impact on the mass of a OTR power system as the power level increases (Figure 3.3). Maximum fuel temperature is important, because of its impact on the core surface temperature (Equation 2.3), which impacts the core thermal flux and core surface area (Equations 2.2 and 2.1). For a 30 kWe OTR power system, the mass increases by 14% if the maximum fuel temperature drops from 2300 K to 2200 K and increases by 36% if it drops to 2100 K. On the other hand, the system mass decreases by 11% if the maximum fuel temperature can be increased to 2400 K.

3.2.3 TI Converter Emitter Temperature

The temperature of the thermionic converter emitter, T_e , can play an important role in the performance of an OTR power system, because it impacts both the converter efficiency (Figure 1.4) and the core thermal flux through its impact on the converter hot shoe temperature (Equation 2.2). (Note: $T_{hs}=T_e+k\phi_{th}$, where k is a positive constant.) Specifically, as the emitter temperature increases, the converter efficiency increases and the thermal flux decreases. These two effects tend to counter one another as can be seen in Equation 2.1.

The impact of emitter temperature on the mass of a 20 kWe OTR power system is presented in Figure 3.4. As can be seen, the consequence of decreasing the emitter temperature from its optimum of 2000 K to 1850 K is very minor--power system mass increases by only 1%. Decreasing the emitter temperature to 1800 K increases system mass by 4%.

3.2.4 Thermal Conductivity of Graphite

The thermal conductivity of graphite, k_g , is important in the design of an OTR, because it has an impact on the temperature of the core surface (Equation 2.3). Figure 3.5 shows the impact of the thermal conductivity on the mass of a 20 kWe OTR power system. As is expected, as the thermal conductivity increases, the system mass decreases somewhat. Increasing the conductivity from 40 to 70 W/mK reduces the system mass by 6%.

3.2.5 Core Aspect Ratio

As was mentioned in Section 2.3.4, the core aspect ratio is an important parameter in OTR design, because of its impact on the core mass required to obtain the necessary core surface area and on the size of the radiation shield. Figure 3.6 shows the impact of core aspect ratio on the mass of a 30 kWe OTR power system. If the aspect ratio can be increased from 2.5 to 3.0, the system mass decreases by 2%. On the other hand, if the ratio drops to 2.0, the mass increases by 4%. These changes are smaller than the changes for a 30 kWe STAR-C (Figure 2.10). This is because the OTR power system has been optimized and as a result there is less room for improvement.

3.3 OTR Power System Design Changes

Along with investigating the impact of key system parameters on OTR power system mass, the impacts of two system design changes have been investigated. These design changes are (1) changing the fuel form to a particle fuel and (2) assuming that electronics that should be available in 1995 will be used in the payload. These design changes are discussed below.

3.3.1 Particle Fuel

The fuel form used in all of the calculations so far has been monolithic blocks of UC_2 in graphite trays (Figure 1.2). If the power system is required to retain all fission products, then it will be necessary to either design an elaborate system for capturing the gaseous and volatile fission products or to change to a fuel form that retains all fission products. For the purposes of this investigation, it was assumed that a triso-type fuel particle that would retain fission products could be manufactured. First order calculations were used to determine the dimensions of the particle; the UC_2 fuel kernel has a radius of 200 μm , the porous graphite layer around the UC_2 has a thickness of 50 μm , and the ZrC coating over the graphite has a thickness of 25 μm . It was further assumed that the particles could be packed in graphite so as to comprise 55% of the fuel volume. The final assumptions made were that the thermal conductivity and maximum temperature of this fuel was the same as for the base case fuel. (Note: The particle fuel described here is purely hypothetical. Fuel testing would be required to determine if fission products could be retained for 10 years at the appropriate operating conditions. The above fuel description has been made so that illustrative calculations could be performed.)

Figure 3.7 shows the impact of changing from a monolithic fuel to a particle fuel. The mass of an OTR system with particle fuel is always greater under the assumptions made for this analysis. This can be explained as follows. As has been discussed previously, the mass of an OTR power system is minimized by making the ratio of the inner to outer fuel diameter a minimum. Since the UC_2 fuel density is lower for our hypothetical particle fuel by about a factor of 2.0, a larger ratio of inner to outer fuel diameter is required to achieve criticality. For example, for a 20 kWe power system, this ratio changes from 0.60 to 0.51 when going from monolithic to particle fuel. Under the assumptions that the maximum fuel temperature and fuel thermal conductivity are the same for the two fuel types, this results in a lower core surface temperature for the particle fuel (Equation 2.3). This results in a lower thermal flux and larger core surface area (Equations 2.2 and 2.1).

Two factors must be considered before the conclusion can be reached that an OTR power system will always be more massive when particle fuel is used. First, it is possible that the maximum fuel temperature for particle fuel is higher than that of monolithic fuel. And second, the OTR system code does not include a mass for a fission product trapping system. It should be noted that a fission product trapping system may prevent the use of a central control rod if it were needed for safety purposes. Also, a fission product

trapping system may preclude the use of a movable upper reflector as a safety feature.

3.3.2 Advanced Rad-Hard Electronics

Under the current political climate in the U.S., it is doubtful that a space nuclear power system will be required before about 2005. If this is the case, it is reasonable to assume that 1995 electronics will be used in the power system and payload. These electronics could be much harder to radiation than current electronics. The Weapons Laboratory currently has a program in place that should result in space qualified integrated circuits and memory chips that will have hardness values of 100 Mrad gamma and 10^{15} nvt neutrons [7,8,9,10]. This is substantially higher than the 0.5 Mrad and 10^{13} nvt used in this report. If a similar program were in place to develop power electronics that could withstand the higher radiation levels as well as single event burn-out, which can be induced by cosmic radiation, a substantial mass savings could be realized for space nuclear power systems. It should be noted, however, that the technical issues associated with hardening high voltage power electronics will be more difficult to solve than those associated with lower voltage integrated circuits and memory chips [10]. This is an area where a research program could have a high pay-off.

Figure 3.8 compares the masses of OTR power systems with current and advanced electronics for various power levels. Significant mass savings are realized when the radiation hardness of the electronics increases by two orders of magnitude. At 10 kWe the power system mass decreases by 26%, and at 30 kWe the power system mass decreases by 21%. At the same time, the length of the separation boom decreases; for the 30 kWe system the length drops from 20 m to 7 m with the increase in radiation hardness of the electronics.

Table 3.1
Sandia Mass Estimates For An
Optimized OTR Power System

Power (kWe)	Mass (kg)
5	861
6	909
8	981
10	1055
15	1292
20	1493
30	1867
40	2249
50	2745

Figure 3.1
Scalability of the OTR and STAR-C Power Systems

Figure 3.2
Impact of Core Surface Emissivity on the
Mass of a 20 kWe OTR

Figure 3.3
Impact of Maximum Fuel Temperature on the
Scalability of OTR Power Systems

Figure 3.4
Impact of TI Converter Emitter Temperature on the
Mass of a 20 kWe OTR

Figure 3.5
Impact of Graphite Thermal Conductivity on the
Mass of a 20 kWe OTR

Figure 3.6
Impact of Core Aspect Ratio on the
Mass of a 30 kWe OTR

Figure 3.7
Impact of a Particle Fuel on the Scalability of
Power Systems

Figure 3.8
Impact of Improved Rad-Hard Electronics on the
Scalability of an OTR Power System

4.0 Conclusions

The objectives of this work were (1) to determine how well an OTR can scale with power level, (2) to determine the impact of key system parameters on OTR system performance, and (3) to compare the system performance of an optimized OTR power system with that of the STAR-C power system on a consistent basis.

The ability of an OTR power system to scale with power level is shown in Figure 4.1 [6]. This figure compares the scalability of STAR-C and OTR power systems with other nuclear power system options, e.g., the innovative SP-100, on a consistent basis. The mass estimates for the other power systems were obtained with power system codes developed at Sandia that are similar in nature to the OTR power system code. These codes will be documented in Reference 6. Figure 4.1 shows that an optimized OTR power system is the least massive nuclear power system up to about 25 kWe and that it is less massive than both the SP-100 and innovative SP-100 at all power levels up to 50 kWe, which is about as large a power level as can be obtained with a single OTR. The one near-term power system that appears lighter than an OTR between 25 and 50 kWe is the SP-100 reactor with a Brayton conversion system. (Note: The SP-100/Stirling system shown in Figure 4.1 assumes the use of refractory metals, which means that it, along with the SP-100/Rankine system, will not be available without several extra years of technology development. An SP-100/Stirling system using superalloys would be a near-term system that might be lighter than an OTR in the 25 to 50 kWe power range.)

The system parameters that can have a significant impact on the scalability of an OTR power system are the aspect ratio of the core and those parameters that impact TI converter efficiency and core thermal flux. The aspect ratio is important because it impacts the core volume and the diameter of the radiation shield. TI converter efficiency and core thermal flux are important because they determine the required core surface area for power systems above about 8 kWe (Equation 2.1). For the work performed here, it was assumed that the maximum core aspect ratio is 2.5. If the aspect ratio must be reduced, the system mass increases. This effect is more pronounced as the power level increases. Paradoxically, the parameters such as emitter temperature that effect TI converter efficiency and core thermal flux have a smaller than expected effect on OTR power system mass. This is because a change in one parameter can be compensated for by changes in other parameters.

Comparisons of an optimized OTR power system with the STAR-C power system are given in Figures 3.1 and 4.1. These figures show that an optimized OTR scales better with power level than the STAR-C at all power levels, and this difference becomes significant at about 15 kWe. At 30 kWe, the STAR-C system mass is 41% higher than the OTR power system mass. A major consequence of the relatively poor STAR-C scalability is that it does not compare favorably with the innovative SP-100 above 15 kWe. There are two major reasons that the STAR-C does not scale well with power level. First, GA chose to allow only two core diameters, 26 and 42 cm, rather than optimizing the core diameter (and aspect ratio) for each power level. As a result, the reactor and shield masses are higher than they need to be. Second, GA chose to set the inner to outer fuel diameter to 0.333 for all reactor designs rather than to maximize this ratio. As a result, the maximum core surface temperature for a STAR-C power system is about 2000 K. This is based on a maximum fuel temperature of 2300 K. If the inner to outer fuel diameter ratio is maximized, the core surface temperature can be increased (Equation 2.3). (Many of the optimized OTR power systems had core surface temperatures of about 2100 K.) This results in a higher thermal flux (Equation 2.2), which reduces the required core surface area (Equation 2.1).

Figure 4.1
Comparison of the Scalability of OTR and STAR-C
Power Systems With Other Space Nuclear Power Systems

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10. William Dawes, Sandia National Laboratories, private communications, November 10, 1989.

**Appendix A: Input Parameters for the
Sandia OTR Systems Model**

```

*
*
* THE REQUIRED INPUT DATA FOR THE REACTOR ARE:
*
*   TITLE = TITLE OF THE CASE BEING EVALUATED (A80 FORMAT)
*
*   P = REACTOR POWER (kWe)
*
*   TIME = MISSION LIFETIME (YEARS)
*
*   ETH = THERMAL EFFICIENCY OF THE POWER SYSTEM, I.E., FRACTION OF THE
*         CORE THERMAL POWER GOING TO THE TI DEVICES
*
*   ENR = FRACTIONAL ENRICHMENT OF THE U-235 FUEL
*
*   BETA = FRACTIONAL BURNUP LIMIT
*
*   UR = SPECIFIC MASS OF THE WASTE HEAT RADIATOR RADIATOR (kg/sqm)
*
*   EPSRAD = EMISSIVITY OF THE WASTE HEAT RADIATOR
*
*   AMIN = MINIMUM LENGTH TO DIAMETER RATIO FOR THE CORE
*
*   AMAX = MAXIMUM LENGTH TO DIAMETER RATIO FOR THE CORE
*
*   NA = NUMBER OF LENGTH TO DIAMETER RATIOS TO BE CONSIDERED
*
*   BMIN = MINIMUM RATIO OF FUEL INSIDE DIAMETER TO CORE OUTER DIAMETER
*
*   BMAX = MAXIMUM RATIO OF FUEL INSIDE DIAMETER TO CORE OUTER DIAMETER
*
*   NB = NUMBER OF FUEL TO CORE RATIOS TO BE CONSIDERED
*
*   ISTARC = 0, CORE GEOMETRY IS SET BY AMIN, AMAX, BMIN, AND BMAX AND THE
*            SANDIA CORE THERMAL MODEL IS USED
*           = 1, THE STAR-C POWER SYSTEM AS DESCRIBED BY GA TECHNOLOGIES IS
*            MODELED (ETI=.141, PHITMIN=15.3, ETC)
*           = 2, THE GA STAR-C CORE GEOMETRY IS MODELED; THE GA THERMAL MODEL
*            IS USED WITH THE EXCEPTION THAT THE INPUT VALUES FOR EPSC AND
*            EPSHS ARE USED; THE TI DIODE INPUT PARAMETERS FOR ITI=1 ARE USED
*           = 3, CORE GEOMETRY IS SET BY AMIN, AMAX, BMIN, AND BMAX; THE GA
*            THERMAL MODEL IS USED; INPUT VALUES FOR EPSC AND EPSHS ARE
*            USED; THE CORE SURFACE TEMPERATURE IS SET AT 2000K; STAR-C
*            TI DIODE PARAMETERS ARE USED
*           = 4, CORE GEOMETRY IS SET BY AMIN, AMAX, BMIN, AND BMAX; THE
*            GA CORE THERMAL MODEL IS USED; THE INPUT VALUES FOR EPSC AND
*            EPSHS ARE USED; STAR-C TI DIODE PARAMETERS ARE USED
*
*   Z = RATIO OF FUEL OUTER DIAMETER TO THE CORE TOTAL DIAMETER
*
*   CM = CRITICAL MASS CORRECTION FACTOR
*
*   VFFF = VOLUME FRACTION OF FUEL IN THE FUEL IN THE FUEL ANNULUS
*
*   VFFM = VOLUME FRACTION OF MODERATOR IN THE FUEL ANNULUS
*
*   RHOF = FUEL DENSITY (g/cc)
*
*   RHOM = MODERATOR DENSITY (g/cc)
*

```

```

*      AWM = MODERATOR ATOMIC WEIGHT
*
*      D1 = CONSTANT INSTRUMENTATION AND CONTROL MASS (kg)
*
*      D2 = PROPORTIONALITY CONSTANT FOR CONTROL MASS (kg/sqm)
*
*      D3 = PROPORTIONALITY CONSTANT FOR CABLE MASS (kg/m)
*
*      TFMAX = MAXIMUM TEMPERATURE OF FUEL (K)
*
*      EPSC = EMISSIVITY OF THE CORE SURFACE
*
*      EPSHS = EMISSIVITY OF THE HOT SHOE OF THE THERMIONIC ELEMENTS
*
*      PF = PEAK/AVERAGE CORE POWER
*
*      KF = FUEL REGION THERMAL CONDUCTIVITY (W/mK)
*
*      KG = GRAPHITE THERMAL CONDUCTIVITY (W/mK)
*
*      FS= STRUCTURE VOLUME FRACTION
*
*      RHOS = STRUCTURAL DENSITY (g/cc)
*
*      T = REFLECTOR THICKNESS (cm)
*
*      RHORF = REFLECTOR DENSITY (g/cc)
*
*      IHS = 0, NO LOWER RE-ENTRY HEAT SHIELD
*           1, LOWER RE-ENTRY HEAT SHIELD REQUIRED
*
*****
*
*      THE REQUIRED INPUT DATA FOR THE SHIELD ARE:
*
*      DN = NEUTRON DOSE LIMIT FOR THE PAYLOAD (nvt)
*
*      DG = GAMMA DOSE LIMIT FOR THE PAYLOAD (rad)
*
*      RP = PAYLOAD SEPARATION DISTANCE (m)
*
*      DPAY = DIAMETER OF PAYLOAD (m)
*
*      CHAMIN = MINIMUM CONE HALF ANGLE FOR THE SHIELD
*
*      TGMIN = MINIMUM GAMMA SHIELD THICKNESS (cm)
*
*      TGMAX = MAXIMUM GAMMA SHIELD THICKNESS (cm)
*
*      NG = NUMBER OF GAMMA SHIELD THICKNESSES CONSIDERED
*
*      CNS = CORRECTION FACTOR FOR THE NEUTRON SHIELD THICKNESS
*
*      CGS = CORRECTION FACTOR FOR THE GAMMA SHIELD THICKNESS
*
*      FBM = BOOM MASS CONSTANT (kg/m)
*
*****
*
*      THE INPUT DATA REQUIRED FOR THE THERMIONIC DEVICES ARE:

```

```

*
*   ITI = 1, ALL THERMIONIC OPERATING DATA IS INPUT
*   = 2, THERMIONIC DIODE IS BASED ON THE RASOR P-6 DIODE, WHICH HAS
*   A DUPLEX TUNGSTEN EMITTER AND NIOBIUM COLLECTOR
*   = 3, THERMIONIC DIODE IS BASED ON THE THERMOELECTRON DATA, WHICH
*   IS FOR A DUPLEX TUNGSTEN EMITTER AND MOLYBDENUM COLLECTOR
*
*   ETI = EFFICIENCY OF THE THERMIONIC DEVICES (ONLY USED IF ITI.LE.1)
*
*   PHITI = POWER DENSITY OF THE THERMIONIC DEVICES (W/sqcm) (ONLY USED IF
*   ITI.LE.1)
*
*   AE = AREA OF THE EMITTER OF THE TI DEVICE (sqcm)
*
*   PHITMIN = MINIMUM THERMAL FLUX EMITTED BY THE REACTOR CORE (W/sqcm)
*
*   PHITMAX = MAXIMUM THERMAL FLUX EMITTED BY THE REACTOR CORE (W/sqcm)
*
*   NPHIT = NUMBER OF CORE THERMAL FLUXES TO BE CONSIDERED
*
*   UTI = MASS OF AN INDIVIDUAL TI DEVICE (kg)
*
*   TEMIN = MINIMUM EMITTER TEMPERATURE TO BE CONSIDERED (K)
*
*   TEMAX = MAXIMUM EMITTER TEMPERATURE TO BE CONSIDERED (K)
*
*   NTE = NUMBER OF EMITTER TEMPERATURES TO BE CONSIDERED
*
*   TCMIN = MINIMUM COLLECTOR TEMPERATURE TO BE CONSIDERED (K)
*
*   TCMAX = MAXIMUM COLLECTOR TEMPERATURE TO BE CONSIDERED (K)
*
*   NTC = NUMBER OF COLLECTOR TEMPERATURES TO BE CONSIDERED
*
*   VEMIN = MINIMUM ELECTRODE VOLTAGE TO BE CONSIDERED (V)
*
*   VEMAX = MAXIMUM ELECTRODE VOLTAGE TO BE CONSIDERED (V)
*
*   NVE = NUMBER OF ELECTRODE VOLTAGES TO BE CONSIDERED
*
*   EL = ELECTRICAL EFFICIENCY OF THE DIODE LEADS (%) (NOT USED IF ITI.LE.1)
*
*   FPLL = FRACTIONAL THERMAL POWER LOSS DOWN THE LEADS (NOT USED IF ITI.LE.1)
*
*   EPSE = EFFECTIVE THERMAL EMISSIVITY BETWEEN THE ELECTRODES (NOT USED IF
*   ITI.LE.1)
*
*   VTI = OUTPUT VOLTAGE AT THE LEADS OF THE TI DEVICES (V) (ONLY USED IF
*   ITI.LE.1)
*
*   REDTI = REDUNDANCY IN THERMIONICS (%)
*
*   NPARMIN = MINIMUM NUMBER OF TI ELEMENTS TO BE CONNECTED IN PARALLEL
*
*   ESTRAP = FRACTIONAL EFFICIENCY OF THE ELECTRICAL STRAPS CONNECTING THE
*   TI DIODES
*
*   RHOSTR = DENSITY OF THE STRAP MATERIAL (g/cc)
*
*   RS = RESISTIVITY OF THE STRAP (ohm*m)

```

```

*
*   RST = TEMPERATURE COEFFICIENT OF RESISTIVITY OF THE STRAP (per K)
*
*   TSR = TEMPERATURE AT WHICH 'RS' APPLIES (K)
*
*   EMS = EMISSIVITY OF STRAP
*
* *****
*
* THE INPUT DATA REQUIRED FOR THE POWER CONDITIONING SYSTEM ARE:
*
*   EPC = EFFICIENCY OF THE POWER CONDITION EQUIPMENT
*
*   IPC = 0, POWER CONDITIONING AGAINST THE SHIELD
*         = 1, POWER CONDITIONING AT THE END OF THE BOOM
*
*   NV = NUMBER OF VOLTAGES DOWN THE BOOM (ONLY USED IF IPC=0)
*
*   VB(I) = BOOM VOLTAGE (V). IF IPC=0, NV VALUES ARE REQUIRED.
*           IF IPC=1 AND VB(1)=0.0, VB(1) WILL BE DETERMINED BY THE CODE.
*
*   VP(I) = FRACTION OF POWER AT VOLTAGE VB(I). IF IPC=0, NV VALUES ARE
*           REQUIRED. IF IPC=1, THE CODE WILL SET VP(1)=1, BUT A VALUE
*           MUST BE SUPPLIED.
*
*   T1 = INITIAL ESTIMATE OF TRANSMISSION LINE TEMPERATURE (K)
*
*   RC = TRANSMISSION LINE CONDUCTOR RESISTIVITY (ohm*m)
*
*   RT = TRANSMISSION LINE CONDUCTOR RESISTIVITY COEFFICIENT (per K)
*
*   RHOC = DENSITY OF CONDUCTOR MATERIAL (g/cc)
*
*   REDC = CABLE REDUNDANCY IN TRANSMISSION LINE (%)
*
*   NCMIN = MINIMUM NUMBER OF WIRES IN CABLE
*
*   NCMAX = MAXIMUM NUMBER OF WIRES IN CABLE
*
*   DI = DIELECTRIC STRENGTH OF THE INSULATION (V/mm)
*
*   RHOI = DENSITY OF THE INSULATION MATERIAL (g/cc)
*
*   PFC = PACKING FACTOR OF THE CONDUCTOR
*
*   PPL = PERCENT POWER LOSS ALLOWED IN EACH TRANSMISSION LINE (%)
*
*   NVPC = NUMBER OF VOLTAGES OUT OF THE PC SUBSYSTEM. IF NV IS GREATER
*          THAN 1 AND NVPC IS GREATER THAN 1, THEN NVPC MUST EQUAL NV.
*
*   VPCO(I) = VOLTAGES OUT OF THE PC SUBSYSTEM (V). NVPC VALUES REQUIRED.
*             IF NV AND NVPC BOTH ARE GREATER THAN 1, THEN VPCO(I) MUST
*             BE WITHIN 1 V OF VB(I)
*
*   VPPC(I) = FRACTIONAL POWER AT VPCO(I). NVPC VALUES REQUIRED. IF NV
*             AND NVPC BOTH ARE GREATER THAN 1, THEN VPPC(I) MUST BE
*             WITHIN 0.05 OF VP(I).
*

```

* MRLFLT = MASS OF RELAY AND FILTER WITHOUT CONVERTER (kg)
*
* MCTRL = MASS OF CONTROL ELECTRONICS (kg)
*
* SSWIT = SPECIFIC MASS OF POWER DISTRIBUTION SWITCH (kg/kW)
*
* VMOD = VOLUME OF PC ELECTRONICS MODULE (cc/kW)
*
* UPCRAD = SPECIFIC MASS OF THE POWER CONDITIONING RADIATOR (kg/sqm)
*
* UPCSHLD = SPECIFIC MASS OF THE POWER CONDITIONING RADIATION SHIELD (g/sqcm)
*
* REDPC = REDUNDANCY IN POWER CONDITIONING (%)
*

**Appendix B: Example Input for the
Sandia OTR Systems Model**

30 kWe OTR, Base Case (Nov. 30, 1989)

30.	P
10.	TIME
.96	ETH
.97	ENR
0.01	BETA
20.	UR
0.85	EPSRAD
2.0 2.5 6	AMIN,AMAX,NA
.60 .80 9	BMIN,BMAX,NB
0	ISTARC
.925	Z
1.10	CM
.50	VFFF
.50	VFFM
11.8	RHOF
1.85	RHOM
12.	AWM
79.	D1
707.	D2
0.9	D3
2300.	TFMAX
0.85	EPSC
0.85	EPSHS
1.2	PF
35.	KF
40.	KG
0.	FS
0.00	RHOS
10.	T
1.47	RHORF
0	IHS
1.0E13	DN
5.0E5	DG
20.0	RP
4.0	DPAY
0.0	CHAMIN
10.0 20.0 11	TGMIN,TGMAX,NG
1.00	CNS
1.00	CGS
9.	FBM
3	ITI
.141	ETI
8.5	PHITI
4.9	AE
17.5 32.5 7	PHITMIN,PHITMAX,NPHIT
.2	UTI
1850. 2000. 4	TEMIN,TEMAX,NTE
1000. 1000. 1	TCMIN,TCMAX,NTC
.600 1.00 9	VEMIN,VEMAX,NVE
98.0	EL
0.05	FPPL
0.15	EPSE
.67	VTI
5.	REDTI
8	NPARMIN
.9700	ESTRAP
18.5	RHOSTR
2.32E-5	RS
.00205	RST

900.	TSR
.75	EMS
0.91	EPC
1	IPC
1	NV
00.	VB(.)
1.	VP(.)
300.	T1
2.65E-8	RC
4.29E-3	RT
2.7	RHOC
10.0	REDC
10	NCMIN
50	NCMAX
2000.	DI
2.5	RHOI
1.2	PFC
1.5	PPL
3	NVPC
5. 28. 100.	VPCO(I)
.15 .55 .30	VPPC(I)
.09	MRLFLT
.8	MCTRL
.06	SSWIT
300.	VMOD
7.5	UPCRAD
4.0	UPCSHLD
10.	REDPC

**Appendix C: Example Output from the
Sandia OTR Systems Model**

30 kWe OTR, Base Case (Nov. 30, 1989)

REACTOR INPUT DATA

30.0 P, POWER (KWE)
10.0 TIME, OPERATION TIME (YEARS)
0.960 ETH, THERMAL EFFICIENCY OF THE POWER SYSTEM
0.970 ENR, FRACTIONAL ENRICHMENT
0.0100 BETA, FRACTIONAL BURNUP LIMIT
20.00 UR, MASS TO POWER RATIO FOR RADIATOR (KG/SQM)
0.85 EPSRAD, RADIATOR EMISSIVITY
2.00 AMIN, MIN LENGTH TO DIAMETER RATIO
2.50 AMAX, MAX LENGTH TO DIAMETER RATIO
6 NA, NUMBER OF L/D RATIOS
0.60 BMIN, MIN FUEL TO CORE DIAMETER RATIO
0.80 BMAX, MAX FUEL TO CORE DIAMETER RATIO
9 NB, NUMBER OF DIAMETER RATIOS
0 ISTARC, FLAG FOR CORE GEOMETRY (GA'S STAR-C)
0.93 Z, FUEL TO CORE DIAMETER RATIO
1.10 CM, CRITICAL MASS CORRECTION FACTOR
0.500 VFFF, VOLUME FRACTION OF FUEL IN FUEL ANNULUS
0.500 VFFM, VOLUME FRACTION OF MODERATOR IN FUEL ANNULUS
11.80 RHOF, FUEL DENSITY (G/CC)
1.85 RHOM, MODERATOR DENSITY (G/CC)
12.0 AWM, MODERATOR ATOMIC WEIGHT
79. D1, I&C CONSTANT MASS (KG)
707. D2, PROP CONSTANT FOR CONTROL MASS (KG/SQM)
0.90 D3, PROP CONSTANT FOR CABLE MASS (KG/M)
2300. TFMAX, MAX TEMPERATURE OF FUEL (K)
0.85 EPSC, EMISSIVITY OF CORE SURFACE
0.85 EPSHS, EMISSIVITY OF THERMIONIC ELEMENT HOT SHOE
1.20 PF, PEAK/AVERAGE CORE POWER
35.0 KF, FUEL REGION THERMAL CONDUCTIVITY (W/M*K)
40.0 KG, GRAPHITE THERMAL CONDUCTIVITY (W/M*K)
0.000 FS, STRUCTURE VOLUME FRACTION
0.00 RHOS, STRUCTURE DENSITY (G/CC)
10.0 T, REFLECTOR THICKNESS (CM)
1.47 RHORF, REFLECTOR DENSITY (G/CC)
0 IHS, FLAG FOR LOWER RE-ENTRY HEAT SHIELD

SHIELD INPUT DATA

1.00E+13 DN, NEUTRON DOSE LIMIT (NVT)
5.00E+05 DG, GAMMA DOSE LIMIT (RAD)
20.0 RP, PAYLOAD SEPARATION DISTANCE (M)
4.00 DPAY, PAYLOAD DIAMETER (M)
0.0 CHAMIN, MINIMUM CONE HALF ANGLE FOR THE SHIELD (DEG)
10.00 TGMIN, MINIMUM GAMMA SHIELD THICKNESS (CM)
20.00 TGMAX, MAXIMUM GAMMA SHIELD THICKNESS (CM)
11 NG, NUMBER OF GAMMA SHIELD THICKNESSES
1.00 CNS, NEUTRON SHIELD CORRECTION FACTOR
1.00 CGS, GAMMA SHIELD CORRECTION FACTOR
9.0 FBM, BOOM MASS CONSTANT (KG/M)

THERMIONIC DEVICE INPUT DATA

3 ITI, FLAG FOR THERMIONIC DEVICE TYPE
 0.141 ETI, THERMIONIC DEVICE EFFICIENCY
 8.50 PHITI, TI POWER DENSITY (W/SQCM)
 4.90 AE, AREA OF THE TI EMITTER (SQCM)
 17.50 PHITMIN, MINIMUM THERMAL FLUX FROM CORE (W/SQCM)
 32.50 PHITMAX, MAXIMUM THERMAL FLUX FROM CORE (W/SQCM)
 7 NPHIT, NUMBER OF CORE THERMAL FLUXES CONSIDERED
 0.20 UTI, MASS OF A TI DEVICE (KG)
 1850. TEMIN, MINIMUM EMITTER TEMPERATURE (K)
 2000. TEMAX, MAXIMUM EMITTER TEMPERATURE (K)
 4 NTE, NUMBER OF EMITTER TEMPERATURES CONSIDERED
 1000. TCMIN, MINIMUM COLLECTOR TEMPERATURE (K)
 1000. TCMAX, MAXIMUM COLLECTOR TEMPERATURE (K)
 1 NTC, NUMBER OF COLLECTOR TEMPERATURES CONSIDERED
 0.60 VEMIN, MINIMUM ELECTRODE VOLTAGE (V)
 1.00 VEMAX, MAXIMUM ELECTRODE VOLTAGE (V)
 9 NVE, NUMBER OF ELECTRODE VOLTAGES
 98.0 EL, TI LEAD EFFICIENCY (%)
 0.050 FPLL, FRACTIONAL THERMAL POWER LOSS IN LEAD
 0.150 EPSE, THERMAL EMISSIVITY IN INTERELECTRODE GAP
 0.67 VTI, TI OUTPUT VOLTAGE (V)
 5.0 REDTI, REDUNDANCY IN THERMIONICS (%)
 8 NPARMIN, MINIMUM PARALLEL CONNECTIONS OF TI DEVICES
 0.97 ESTRAP, EFFICIENCY OF ELECTRICAL STRAPS
 18.50 RHOSTR, DENSITY OF STRAP MATERIAL (G/CC)
 2.32E-05 RS, STRAP RESISTIVITY (OHM*M)
 0.00205 RST, STRAP TEMPERATURE COEFF OF RESISTIVITY (K-1)
 900. TSR, TEMPERATURE AT WHICH RS IS APPLICABLE (K)
 0.75 EMS, STRAP EMISSIVITY

POWER CONDITIONING INPUT DATA

0.91 EPC, EFFICIENCY OF POWER CONDITIONING
 1 IPC, LOCATION OF POWER CONDITIONING MODULE
 1 NV, NUMBER OF VOLTAGES DOWN BOOM
 0.00 VB(1), BOOM VOLTAGE 1
 1.000 VP(1), PERCENT POWER AT VB(1)
 300. T1, ESTIMATED CABLE TEMPERATURE (K)
 2.65E-08 RC, CONDUCTOR RESISTIVITY (OHM*M)
 4.29E-03 RT, CONDUCTOR RESISTIVITY COEFFICIENT (K-1)
 2.70 RHOC, CONDUCTOR DENSITY (G/CC)
 10.0 REDC, CABLE REDUNDANCY
 10 NCMIN, MINIMUM NUMBER OF CABLES CONSIDERED
 50 NCMAX, MAXIMUM NUMBER OF CABLES CONSIDERED
 2000.00 DI, DIELECTRIC STRENGTH OF INSULATION
 2.50 RHOI, DENSITY OF INSULATION MATERIAL (G/CC)
 1.20 PFC, PACKING FRACTION OF CABLES
 1.50 PPL, PERCENT POWER LOSS ALLOWED IN TRANSMISSION LINE
 3 NVPC, NUMBER OF VOLTAGES OUT OF PC
 5.00 VPCO(1), POWER CONDITIONING VOLTAGE 1
 0.15 VPPC(1), FRACTION OF POWER AT VPCO(1)
 28.00 VPCO(2), POWER CONDITIONING VOLTAGE 2
 0.55 VPPC(2), FRACTION OF POWER AT VPCO(2)
 100.00 VPCO(3), POWER CONDITIONING VOLTAGE 3
 0.30 VPPC(3), FRACTION OF POWER AT VPCO(3)
 0.09 MRLFLT, MASS OF RELAY AND FILTER W/O CONVERTER (KG)
 0.80 MCTRL, MASS OF PC CONTROL ELECTRONICS (KG)
 0.060 SSWIT, SPECIFIC MASS OF POWER DIST SWITCH (KG/KW)
 300. VMOO, SPECIFIC VOLUME OF PC ELEC MODULE (CC/KW)
 7.50 UPCRAD, SPECIFIC MASS OF PC RADIATOR (KG/SQM)
 4.00 UPCHLD, SPECIFIC MASS OF PC RADIATION SHIELD (G/SCQM)
 10.0 REDPC, REDUNDANCY IN POWER CONDITIONING (%)

30 kWe OTR, Base Case (Nov. 30, 1989)

POWER = 30.0 KWE OPERATION TIME = 10. YEARS

EMITTER TEMP (K)	COLLECTOR TEMP (K)	ELECTRODE VOLT (V)	POWER (W/SQCM)	LEAD VOLT (V)	THERMIONIC EFF (%)	SYSTEM EFF (%)	THERM FLUX (W/SQCM)	REACTOR MASS (KG)	SHIELD MASS (KG)	TOTAL MASS (KG)
1900.	1000.	0.75	6.4	0.74	15.1	12.6	25.0	537.	394.	1867.
1950.	1000.	0.80	7.9	0.78	16.1	13.4	22.5	560.	385.	1868.
1950.	1000.	0.75	9.2	0.74	16.2	13.5	22.5	560.	383.	1872.
1900.	1000.	0.70	7.5	0.69	15.3	12.7	25.0	537.	393.	1873.
2000.	1000.	0.90	9.3	0.88	17.5	14.6	20.0	588.	404.	1892.
2000.	1000.	0.95	8.2	0.93	17.3	14.4	20.0	588.	406.	1899.
1950.	1000.	0.70	10.1	0.69	15.9	13.3	22.5	560.	387.	1900.
1900.	1000.	0.65	8.3	0.64	15.0	12.5	25.0	541.	397.	1904.
2000.	1000.	0.85	10.2	0.83	17.4	14.6	20.0	588.	405.	1906.
1950.	1000.	0.85	6.4	0.83	15.5	12.9	22.5	583.	395.	1917.
1900.	1000.	0.70	7.5	0.69	15.3	12.7	27.5	579.	394.	1922.
2000.	1000.	1.00	7.1	0.98	16.8	14.0	20.0	602.	405.	1922.
1850.	1000.	0.60	6.8	0.59	14.1	11.7	27.5	532.	409.	1925.
2000.	1000.	0.90	9.3	0.88	17.5	14.6	22.5	626.	398.	1929.
1850.	1000.	0.65	5.8	0.64	14.1	11.8	27.5	531.	409.	1930.
2000.	1000.	0.95	8.2	0.93	17.3	14.4	22.5	626.	399.	1934.
1900.	1000.	0.75	6.4	0.74	15.1	12.6	27.5	592.	398.	1936.
1900.	1000.	0.70	7.5	0.69	15.3	12.7	22.5	584.	396.	1938.
2000.	1000.	0.80	11.0	0.78	17.1	14.3	20.0	601.	401.	1939.
1900.	1000.	0.75	6.4	0.74	15.1	12.6	22.5	591.	398.	1939.
1850.	1000.	0.60	6.8	0.59	14.1	11.7	30.0	560.	396.	1940.
2000.	1000.	0.85	10.2	0.83	17.4	14.6	22.5	626.	399.	1941.
1950.	1000.	0.75	9.2	0.74	16.2	13.5	25.0	588.	416.	1943.
1900.	1000.	0.60	8.9	0.59	14.5	12.1	25.0	560.	391.	1946.
1950.	1000.	0.80	7.9	0.78	16.1	13.4	25.0	593.	418.	1946.
1900.	1000.	0.80	5.1	0.78	14.5	12.1	25.0	560.	391.	1947.
1850.	1000.	0.65	5.8	0.64	14.1	11.8	30.0	560.	396.	1948.
1850.	1000.	0.60	6.8	0.59	14.1	11.7	25.0	567.	397.	1959.
2000.	1000.	0.80	11.0	0.78	17.1	14.3	22.5	626.	399.	1962.
1850.	1000.	0.65	5.8	0.64	14.1	11.8	25.0	567.	397.	1964.
1850.	1000.	0.70	4.7	0.69	13.7	11.5	27.5	537.	406.	1969.
1950.	1000.	0.85	6.4	0.83	15.5	12.9	25.0	607.	419.	1974.
1950.	1000.	0.80	7.9	0.78	16.1	13.4	20.0	626.	401.	1974.
2000.	1000.	0.90	9.3	0.88	17.5	14.6	17.5	653.	403.	1975.
1950.	1000.	0.75	9.2	0.74	16.2	13.5	20.0	627.	397.	1975.
1900.	1000.	0.70	7.5	0.69	15.3	12.7	30.0	601.	417.	1975.
2000.	1000.	0.75	11.6	0.74	16.7	13.9	20.0	613.	400.	1977.
1900.	1000.	0.65	8.3	0.64	15.0	12.5	27.5	575.	427.	1979.
1950.	1000.	0.70	10.1	0.69	15.9	13.3	25.0	601.	415.	1980.
1900.	1000.	0.65	8.3	0.64	15.0	12.5	22.5	598.	400.	1982.
1900.	1000.	0.75	6.4	0.74	15.1	12.6	30.0	613.	417.	1984.
2000.	1000.	1.00	7.1	0.98	16.8	14.0	22.5	654.	408.	1986.
2000.	1000.	0.95	8.2	0.93	17.3	14.4	17.5	663.	408.	1995.
2000.	1000.	0.85	10.2	0.83	17.4	14.6	17.5	657.	405.	1995.
1950.	1000.	0.65	10.6	0.64	15.3	12.8	22.5	597.	400.	1999.
1950.	1000.	0.75	9.2	0.74	16.2	13.5	27.5	646.	406.	1999.
1950.	1000.	0.70	10.1	0.69	15.9	13.3	20.0	626.	403.	2009.
1900.	1000.	0.65	8.3	0.64	15.0	12.5	30.0	613.	417.	2011.
1950.	1000.	0.80	7.9	0.78	16.1	13.4	27.5	657.	409.	2012.
1900.	1000.	0.60	8.9	0.59	14.5	12.1	27.5	588.	427.	2018.
1950.	1000.	0.85	6.4	0.83	15.5	12.9	20.0	646.	412.	2018.
1850.	1000.	0.70	4.7	0.69	13.7	11.5	30.0	580.	405.	2019.
1850.	1000.	0.60	6.8	0.59	14.1	11.7	32.5	592.	433.	2021.
1900.	1000.	0.80	5.1	0.78	14.5	12.1	27.5	588.	427.	2023.
1850.	1000.	0.65	5.8	0.64	14.1	11.8	32.5	591.	433.	2029.
1850.	1000.	0.70	4.7	0.69	13.7	11.5	25.0	585.	406.	2029.
2000.	1000.	0.90	9.3	0.88	17.5	14.6	25.0	675.	436.	2032.
1950.	1000.	0.65	10.6	0.64	15.3	12.8	25.0	613.	416.	2033.
2000.	1000.	0.70	12.1	0.69	16.1	13.4	20.0	626.	401.	2036.
1950.	1000.	0.90	5.2	0.88	14.6	12.2	22.5	613.	418.	2040.
2000.	1000.	0.80	11.0	0.78	17.1	14.3	17.5	672.	411.	2042.
2000.	1000.	1.00	7.1	0.98	16.8	14.0	17.5	689.	418.	2044.
2000.	1000.	0.85	10.2	0.83	17.4	14.6	25.0	676.	437.	2046.
2000.	1000.	0.75	11.6	0.74	16.7	13.9	22.5	666.	411.	2046.
1900.	1000.	0.80	5.1	0.78	14.5	12.1	22.5	625.	410.	2049.
1900.	1000.	0.60	8.9	0.59	14.5	12.1	30.0	626.	418.	2050.
1900.	1000.	0.60	8.9	0.59	14.5	12.1	22.5	623.	409.	2051.
1950.	1000.	0.90	5.2	0.88	14.6	12.2	25.0	626.	418.	2053.
2000.	1000.	0.95	8.2	0.93	17.3	14.4	25.0	689.	435.	2053.
1900.	1000.	0.80	5.1	0.78	14.5	12.1	30.0	626.	418.	2057.
1900.	1000.	0.70	7.5	0.69	15.3	12.7	20.0	657.	417.	2059.
1900.	1000.	0.75	6.4	0.74	15.1	12.6	20.0	665.	421.	2061.
1950.	1000.	0.70	10.1	0.69	15.9	13.3	27.5	674.	415.	2065.
1850.	1000.	0.60	6.8	0.59	14.1	11.7	22.5	629.	419.	2066.
2000.	1000.	1.00	7.1	0.98	16.8	14.0	25.0	694.	438.	2069.
1850.	1000.	0.65	5.8	0.64	14.1	11.8	22.5	628.	419.	2070.
1850.	1000.	0.70	4.7	0.69	13.7	11.5	32.5	601.	430.	2073.
1850.	1000.	0.75	3.7	0.74	13.0	10.9	27.5	560.	405.	2079.
2000.	1000.	0.80	11.0	0.78	17.1	14.3	25.0	689.	436.	2080.
1950.	1000.	0.85	6.4	0.83	15.5	12.9	27.5	660.	456.	2082.
1950.	1000.	0.80	7.9	0.78	16.1	13.4	30.0	689.	437.	2085.

30 kWe OTR, Base Case (Nov. 30, 1989)

POWER = 30.0 KWE OPERATION TIME = 10. YEARS

EMITTER TEMP (K)	COLLECTOR TEMP (K)	ELECTRODE VOLT (V)	POWER (W/SQCM)	LEAD VOLT (V)	THERMIONIC EFF (%)	SYSTEM EFF (%)	THERM FLUX (W/SQCM)	REACTOR MASS (KG)	SHIELD MASS (KG)	TOTAL MASS (KG)
1900.	1000.	0.75	6.4	0.74	15.1	12.6	32.5	660.	457.	2088.
1950.	1000.	0.75	9.2	0.74	16.2	13.5	30.0	689.	437.	2088.
1900.	1000.	0.70	7.5	0.69	15.3	12.7	32.5	655.	461.	2092.
1950.	1000.	0.60	11.0	0.59	14.6	12.2	22.5	613.	418.	2097.
1950.	1000.	0.65	10.6	0.64	15.3	12.8	20.0	654.	416.	2097.
1950.	1000.	0.60	11.0	0.59	14.6	12.2	25.0	626.	418.	2103.
2000.	1000.	0.75	11.6	0.74	16.7	13.9	17.5	695.	420.	2105.
1900.	1000.	0.65	8.3	0.64	15.0	12.5	20.0	673.	424.	2109.
1900.	1000.	0.65	8.3	0.64	15.0	12.5	32.5	660.	457.	2114.
1950.	1000.	0.85	6.4	0.83	15.5	12.9	30.0	705.	438.	2114.
2000.	1000.	0.75	11.6	0.74	16.7	13.9	25.0	704.	436.	2119.
1950.	1000.	0.70	10.1	0.69	15.9	13.3	30.0	704.	437.	2127.
2000.	1000.	0.70	12.1	0.69	16.1	13.4	22.5	660.	451.	2129.
1950.	1000.	0.75	9.2	0.74	16.2	13.5	17.5	720.	428.	2131.
1950.	1000.	0.80	7.9	0.78	16.1	13.4	17.5	727.	430.	2133.
1950.	1000.	0.95	4.3	0.93	13.9	11.6	22.5	640.	423.	2133.
1850.	1000.	0.70	4.7	0.69	13.7	11.5	22.5	648.	426.	2134.
1950.	1000.	0.65	10.6	0.64	15.3	12.8	27.5	660.	457.	2134.
2000.	1000.	0.65	12.6	0.64	15.4	12.8	20.0	652.	415.	2136.
1900.	1000.	0.60	8.9	0.59	14.5	12.1	32.5	675.	457.	2153.
1950.	1000.	0.90	5.2	0.88	14.6	12.2	20.0	695.	434.	2158.
1950.	1000.	0.90	5.2	0.88	14.6	12.2	27.5	675.	457.	2159.
1900.	1000.	0.80	5.1	0.78	14.5	12.1	32.5	675.	457.	2163.
1850.	1000.	0.75	3.7	0.74	13.0	10.9	30.0	595.	439.	2163.
1900.	1000.	0.85	3.8	0.83	13.2	11.0	25.0	613.	432.	2164.
1900.	1000.	0.85	3.8	0.83	13.2	11.0	27.5	615.	432.	2165.
1950.	1000.	0.70	10.1	0.69	15.9	13.3	17.5	719.	437.	2171.
1950.	1000.	0.85	6.4	0.83	15.5	12.9	17.5	740.	444.	2174.
2000.	1000.	0.70	12.1	0.69	16.1	13.4	25.0	719.	437.	2178.
1950.	1000.	0.65	10.6	0.64	15.3	12.8	30.0	719.	438.	2180.
1850.	1000.	0.75	3.7	0.74	13.0	10.9	25.0	624.	424.	2180.
1900.	1000.	0.80	5.1	0.78	14.5	12.1	20.0	703.	437.	2180.
1850.	1000.	0.75	3.7	0.74	13.0	10.9	32.5	626.	428.	2186.
1900.	1000.	0.60	8.9	0.59	14.5	12.1	20.0	702.	437.	2187.
2000.	1000.	0.70	12.1	0.69	16.1	13.4	17.5	727.	430.	2200.
2000.	1000.	0.65	12.6	0.64	15.4	12.8	22.5	675.	452.	2201.
1950.	1000.	0.60	11.0	0.59	14.6	12.2	27.5	675.	457.	2204.
1950.	1000.	0.95	4.3	0.93	13.9	11.6	25.0	648.	476.	2204.
2000.	1000.	0.90	9.3	0.88	17.5	14.6	27.5	820.	445.	2216.
1900.	1000.	0.70	7.5	0.69	15.3	12.7	17.5	753.	448.	2219.
1900.	1000.	0.75	6.4	0.74	15.1	12.6	17.5	761.	450.	2220.
1850.	1000.	0.60	6.8	0.59	14.1	11.7	20.0	719.	450.	2221.
1950.	1000.	0.60	11.0	0.59	14.6	12.2	20.0	695.	433.	2223.
1850.	1000.	0.65	5.8	0.64	14.1	11.8	20.0	719.	449.	2223.
1950.	1000.	1.00	3.8	0.98	13.4	11.2	22.5	669.	433.	2226.
2000.	1000.	0.85	10.2	0.83	17.4	14.6	27.5	831.	448.	2243.
1950.	1000.	0.95	4.3	0.93	13.9	11.6	27.5	704.	457.	2250.
1900.	1000.	0.85	3.8	0.83	13.2	11.0	22.5	682.	437.	2256.
2000.	1000.	0.95	8.2	0.93	17.3	14.4	27.5	846.	452.	2260.
1950.	1000.	0.65	10.6	0.64	15.3	12.8	17.5	749.	447.	2261.
1950.	1000.	0.90	5.2	0.88	14.6	12.2	30.0	765.	452.	2262.
1950.	1000.	1.00	3.8	0.98	13.4	11.2	25.0	660.	474.	2264.
1950.	1000.	0.95	4.3	0.93	13.9	11.6	20.0	719.	453.	2268.
1850.	1000.	0.70	4.7	0.69	13.7	11.5	20.0	728.	456.	2272.
1900.	1000.	0.65	8.3	0.64	15.0	12.5	17.5	770.	453.	2273.
1900.	1000.	0.85	3.8	0.83	13.2	11.0	30.0	660.	477.	2273.
2000.	1000.	0.60	12.9	0.59	14.6	12.2	20.0	695.	434.	2275.
2000.	1000.	0.60	12.9	0.59	14.6	12.2	22.5	689.	456.	2284.
2000.	1000.	0.65	12.6	0.64	15.4	12.8	25.0	755.	448.	2285.
1850.	1000.	0.75	3.7	0.74	13.0	10.9	22.5	692.	441.	2287.
1950.	1000.	0.60	11.0	0.59	14.6	12.2	30.0	763.	452.	2300.
2000.	1000.	0.65	12.6	0.64	15.4	12.8	17.5	746.	446.	2302.
1900.	1000.	0.85	3.8	0.83	13.2	11.0	32.5	706.	459.	2308.
1950.	1000.	1.00	3.8	0.98	13.4	11.2	27.5	719.	458.	2315.
2000.	1000.	0.80	11.0	0.78	17.1	14.3	27.5	867.	458.	2317.
1950.	1000.	0.90	5.2	0.88	14.6	12.2	17.5	796.	461.	2319.
1950.	1000.	0.75	9.2	0.74	16.2	13.5	32.5	870.	461.	2331.
1900.	1000.	0.80	5.1	0.78	14.5	12.1	17.5	806.	464.	2342.
1950.	1000.	0.80	7.9	0.78	16.1	13.4	32.5	885.	466.	2350.
1900.	1000.	0.60	8.9	0.59	14.5	12.1	17.5	804.	463.	2357.
1950.	1000.	1.00	3.8	0.98	13.4	11.2	20.0	752.	467.	2369.
2000.	1000.	1.00	7.1	0.98	16.8	14.0	27.5	915.	471.	2372.
1850.	1000.	0.65	5.8	0.64	14.1	11.8	17.5	832.	472.	2391.
1850.	1000.	0.60	6.8	0.59	14.1	11.7	17.5	833.	472.	2391.
1950.	1000.	0.60	11.0	0.59	14.6	12.2	17.5	796.	461.	2394.
1900.	1000.	0.85	3.8	0.83	13.2	11.0	20.0	766.	472.	2402.
1950.	1000.	0.70	10.1	0.69	15.9	13.3	32.5	908.	472.	2408.
2000.	1000.	0.75	11.6	0.74	16.7	13.9	27.5	932.	475.	2433.
1850.	1000.	0.75	3.7	0.74	13.0	10.9	20.0	777.	476.	2435.
2000.	1000.	0.60	12.9	0.59	14.6	12.2	17.5	797.	461.	2449.
1950.	1000.	0.95	4.3	0.93	13.9	11.6	17.5	848.	477.	2454.

30 kWe OTR, Base Case (Nov. 30, 1989)

POWER = 30.0 KWE OPERATION TIME = 10. YEARS

EMITTER TEMP (K)	COLLECTOR TEMP (K)	ELECTRODE VOLT (V)	POWER (W/SQCM)	LEAD VOLT (V)	THERMIONIC EFF (%)	SYSTEM EFF (%)	THERM FLUX (W/SQCM)	REACTOR MASS (KG)	SHIELD MASS (KG)	TOTAL MASS (KG)
1850.	1000.	0.70	4.7	0.69	13.7	11.5	17.5	859.	481.	2463.
1850.	1000.	0.80	2.9	0.78	11.9	10.0	32.5	719.	469.	2474.
1850.	1000.	0.80	2.9	0.78	11.9	10.0	30.0	719.	469.	2475.
1850.	1000.	0.80	2.9	0.78	11.9	10.0	27.5	719.	469.	2476.
1950.	1000.	0.95	4.3	0.93	13.9	11.6	30.0	869.	482.	2476.
1850.	1000.	0.80	2.9	0.78	11.9	10.0	25.0	719.	469.	2477.
1950.	1000.	0.85	6.4	0.83	15.5	12.9	32.5	975.	489.	2494.
2000.	1000.	0.60	12.9	0.59	14.6	12.2	25.0	861.	479.	2508.
1850.	1000.	0.80	2.9	0.78	11.9	10.0	22.5	747.	475.	2520.
1900.	1000.	0.90	2.8	0.88	11.6	9.6	30.0	738.	480.	2528.
1900.	1000.	0.90	2.8	0.88	11.6	9.6	27.5	738.	480.	2529.
1900.	1000.	0.90	2.8	0.88	11.6	9.6	25.0	738.	480.	2530.
1950.	1000.	1.00	3.8	0.98	13.4	11.2	17.5	888.	492.	2564.
1950.	1000.	0.65	10.6	0.64	15.3	12.8	32.5	999.	495.	2577.
1900.	1000.	0.90	2.8	0.88	11.6	9.6	22.5	779.	488.	2589.
1900.	1000.	0.85	3.8	0.83	13.2	11.0	17.5	905.	499.	2602.
2000.	1000.	0.70	12.1	0.69	16.1	13.4	27.5	1020.	498.	2603.
1850.	1000.	0.75	3.7	0.74	13.0	10.9	17.5	918.	504.	2639.
1950.	1000.	1.00	3.8	0.98	13.4	11.2	30.0	952.	505.	2649.
1850.	1000.	0.80	2.9	0.78	11.9	10.0	20.0	865.	504.	2696.
1900.	1000.	0.90	2.8	0.88	11.6	9.6	20.0	902.	515.	2769.
1950.	1000.	0.90	5.2	0.88	14.6	12.2	32.5	1134.	528.	2786.
1900.	1000.	0.90	2.8	0.88	11.6	9.6	32.5	918.	519.	2787.
1950.	1000.	0.60	11.0	0.59	14.6	12.2	32.5	1131.	527.	2819.
2000.	1000.	0.65	12.6	0.64	15.4	12.8	27.5	1143.	527.	2831.
1850.	1000.	0.80	2.9	0.78	11.9	10.0	17.5	1024.	543.	2931.
2000.	1000.	0.90	9.3	0.88	17.5	14.6	30.0	1339.	542.	2938.
2000.	1000.	0.85	10.2	0.83	17.4	14.6	30.0	1357.	546.	2973.
1900.	1000.	0.95	2.3	0.93	10.5	8.7	30.0	947.	544.	2984.
1900.	1000.	0.95	2.3	0.93	10.5	8.7	27.5	947.	544.	2984.
1900.	1000.	0.95	2.3	0.93	10.5	8.7	25.0	947.	544.	2985.
1900.	1000.	0.95	2.3	0.93	10.5	8.7	22.5	947.	544.	2986.
2000.	1000.	0.95	8.2	0.93	17.3	14.4	30.0	1382.	551.	3004.
1900.	1000.	0.90	2.8	0.88	11.6	9.6	17.5	1069.	559.	3018.
1950.	1000.	0.95	4.3	0.93	13.9	11.6	32.5	1293.	565.	3070.
2000.	1000.	0.80	11.0	0.78	17.1	14.3	30.0	1419.	559.	3079.
1900.	1000.	0.95	2.3	0.93	10.5	8.7	20.0	1020.	557.	3089.
1850.	1000.	0.85	2.2	0.83	10.5	8.8	32.5	1007.	554.	3100.
1850.	1000.	0.85	2.2	0.83	10.5	8.8	30.0	1007.	554.	3101.
1850.	1000.	0.85	2.2	0.83	10.5	8.8	27.5	1007.	554.	3102.
1850.	1000.	0.85	2.2	0.83	10.5	8.8	25.0	1007.	554.	3103.
1850.	1000.	0.85	2.2	0.83	10.5	8.8	22.5	1007.	554.	3104.
1850.	1000.	0.85	2.2	0.83	10.5	8.8	20.0	1014.	555.	3114.
2000.	1000.	0.60	12.9	0.59	14.6	12.2	27.5	1310.	565.	3128.
2000.	1000.	1.00	7.1	0.98	16.8	14.0	30.0	1500.	575.	3177.
1900.	1000.	1.00	2.1	0.98	10.2	8.5	30.0	1045.	569.	3185.
1900.	1000.	1.00	2.1	0.98	10.2	8.5	27.5	1045.	569.	3185.
1900.	1000.	1.00	2.1	0.98	10.2	8.5	25.0	1045.	569.	3186.
1900.	1000.	1.00	2.1	0.98	10.2	8.5	22.5	1045.	569.	3187.
1900.	1000.	1.00	2.1	0.98	10.2	8.5	20.0	1059.	572.	3207.
2000.	1000.	0.75	11.6	0.74	16.7	13.9	30.0	1528.	581.	3251.
1950.	1000.	1.00	3.8	0.98	13.4	11.2	32.5	1421.	593.	3298.
1900.	1000.	0.95	2.3	0.93	10.5	8.7	32.5	1174.	589.	3302.
1900.	1000.	0.95	2.3	0.93	10.5	8.7	17.5	1210.	597.	3360.
1850.	1000.	0.85	2.2	0.83	10.5	8.8	17.5	1202.	595.	3383.
1900.	1000.	1.00	2.1	0.98	10.2	8.5	17.5	1256.	609.	3484.
1900.	1000.	1.00	2.1	0.98	10.2	8.5	32.5	1266.	612.	3492.
2000.	1000.	0.70	12.1	0.69	16.1	13.4	30.0	1679.	609.	3496.
2000.	1000.	0.65	12.6	0.64	15.4	12.8	30.0	1888.	647.	3828.
1850.	1000.	0.90	1.7	0.88	9.2	7.6	32.5	1415.	661.	3926.
1850.	1000.	0.90	1.7	0.88	9.2	7.6	30.0	1415.	661.	3927.
1850.	1000.	0.90	1.7	0.88	9.2	7.6	27.5	1415.	661.	3927.
1850.	1000.	0.90	1.7	0.88	9.2	7.6	25.0	1415.	661.	3928.
1850.	1000.	0.90	1.7	0.88	9.2	7.6	22.5	1415.	661.	3929.
1850.	1000.	0.90	1.7	0.88	9.2	7.6	20.0	1415.	661.	3930.
1850.	1000.	0.90	1.7	0.88	9.2	7.6	17.5	1439.	665.	3965.
2000.	1000.	0.60	12.9	0.59	14.6	12.2	30.0	2172.	696.	4266.
2000.	1000.	0.90	9.3	0.88	17.5	14.6	32.5	2476.	703.	4428.
2000.	1000.	0.85	10.2	0.83	17.4	14.6	32.5	2510.	709.	4483.
1850.	1000.	0.95	1.4	0.93	8.4	7.0	32.5	1723.	735.	4526.
1850.	1000.	0.95	1.4	0.93	8.4	7.0	30.0	1723.	735.	4527.
1850.	1000.	0.95	1.4	0.93	8.4	7.0	27.5	1723.	735.	4527.
1850.	1000.	0.95	1.4	0.93	8.4	7.0	25.0	1723.	735.	4528.
1850.	1000.	0.95	1.4	0.93	8.4	7.0	22.5	1723.	735.	4528.
1850.	1000.	0.95	1.4	0.93	8.4	7.0	20.0	1723.	735.	4529.
1850.	1000.	0.95	1.4	0.93	8.4	7.0	17.5	1723.	735.	4530.
2000.	1000.	0.95	8.2	0.93	17.3	14.4	32.5	2558.	716.	4541.
2000.	1000.	0.80	11.0	0.78	17.1	14.3	32.5	2629.	726.	4656.
1850.	1000.	1.00	1.4	0.98	8.3	7.0	32.5	1809.	751.	4684.
1850.	1000.	1.00	1.4	0.98	8.3	7.0	30.0	1809.	751.	4685.
1850.	1000.	1.00	1.4	0.98	8.3	7.0	27.5	1809.	751.	4685.

30 kWe OTR, Base Case (Nov. 30, 1989)

POWER = 30.0 KWE OPERATION TIME = 10. YEARS

EMITTER TEMP (K)	COLLECTOR TEMP (K)	ELECTRODE VOLT (V)	POWER (W/SQCM)	LEAD VOLT (V)	THERMIONIC EFF (%)	SYSTEM EFF (%)	THERM FLUX (W/SQCM)	REACTOR MASS (KG)	SHIELD MASS (KG)	TOTAL MASS (KG)
1850.	1000.	1.00	1.4	0.98	8.3	7.0	25.0	1809.	751.	4686.
1850.	1000.	1.00	1.4	0.98	8.3	7.0	22.5	1809.	751.	4686.
1850.	1000.	1.00	1.4	0.98	8.3	7.0	20.0	1809.	751.	4687.
1850.	1000.	1.00	1.4	0.98	8.3	7.0	17.5	1809.	751.	4688.
2000.	1000.	1.00	7.1	0.98	16.8	14.0	32.5	2785.	748.	4844.
2000.	1000.	0.75	11.6	0.74	16.7	13.9	32.5	2839.	755.	4946.
2000.	1000.	0.70	12.1	0.69	16.1	13.4	32.5	3127.	795.	5354.
2000.	1000.	0.65	12.6	0.64	15.4	12.8	32.5	3530.	847.	5912.
2000.	1000.	0.60	12.9	0.59	14.6	12.2	32.5	4078.	914.	6657.

30 kWe OTR, Base Case (Nov. 30, 1989)

THERMIONIC DATA

TI DEVICE POWER	31. W
TI DEVICE VOLTAGE	0.73 V
TI DEVICE EFF	15.1 %
EMITTER AREA	60.3 %
TI NETWORK VOLTAGE	103.2 V
NUMBER OF DEVICES	1179
MASS OF DEVICES	236. KG

STRAP DATA

EFFICIENCY	97.0 %
MASS	27. KG
DIAMETER	0.52 CM
LENGTH	67.93 M
TEMPERATURE	1005. K

POWER CONDITIONING DATA

EFFICIENCY	91.0 %
VOLUME	0.002 M**3
MASS	39. KG
SHIELD MASS	3. KG
RADIATOR MASS	17. KG
RADIATOR AREA	2.22 M**2

EFFICIENCY SUMMARY

THERMIONICS	15.1 %
STRAP	97.0 %
TRANSMISSION LINE	98.4 %
POWER CONDITIONING	91.0 %
NET ELECTRICAL	13.1 %

30 kWe OTR, Base Case (Nov. 30, 1989)
 POWER = 34.5 KW
 VOLTAGE = 100.0 V
 WIRE GAUGE = 7

TRANSMISSION LINE TABLE (NO REDUNDANCY)

NO. OF WIRES	PCT LOSS	LOSS (W)	LOSS (W/M)	CONDTC (MHOS)	RESIST (OHMS)	AMPS/ COND (A)	MASS (KG)	DIA (CM)	TEMP (K)
50	0.56	193.6	4.8	614.9	1.63E-03	6.9	57.0	3.110	248.
49	0.57	197.6	4.9	602.6	1.66E-03	7.0	55.9	3.079	248.
48	0.58	201.7	5.0	590.3	1.69E-03	7.2	54.7	3.047	249.
47	0.60	206.0	5.2	578.0	1.73E-03	7.3	53.6	3.015	249.
46	0.61	210.5	5.3	565.7	1.77E-03	7.5	52.5	2.983	250.
45	0.62	215.2	5.4	553.4	1.81E-03	7.7	51.3	2.950	251.
44	0.65	223.6	5.6	532.7	1.88E-03	7.8	50.2	2.917	252.
43	0.66	228.8	5.7	520.6	1.92E-03	8.0	49.1	2.884	253.
42	0.68	234.2	5.9	508.5	1.97E-03	8.2	47.9	2.850	254.
41	0.71	243.5	6.1	489.1	2.04E-03	8.4	46.8	2.816	255.
40	0.72	249.5	6.2	477.2	2.10E-03	8.6	45.6	2.782	256.
39	0.74	255.9	6.4	465.3	2.15E-03	8.8	44.5	2.747	257.
38	0.77	267.1	6.7	445.8	2.24E-03	9.1	43.4	2.711	258.
37	0.79	274.3	6.9	434.1	2.30E-03	9.3	42.2	2.675	259.
36	0.83	285.8	7.1	416.7	2.40E-03	9.6	41.1	2.639	261.
35	0.85	293.9	7.3	405.1	2.47E-03	9.9	39.9	2.602	262.
34	0.89	307.0	7.7	387.9	2.58E-03	10.1	38.8	2.564	264.
33	0.92	316.3	7.9	376.5	2.66E-03	10.5	37.7	2.526	265.
32	0.96	331.5	8.3	359.2	2.78E-03	10.8	36.5	2.488	267.
31	0.99	342.2	8.6	348.0	2.87E-03	11.1	35.4	2.449	269.
30	1.04	360.1	9.0	330.7	3.02E-03	11.5	34.2	2.409	271.
29	1.08	372.5	9.3	319.6	3.13E-03	11.9	33.1	2.368	273.
28	1.14	393.9	9.8	302.3	3.31E-03	12.3	32.0	2.327	276.
27	1.20	414.0	10.4	287.6	3.48E-03	12.8	30.8	2.285	278.
26	1.25	429.9	10.7	277.0	3.61E-03	13.3	29.7	2.243	280.
25	1.33	457.9	11.4	260.0	3.85E-03	13.8	28.5	2.199	284.
24	1.41	484.8	12.1	245.6	4.07E-03	14.4	27.4	2.155	287.
23	1.49	514.0	12.9	231.7	4.32E-03	15.0	26.3	2.109	291.
* 22	1.58	546.4	13.7	217.9	4.59E-03	15.7	25.1	2.063	295.
21	1.69	582.9	14.6	204.3	4.89E-03	16.4	24.0	2.015	299.
20	1.81	624.0	15.6	190.8	5.24E-03	17.3	22.8	1.967	304.
19	1.94	670.9	16.8	177.5	5.63E-03	18.2	21.7	1.917	309.
18	2.10	724.6	18.1	164.3	6.08E-03	19.2	20.6	1.866	315.
17	2.28	786.5	19.7	151.4	6.61E-03	20.3	19.4	1.813	322.
16	2.49	858.7	21.5	138.7	7.21E-03	21.6	18.3	1.759	329.
15	2.73	943.6	23.6	126.2	7.92E-03	23.0	17.1	1.703	338.
14	3.03	1044.6	26.1	114.0	8.77E-03	24.6	16.0	1.646	347.
13	3.38	1166.0	29.2	102.1	9.79E-03	26.5	14.9	1.586	358.
12	3.81	1314.3	32.9	90.6	1.10E-02	28.8	13.7	1.524	370.
11	4.34	1498.2	37.5	79.5	1.26E-02	31.4	12.6	1.459	385.
10	5.08	1753.3	43.8	67.9	1.47E-02	34.5	11.5	1.391	403.

* - TRANSMISSION LINE SELECTED

30 kWe OTR, Base Case (Nov. 30, 1989)

LOWEST NUCLEAR SUBSYSTEM MASS OPTION

POWER = 30.0 KWE OPERATION TIME = 10.0 YEARS THERMAL EFFICIENCY = 12.6 %

1235. KG - NUCLEAR SUBSYSTEM MASS
537. KG - REACTOR MASS
394. KG - SHIELD MASS
2.300 - LENGTH TO DIAMETER RATIO
0.750 - INSIDE FUEL TO CORE DIAMETER RATIO
0.337 M - CORE DIAMETER
0.776 M - CORE LENGTH
0.069 M**3 - CORE VOLUME
123.0 KG - ACTUAL FUEL MASS
122.3 KG - FUEL MASS BASED ON THERMIONICS
108.5 KG - FUEL MASS BASED ON FUEL DAMAGE
120.1 KG - FUEL MASS BASED ON TEMPERATURE
123.0 KG - FUEL MASS BASED ON NEUTRONICS
0.17 - MOLECULAR MODERATOR TO FUEL RATIO
62.2 KG - COMPACTED CRITICAL MASS
0.000 KG - MASS OF FUEL BURNED UP
109. KG - MODERATOR MASS
82. KG - MASS OF REACTOR STRUCTURE
223. KG - REFLECTOR MASS
0.140 M - TOTAL GAMMA SHIELD THICKNESS
0.441 M - TOTAL NEUTRON SHIELD THICKNESS
154. KG - NEUTRON SHIELD MASS
240. KG - GAMMA SHIELD MASS
394. KG - TOTAL SHIELD MASS
1933. K - TI DIODE HOT SHOE TEMPERATURE
2112. K - TEMPERATURE OF THE CORE SURFACE

NEUTRON DOSE BEHIND SHIELD 5.15E+15 NVT
GAMMA DOSE BEHIND SHIELD 2.57E+08 RAD

30 kWe OTR, Base Case (Nov. 30, 1989)

POWER = 30.0 KWE

OPERATION TIME = 10.0 YEARS

THERMAL EFFICIENCY = 12.6 %

(A) ASPECT RATIO	(B) INNER DIAMETER RATIO	(R) MODERATOR TO FUEL RATIO	(C) CRITICAL MASS CORRECT	(ME) FUEL MASS NEUTRONIC (KG)	(MF) FUEL MASS DAMAGE (KG)	(MTH) FUEL MASS THERMIONIC (KG)	(MP) FUEL MASS THERMAL (KG)	(D) CORE DIAMETER (M)	(MR) REACTOR MASS (KG)	(MTS) SHIELD MASS (KG)	(MTOT) SYSTEM MASS (KG)
2.30	0.750	0.17	1.62	122.95	108.45	122.31	120.09	0.34	537.	394.	1235.
2.40	0.750	0.17	1.65	125.72	108.45	119.74	110.29	0.33	548.	388.	1243.
2.50	0.750	0.17	1.69	128.49	108.45	117.32	101.65	0.33	560.	388.	1256.
2.20	0.750	0.17	1.58	120.19	108.45	125.06	131.26	0.35	564.	410.	1286.
2.00	0.775	0.18	1.51	118.38	108.45	114.11	91.24	0.37	563.	434.	1314.
2.10	0.775	0.18	1.54	121.20	108.45	111.36	82.76	0.36	575.	426.	1321.
2.20	0.775	0.18	1.58	124.04	108.45	108.80	75.40	0.36	588.	418.	1328.
2.30	0.775	0.18	1.62	126.88	108.45	106.40	68.99	0.36	601.	417.	1342.
2.40	0.775	0.18	1.65	129.74	108.45	104.16	63.36	0.35	613.	417.	1357.
2.10	0.750	0.18	1.54	117.44	108.45	128.01	144.06	0.37	607.	429.	1361.
2.50	0.725	0.17	1.69	123.99	108.45	132.08	164.47	0.35	637.	406.	1366.
2.50	0.775	0.18	1.69	132.60	108.45	102.06	58.39	0.35	626.	413.	1368.
2.40	0.725	0.18	1.65	121.31	108.45	134.80	178.46	0.36	679.	422.	1436.
2.00	0.750	0.19	1.51	114.71	108.45	131.17	158.82	0.38	656.	452.	1445.
2.00	0.800	0.20	1.51	122.70	108.45	96.49	47.43	0.39	646.	458.	1447.
2.10	0.800	0.19	1.54	125.62	108.45	94.16	43.02	0.39	660.	457.	1463.
2.20	0.800	0.19	1.58	128.56	108.45	92.00	39.20	0.38	675.	456.	1478.
2.30	0.800	0.19	1.62	131.51	108.45	89.97	35.86	0.38	689.	448.	1488.
2.40	0.800	0.19	1.65	134.47	108.45	88.08	32.94	0.38	704.	441.	1498.
2.50	0.800	0.19	1.69	137.43	108.45	86.30	30.35	0.38	719.	438.	1513.
2.30	0.725	0.19	1.62	118.64	108.45	137.70	194.32	0.38	727.	441.	1515.
2.20	0.725	0.20	1.58	115.98	108.45	140.79	212.39	0.39	782.	462.	1603.
2.50	0.700	0.19	1.69	119.54	108.45	146.34	251.65	0.39	854.	443.	1665.
2.10	0.725	0.21	1.54	113.33	108.45	144.11	233.10	0.41	843.	485.	1702.
2.40	0.700	0.20	1.65	116.97	108.45	149.35	273.06	0.40	913.	463.	1756.
2.00	0.725	0.22	1.51	110.69	108.45	147.67	256.99	0.43	914.	512.	1815.
2.30	0.700	0.21	1.62	114.39	108.45	152.57	297.32	0.42	980.	484.	1858.
2.20	0.700	0.22	1.58	111.82	108.45	155.99	324.97	0.44	1055.	508.	1973.
2.50	0.675	0.21	1.69	115.57	108.45	160.09	368.38	0.43	1122.	495.	2032.
2.10	0.700	0.23	1.54	109.27	108.45	159.66	356.65	0.46	1141.	534.	2103.
2.40	0.675	0.22	1.65	113.07	108.45	163.40	399.72	0.44	1202.	517.	2149.
2.00	0.700	0.24	1.51	106.73	108.45	163.61	393.21	0.48	1239.	564.	2251.
2.30	0.675	0.23	1.62	110.59	108.45	166.91	435.23	0.46	1292.	542.	2281.
2.20	0.675	0.24	1.58	108.10	108.45	170.66	475.70	0.48	1393.	569.	2429.
2.50	0.650	0.23	1.69	111.97	108.45	173.35	520.18	0.47	1448.	532.	2446.
2.40	0.650	0.24	1.65	109.56	108.45	176.93	564.43	0.49	1553.	557.	2594.
2.10	0.675	0.25	1.54	105.63	108.45	174.68	522.08	0.51	1509.	600.	2596.
2.30	0.650	0.25	1.62	107.14	108.45	180.73	614.58	0.51	1671.	584.	2760.
2.00	0.675	0.27	1.51	103.18	108.45	178.99	575.59	0.53	1643.	634.	2787.
2.50	0.625	0.25	1.69	108.69	108.45	186.11	712.88	0.51	1839.	585.	2945.
2.20	0.650	0.26	1.58	104.74	108.45	184.79	671.72	0.53	1806.	614.	2947.
2.40	0.625	0.26	1.65	106.35	108.45	189.95	773.53	0.53	1975.	613.	3130.
2.10	0.650	0.28	1.54	102.34	108.45	189.14	737.22	0.55	1959.	648.	3159.
2.30	0.625	0.27	1.62	104.01	108.45	194.03	842.25	0.55	2128.	644.	3337.
2.00	0.650	0.29	1.51	99.96	108.45	193.81	812.78	0.58	2135.	687.	3401.
2.50	0.600	0.27	1.69	105.77	108.45	198.37	952.54	0.55	2302.	628.	3510.
2.20	0.625	0.29	1.58	101.67	108.45	198.39	920.56	0.57	2302.	678.	3571.
2.40	0.600	0.28	1.65	103.49	108.45	202.46	1033.58	0.57	2475.	658.	3738.
2.10	0.625	0.30	1.54	99.35	108.45	203.06	1010.32	0.60	2500.	717.	3837.
2.30	0.600	0.30	1.62	101.21	108.45	206.81	1125.41	0.59	2670.	692.	3993.
2.00	0.625	0.32	1.51	97.04	108.45	208.08	1113.88	0.63	2728.	761.	4141.
2.20	0.600	0.31	1.58	98.94	108.45	211.46	1230.04	0.62	2891.	729.	4281.
2.10	0.600	0.32	1.54	96.67	108.45	216.43	1349.98	0.65	3144.	772.	4609.
2.00	0.600	0.34	1.51	94.43	108.45	221.78	1488.35	0.68	3434.	820.	4984.

30 kWe OTR, Base Case (Nov. 30, 1989)

POWER = 30. KWE
OPERATION TIME = 10.0 YEARS
ELECTRICAL EFFICIENCY = 13.1 %

OPTIMIZED POWER SYSTEM MASS SUMMARY

REACTOR

FUEL	123.	
MODERATOR	109.	
STRUCTURE	82.	
REFLECTOR	223.	
TOTAL		537.

INST & CONTROL 216.

SAFETY SYSTEMS

RE-ENTRY SHIELD	25.	
RODS & DRIVES	63.	
TOTAL		88.

SHIELD

NEUTRON	154.	
GAMMA	240.	
TOTAL		394.

THERMIONICS 236.

ELECTRICAL SUBSYSTEM

POWER COND	39.	
PC RADIATOR	17.	
PC RAD SHIELD	3.	
TI STRAPS	27.	
TRANS LINE	46.	
TOTAL		131.

RADIATOR 84.

BOOM 180.

TOTAL SYSTEM 1867. KG

OPTIMIZED POWER SYSTEM DIMENSION SUMMARY

REACTOR

CORE LENGTH	77.56 CM
CORE DIAMETER	33.72 CM
REFLECTOR THICK	10.00 CM
TOTAL VOLUME	0.221 M**3

SHIELD

NEUTRON THICK	44.15 CM
GAMMA THICK	14.00 CM
FRONT DIAMETER	70.65 CM
TOTAL VOLUME	0.23 M**3

CONE HALF ANGLE 4.7 DEG

BOOM LENGTH 20.0 M

RADIATOR AREA 4.2 M**2

PC RADIATOR AREA 2.2 M**2

POW COND VOLUME 0.002 M**3

***** CAUTION: RADIATOR DOES NOT FIT ABOVE SHIELD *****

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1512	D. Rader	9140	D. Rigali
1810	G. Kepler	9320	M. Navatril
1830	M. Davis	9321	B. Boyer
1832	W. Jones	9340	W. Beezhold
1840	R. Eagan	9350	J. Reinken
2110	R. Bair	9351	F. Hartman
2150	E. Graham, Jr.		
2560	J. Cutchen		
2175	J. Meyer		
2330	J. Stichman		
2336	E. Nava		
2346	B. O'Nan		
3141	S. A. Landenberger (5)		
3151	W. L. Klein (3)		
3154-1	D. H. Dalin (8)		
6201	M. Edenburn		
6400	D. J. McCloskey		
6410	D. Dahlgren		
6420	W. Gauster		
6421	P. Pickard		
6422	J. Brockman		
6450	T. Schmidt		
6453	J. Philbin		
6500	A. W. Snyder		
6510	J. Walker		
6512	P. McDaniel		
6512	F. Wyant		
6512	L. Sanchez		
6512	D. Dobranich		
6512	V. Dandini		
6520	D. Berry		
6522	L. Cropp		
6522	W. Champion		
6522	D. Gallup (20)		
6522	W. McCulloch		
6522	D. Monroe		
6522	R. Pepping		
6522	R. Peters		
6522	T. Wheelis		
6524	W. Dawes, Jr.		

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