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**CONCEPTUAL DESIGN
FINAL REPORT
TFE VERIFICATION PROGRAM**

**Prepared under
CONTRACT DE-AC03-86SF16298
FOR THE SAN FRANCISCO OPERATIONS OFFICE
DEPARTMENT OF ENERGY**

**GENERAL ATOMICS PROJECT 3450
MARCH 1994**

MASTER

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TFE CONCEPTUAL DESIGN

1. INTRODUCTION

This report documents the TFE Conceptual Design, which provided the design guidance for the TFE Verification program. The primary goals of this design effort were:

- 1) Establish the conceptual design of an in-core thermionic reactor for a 2 Mw(e) space nuclear power system with a 7-year operating lifetime.
- 2) Demonstrate scalability of the above concept over the output power range of 500 kW(e) to 5 MW(e).
- 3) Define the TFE which is the basis for the 2 MW(e) reactor design. This TFE specification provided the basis for the test program.

These primary goals were achieved. The technical approach taken in the conceptual design effort is discussed in Section 2, and the results are discussed in Section 3.

The remainder of this introduction draws a perspective on the role that this conceptual design task played in the TFE Verification Program.

1.1 Objective of TFE Verification Program

The program objective was to demonstrate the technology readiness of a TFE suitable for use as the basic element in a thermionic reactor with electric power output in the 0.5 to 5.0 MW(e) range, and a full-power life of 7 years. A TFE for a megawatt class system is shown in Figure 1-1. Only six cells are shown for simplicity; a megawatt class TFE would have many more cells, the exact number depending on optimization trade studies.

1.2 Technical Approach of the TFE Verification Program

The TFE Verification Program built directly upon the technology and data base developed in the 1960s and early 1970s in an AEC/NASA program, and in the SP-100 program conducted in 1983, 1984, and 1985. In the SP-100 program, the attractive features of thermionic power conversion technology were recognized but concern was

Figure 1-1. TFE for Megawatt Class System

expressed over the lack of fast reactor irradiation data. The TFE Verification Program addressed that concern.

The technical approach followed to achieve the program objective is shown in Figure 1-2. Five prior programs form the basis for the TFE Verification Program:

- 1) AEC/NASA program of the 1960s and early 1970s.
- 2) SP-100 concept development program (Ref 1-1).
- 3) SP-100 thermionic technology program (Ref 1-2).
- 4) Thermionic irradiations program in TRIGA in FY-86 (Ref 1-3).
- 5) Thermionic Technology Program in 1986 and 1987 (Refs. 1-4, 1-5).

These programs provided both the systems and technology expertise necessary to design and demonstrate a megawatt class TFE.

A TFE was designed that met the reliability and lifetime requirements for a 2 MW(e) conceptual reactor design. Analysis showed that this TFE could be used over the range of 0.5 to 5.0 megawatts. This was used as the basis for designing components for test and evaluation. The demonstration of a 7-year component lifetime capability was through the combined use of analytical models and accelerated, confirmatory tests in a fast reactor. Iterative testing was performed where the results of one test series led to evolutionary improvements in the next test specimens.

The TFE components underwent screening and initial development testing in ex-reactor tests. Several design and materials options were considered for each component. As screening tests permitted, down selection occurred.

In parallel with the ex-reactor testing, and fast reactor component testing, components were integrated into a TFE and tested in the TRIGA test reactor at GA. Realtime testing of partial length TFEs was used to test support, alignment, and interconnective TFE components, and to verify TFE performance in-reactor with integral cesium reservoirs. Realtime testing was also used to verify the relation between TFE performance and fueled emitter swelling, to test the durability of intercell insulation, to check temperature distributions, and to verify the adequacy over time of the fission gas venting channels.

Figure 1-2. Logic to Demonstrate Technology Readiness of Megawatt Class TFE

Predictions of TFE lifetime rested primarily on the accelerated components testing results, as correlated and extended to realtime by the use of analytical models.

1.3 Organization of the TFE Verification Program Participants

Contracting Agency: Department of Energy, San Francisco Operations Office

Prime Contractor: General Atomics (GA)

Subcontractors:

ThermoTrex Corporation (TTC), a subsidiary of Thermo Electron Corporation

Rasor Associates, Incorporated (RAI)

Space Power Incorporated (SPI)

Fast reactor testing manager:

Westinghouse Hanford Corporation (WHC)

Fast reactor facilities:

Fast Flux Test Facility (FFTF), with testing managed by WHC

EBR-II, with testing managed by Argonne National Laboratory-West (ANL-W)

Technical oversight for DOE: Los Alamos National Laboratory (LANL).

1.4 Structure of Test Program

The TFE Verification Program was broken down into 7 tasks, generally corresponding to the components of a TFE. Figure 1-3 shows a thermionic cell with the various components identified.

Figure 1-4 shows a one-cell TFE fabricated for test in the program. A multi-cell TFE has 2 or more cells in series.

When compared to Figure 1-1, it is clear that this test article is not quite prototypical. The test conditions dictate the design to some extent. Als, the test approach is to first test simple TFEs and then gradually test TFEs more prototypic.

Figure 1-3. Thermionic Cell

Figure 1-4. One Cell TFE Test in TFE Verification Program

For each component the work involved:

- 1) Component design and analyses
- 2) Materials evaluation and selection
- 3) Performance testing
- 4) Life testing, both accelerated and realtime.

In addition, performance models were developed from converter performance, fueled emitters, and cesium reservoirs.

A brief description of each task is given below. For each of the component tasks, fabrication process specifications were developed and materials were chosen.

1.4.1 Conceptual Design. This task is the subject of this report. A TFE optimized for a 2 MW(e) system was designed. Its scalability over the range of 500 kW to 5 MW was demonstrated.

1.4.2 Converter Performance. The performance of converters of interest for megawatt class systems was measured and existing models on converter performance were refined.

1.4.3 Insulator Seals. The insulator seal isolates the space filled with gaseous fission products from the cesium-filled interelectrode gap. It also routes the electron flow from the collector of one cell to the emitter of an axially adjacent cell.

1.4.4 Sheath Insulators. The sheath insulator is composed of three layers:

- The inner layer is the collector.
- The middle layer is an insulator isolating the collector from the reactor coolant and structure.
- The outer layer is a metallic sheath that assures the structural integrity of the sheath.

1.4.5 Fueled Emitters. The fueled emitter is the emitter component inside of which are the following components:

- UO₂ fuel.
- Fuel holddown device to prevent damage to the cell during launch and ascent.
- Fission product trapping components to trap solid and condensable fission products and prevent them from exiting the cell.
- Heat shields to protect the upper and lower parts of the emitter from the high temperatures of the UO₂.

1.4.6 Cesium Reservoir and Interconnected Components. The cesium reservoir provides cesium vapor to the interelectrode gap. A graphite cesium reservoir was demonstrated in the program.

Interconnective components are those metal parts and insulators which are necessary to attach one cell in series with another.

1.4.7 TFEs. The TFE is an axial series of one or more cells. It also contains a cesium reservoir. TFEs with one, three, and six cells were fabricated and tested. The TFEs fabricated under the TFE Verification Program are designated the "H" series TFEs, the next series following the "E", "F", and "G" series, which were studied in the 1960s and 1970s. The E series TFEs had an emitter diameter of 0.625 in.; the F series, 1.1 in.; and the H-series, 0.5 in.

A specific TFE has the designation xHy, the "x" being the number of cells in the TFE and the "y" being the specific TFE in question. For example, the TFEs fabricated and tested in the program were:

TFE-1H1, the first of the 1-cell TFEs.

TFE-1H2, the second of the 1-cell TFEs.

TFE-1H3, the third of the 1-cell TFEs.

TFE-3H1, the first of the 3-cell TFEs.

TFE-3H5, the fifth of the 3-cell TFEs. Numbers 2,3, and 4 were eliminated early in the program.

TFE-6H1, the first of the 6-cell TFEs.

1.5 Semiannual Progress reports

Semiannual progress reports provide a running account of technical progress which reflects the work done at GA,TTC,RAI, and SPI. These reports also summarize the status and results of the irradiation program at WHC and ANL-W. The technical work performed at LANL is also summarized there.

Table 1-1 shows a complete list of all semiannual progress reports.

1.6 Final Reports

Final test reports give details on each of the major components outlined in Section 1.4. A list of these final reports is given in Table 1-2. It is assumed in these reports that the reader is familiar with thermionic technology and the structure and operation of thermionic fuel elements and their components.

Table 1-1

SEMIANNUAL PROGRESS REPORTS

Period Ending	Date Issued	Report Number
March 31, 1987	April 1987	GA-A18780
September 30, 1987	March 1988	GA-A19115
April 30, 1988	June 1988	GA-A19269
October 31, 1988	January 1989	GA-A19412
April 30, 1989	September 1989	GA-A19666
September 30, 1989	March 1990	GA-A19876
March 31, 1990	July 1990	GA-A20119
September 30, 1990	January 1991	GA-A20335
March 31, 1991	April 1991	GA-A20493
September 30, 1991	December 1991	GA-A20804
March 31, 1992	April 1992	GA-A20911
September 30, 1992	January 1993	GA-A21210
March 31, 1993	May 1993	GA-A21326
September 30, 1993	January 1994	GA-A21511

Table 1-2

FINAL RESULTS OF TFE VERIFICATION PROGRAM

Report Title	Document No.
TFE Conceptual Design	GA-A21590
Converter Performance Final Test Report	GA-A21591
Insulator Seal Final Test Report	GA-A21592
Sheath Insulator Final Test Report	GA-A21593
Fueled Emitter Final Test Report	GA-A21594
Cesium Reservoir Final Test Report	GA-A21595
TFE Performance Final Test Report	GA-A21596

2. CONCEPTUAL DESIGN TECHNICAL APPROACH

The technical approach taken in the concept design effort was:

- 1) Perform system-level tradeoffs to determine initial TFE features and reactor scalability trends;
- 2) Refine these results and identify the 2 MW(e) reactor general arrangement with primary emphasis on characterizing the features and performance of the TFE;
- 3) Enter this information into the program data base via two separate design description documents:
 - Two MW(e) reactor-converter system description.
 - TFE component specification.

3. DESIGN DESCRIPTIONS

3.1 System

System Design Description Document (SDD) No. 908954 was generated to document the 2 MW(e) Reactor-Converter system design. This document is provided in Appendix A; highlights of the work are presented here.

The 2 MW(e) thermionic space power system arrangement is similar to that shown in Figure 3-1, which shows a TFE-type thermionic reactor outermost from the payload, followed by the radiation shadow shield, the main radiator, and the boom that maintains a discrete separation distance between the reactor and payload. The reactor converts nuclear heat directly into low-voltage dc electric power within the TFEs and transmits this output to a low-voltage power conditioner situated directly behind the shield. The low-voltage power conditioner reconfigures the power to accommodate both the payload and housekeeping needs. A closed, pumped lithium loop cools the reactor and delivers the reject heat to the main radiator, which dumps the heat to space. The main radiator surface consists of finned heat pipes that are arranged to form a conical frustum.

The vital statistics of the system and overall energy balance for the system are presented in Appendix A. These results were optimized to minimize system specific mass, kg/kW(e), using an emitter work function (emitter material parameter) of 4.9 eV. Subsequent to this work, the system was reoptimized for an emitter work function of 4.78 eV, which was felt to be more representative of the thermionic performance being experimentally demonstrated in the program. The reoptimization had a minor impact on the system parameter selections. The changes were not significant enough to affect the matrix of test conditions established for TFE verification hardware. Table 3-1 compares the results of the reoptimized parameters with the original reference values presented in Appendix A. The system tradeoffs supporting this reoptimization are presented later in this section.

3.2 Reactor Overview

The SDD 908954 document described above contains a section describing the design of the 2 MW(e) reactor. Figure 3-2 shows a cutaway schematic of the reactor arrangement, and Figures 3-3 and 3-4 provide elevation and plan section views of the design. A summary of the design features is tabulated in Table 2 of the SDD. The fast spectrum reactor concept follows the generic thermionic space power approach of housing a close-packed array of TFEs within a Nb-1Zr vessel with the lithium coolant flow making one axial pass over the reactor core elements. The multicell TFEs, which contain the nuclear fuel within each thermionic converter, are electrically clustered in groups of seven to help minimize the number of penetrations in the reactor vessel. Reactivity control is provided by an array of cylindrical control drums surrounding the reactor vessel, acting in conjunction with in-core control rods. Reactor control analysis was beyond the scope of this conceptual design effort. The reactor vessel and coolant-exposed internals are an electron beam welded, all-Nb-1Zr alloy assembly.

Table 3-1.
Impact of Reoptimized Parameters for the 2 MW(e) System

	<u>Original Ref</u>	<u>Reoptimized</u>
Emitter Material Parameter	4.9 eV	4.78 eV
Collector Temperature	1070 K	1000 K
Converter W(t)/W(e)	658/65.2	594/55.2
Optimum Diode Gap (Pd)	20 mil-torr	30 mil-torr
Converter W(t)/cm	137.8	124.5
Emitter W(e)/cm ²	3.22	2.72
TFE Electrical Output	782 W(e)	662 W(e)
TFEs per Reactor	2849	3021
System Efficiency	8.9 %	9.3 %
System kg/kW(e)	11.3	12.1
(OTHER PARAMETERS REMAIN UNCHANGED)

Figure 3-1 Space Power System Concept

Figure 3- 2. Schematic of 2 MW(e) Reactor Arrangement

Figure 3-3. Reactor Elevation View

Figure 3-4. Reactor Section View

3.3 TFE Overview

The features of the TFE and the individual thermionic converters which go into its assembly are presented in the Reference TFE Specification, provided in Appendix B. Figure 3-5 shows the arrangement of a typical 7-element TFE cluster, and Figure 3-6 shows the thermionic converter arrangement. The converters within each TFE are series-connected to build up the voltage over the length of the TFE, which can then be connected to its neighbors in a series-parallel network to produce the required voltage and circuit redundancy.

3.4 Reactor Safety Features

The megawatt class thermionic reactor has inherent safety features similar to those of the thermionic SP-100 reactor (Ref. 3-1). The power density of the 2 MW(e) core is significantly lower than that of a typical sodium-cooled breeder reactor, reducing core temperature gradients. One-dimensional thermal analysis shows that the reactor will withstand a sudden loss-of-coolant accident without melting internal core elements [Ref 3-2]. Reactor safety features are discussed in more detail in SDD 908954, Appendix A.

Figure 3-5. TFE Arrangement for 2 MW(e) Reactor

Figure 3-6. Thermionic Converter Arrangement

4. SYSTEM TRADEOFFS

4.1 Technical Approach

System parametric data were generated with "IN-CORE," a flexible in-core thermionic space nuclear power system code initially developed by Space Power Inc., and updated during this task to incorporate additional refinements in the thermionic and nuclear portions of the model. A code description and flow chart are included in SDD 908954.

System specific mass was the parameter used to optimize the concept design. Constraints and assumptions included:

Radiator mass	15 kg/m ²
Coolant	Lithium
Shield cone half-angle	12 deg
Power conditioning	96 % efficient @ 0.3 kg/kW(e)

The radiator mass assumption is very dependent on radiator configuration and orbital environment.

The TFE which emerged from the system studies is defined in Table 3-2, along with the rationale for the specification.

Table 3-2
TFE DEFINITION

Parameter	Nominal Value	Rationale
Emitter Temperature	1800 K	Tradeoff between long life (low temperatures and high performance (high temperatures)
Emitter Diameter	0.5 in.	Small diameters are favored at 2 MW(e). Fabricability considerations limit diameter to 0.5 in. or more Criticality considerations at 500 kW(e) appear acceptable at 0.5 in.
Interelectrode Gap	0.01 in.	Fuel swelling considerations suggest larger gaps. Performance improves with small gaps. The 0.01 in. gap is a compromise which accommodates fuel swelling over a 7-year lifetime.

(continued next page)

Table 3-2
TFE DEFINITION (continued)

Parameter	Nominal Value	Rationale
Fuel Enrichment	93 %	Fuel zoning is accomplished by emitter length and central hole volume variation. Only one enrichment is desired for fabrication plant.
TFE Output Voltage	≤ 15 V	Limit stress on sheath insulator.
Emitter Work Function	4.78 eV	Achievable with oriented tungsten. See earlier remarks in this section on reoptimized parameters.
Emitter Length	2.0 in.	Optimum cell L/D.
Emitter Thickness	≥ 0.040 in.	Smaller values are desired for criticality; larger values yield longer life. The 0.040 in. appears to meet lifetime requirement.
Emitter Current Density	7 amp/cm ²	Near-optimum for system specific mass; acceptable emitter distortion.

4.2 Tradeoffs

Figures 4-1 through 4-4 are parametric surveys at the 2 MW(e) output power level showing how the system specific mass reacts to the changes in important thermionic parameters, assuming an emitter work function of 4.78 eV. The results, which are similar to those of the 4.9 eV study presented in SDD 908954 indicate that the reference TFE design points are near-optimum for low system specific mass. Within the study constraints, some of the more important tradeoffs and trends exhibited are:

1. Emitter Diameter: System specific mass benefits from improving emitter surface-to-volume ratio, reducing the size of the reactor for a given output. The original study presented in SDD 908954 demonstrates this effect. With the emitter diameter at a fabrication minimum, there was no need to reexamine this result in the system reoptimization.
2. Optimum Emitter, Collector Temperatures: Thermionic output improves with higher emitter temperature. The 1800 K nominal emitter temperature

yields good performance and is conservative relative to the technology being demonstrated. The optimum collector temperature, which results from a tradeoff between thermionic performance and radiator size, reoptimized at 1000 K, as shown in Figure 4-1.

3. Optimum Emitter L/D: For a given emitter diameter, the optimum emitter length corresponds to an emitter length-to-diameter ratio of about four, as shown in Figure 4-2. The tradeoff is cell electrical losses against parasitic intercell length.
4. Interelectrode Gap: Specific mass optimizes at a gap pd (cesium pressure multiplied by gap size) of about 30 mil-torr, as shown in Figure 4-3. A gap size of 0.010 in., which is about minimum for a 7-year lifetime and remains within fabrication limits, requires a cesium pressure of about 3 torr. Reducing gap size further, which would produce only marginal improvement.
5. Current Density: The current density optimization balances ohmic losses at high current density against increased emitter surface area needs at low current density. With an emitter work function of 4.78 eV the system specific mass minimizes at emitter current densities in the range of 7 amp/cm², as shown in Figure 4-4, which gives acceptable lifetime.

The specific mass data discussed above do not, of course, reflect spacecraft integration criteria. Nevertheless, they show the low specific mass capability of megawatt-class thermionic power systems. While these results are based on using lithium for the reactor coolant, it should be noted that falling back to NaK-78 may offer dormancy advantages that outweigh its 1 to 2 kg/kW(e) system mass penalty.

Figure 4-1. Collector Temperature Optimization

Emitter dia. = 0.5 in

Figure 4-2. Converter L/D Optimization

Figure 4-3. Interelectrode Gap Pd Optimization

Emitter dia. = 0.5 in

Figure 4-4. Current Density Optimization

5. SYSTEM SCALABILITY

With the parameter selections discussed above, the IN-CORE code was used to develop the scalability characteristics of the 2 MW(e) system. The results are shown in Figure 5-1, which is a semilog plot of system specific mass vs. electrical power output. The study, which covers the output power range of 500 kW(e) to 5 MW(e), shows the economy of scale benefits of going to higher system power levels.

Emitter dia. = 0.5 in

Figure 5-1. System Scalability

6. ALTERNATE DESIGN OPTIONS

Two side studies were included in support of the 2 MW(e) reactor design effort. An alternate emitter stem approach was reviewed as a possible backup for improving reactor core compactness, and the merits of using oxygenated electrodes for improving thermionic performance and/or life time were considered. The results of these investigations are summarized below.

6.1 Alternate Emitter Stem Study

Thermal analysis and materials compatibility reviews were conducted to evaluate the potential benefits in changing the emitter stem material from tungsten to a Mo-Re alloy. The incentives for exercising this option are:

1. Structural improvement - The lower thermal conductivity of Mo-Re alloys compared to that of tungsten suggests that a Mo-Re stem will optimize to a shorter, thicker configuration, resulting in a more rugged emitter construction. The tungsten emitter stem thickness is governed by the minimum practical fabrication limit, which is above thermionic optimum.
2. Thermionic Performance improvement - Temperature dropoff due to thermal conduction out the stem should be reduced in an emitter with a Mo-Re stem.
3. Nuclear Performance Improvement - If, as suggested above, a shorter stem is realizable without compromising performance, the axial gap between converters within a TFE can be reduced. Assuming that the neutronic effect of adding Re is more than offset by the increased core compactness, this should provide additional excess reactivity capability within the TFE envelope, which can be used to flatten the core power distribution and/or reduce the core fuel loading.

Although the chemical compatibility between UO₂ and Mo-Re has not been studied under carefully controlled experimental conditions, some inferences can be made on the basis of previous ~~in place of~~ using devices which contain Mo, Re, and Mo-Re components.

Molybdenum was the emitter material for the French in-pile converters fueled with Mo-UO₂ cermet. Molybdenum was the cladding material in contact with UO₂ fuel in the German in-pile converters. A Mo-UO₂ cermet was also used to fuel the LANL in-pile test devices. These tests have been run over thousands of hours or longer at temperatures of 1873 K or higher. No gross chemical interaction between Mo and UO₂ was reported.

Rhenium was used as the shields directly over the UO₂ fuel in the GA I-4 emitter tested in-pile at 1900 K emitter temperature for 9875 hours. No reaction between the Re and UO₂ was observed.

The alloy Mo-50Re was used as the stem for holding Mo-UO₂ cermet fueled samples tested in-pile at 1700-2140 K fuel temperature for 2300 - 10,400 hr. No gross attack of the Mo-50Re stem by UO₂ was reported.

W-Mo-Re alloys have been used as the cladding for W-UO₂ cermet fuel irradiated at about 1873 K on the GE NMPO program. No gross attack of the cladding by UO₂ was reported.

On the basis of these observations, it is believed that no chemical compatibility problem should be expected for a MoRe stem, and any UO₂ condensed on it, if the temperature is held below 1873 K. However, the fission gas formed from the condensed UO₂ may enter the stem material by fission recoil, leading to the formation of bubbles at the grain boundaries. This effect should not seriously affect stem integrity, because the recoil range is on the order of only a few microns.

• Thermal analysis confirmed that a modest incentive exists to go to a MoRe stem. The results showed that the tungsten stem configuration used in the reference converter design has an efficiency slightly less than optimum and that the efficiency of 0.0508 cm (0.020 in.) thick Mo-Re stems exceeds that of equivalent tungsten geometries at stem lengths up to approximately 1.5 cm. The efficiency advantage of Mo-Re is greater at shorter stem lengths, but is a modest improvement in any event (e.g., ~ 10.8 % compared to 10.5 % for the reference emitter configuration). At this time, the minimum stem length is governed by the insulator seal envelope.

It was concluded that the case for Mo-Re was not strong enough to warrant further investigation, and the subject was shelved, pending further evolution of the TFE design toward shorter stem lengths.

6.2 Oxygenated Electrode Study

Oxygenation permits better cesium adsorption on electrodes. This permits going to a lower interelectrode gap pressure and/or a wider gap, but the thermionic performance

tends to optimize at lower collector temperatures. Based on Thermoelectron Converter #282 [Ref. 3], oxygenated converters require an initial "running in" period of several tens of hours before the anticipated performance increase can be realized.

In the context of the 2 MW(e) reactor design, how to oxygenate becomes an issue because collector temperatures well above optimum can reduce the stability of the oxide layer and promote decomposition. Raising the collector temperature not only exacerbates this problem but also increases back-emission, which degrades performance. Therefore, it appears that the viability of oxygenation (by conventional techniques) as a backup option for increasing the lifetime of the 2 MW(e) reactor hinges upon whether or not the consequences of a lower collector temperature are acceptable. At collector temperatures in the range of 1070 K and above, severe performance degradation can be anticipated. At collector temperatures nearer the optimum for oxygenated electrodes, 850 K to 950 K, preliminary calculations suggest that it may be possible to obtain about the same system specific mass as that of the current reference (non-oxygenated) case. The reactor is smaller, and the radiator is probably somewhat larger. Shield implications were not assessed.

7. REFERENCES

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8. APPENDICES

Two appendices are contained in the following pages. Appendix A is GA Document No. 908954, "Two MW(e) Reactor-Converter System Description Document (SDD)." Appendix B is GA Document No. 908955, "Reference TFE Specification."

APPENDIX A:
REACTOR-CONVERTER SYSTEM DESIGN DESCRIPTION

GA Technologies Inc.

ISSUE SUMMARY

TITLE REACTOR-CONVERTER SYSTEM DESIGN DESCRIPTION ☒ R & D ☐ DV & S ☐ DESIGN APPROVAL LEVEL 5

DISCIPLINE M	SYSTEM NA	DOC. TYPE SDD	PROJECT 3450	DOCUMENT NO. 908954	ISSUE NO./LTR. 0
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QUALITY ASSURANCE LEVEL NA	SAFETY CLASSIFICATION NA	SEISMIC CATEGORY NA	ELECTRICAL CLASSIFICATION NA
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ISSUE	DATE	PREPARED BY	APPROVAL				ISSUE DESCRIPTION/ CWBS NO.
			ENGINEERING	QA	FUNDING PROJECT	APPLICABLE PROJECT	
0	AUG 09 1988	T. Van Hagon <i>T. Van Hagon</i> <i>A.R. Vega</i> <i>M.H. Horner</i> <i>T. Van Hagon</i>	<i>A.R. Vega</i> <i>M.H. Horner</i> <i>T. Van Hagon</i>	<i>J. Dunlap</i> <i>T. Dunlap</i>		<i>R. Dahlberg</i>	Initial issue 345002100

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1. INTRODUCTION AND SCOPE

This document describes the features and parametric aspects of megawatt-class thermionic space power systems with primary emphasis on the reactor and its thermionic performance. The parametric and statistical information presented are based on a system with 7-year output power capability of 2 MW(e). While the system discussed here has been conceived to be a steady-state power producer, it is important to note that megawatt-class thermionic systems based upon the same reactor concept can also be designed with energy storage to provide burst power at 10's to 100's of megawatts capacity.

The reactor design uses nuclear fuel and thermionic power conversion concepts based upon the technology demonstrated in the early 1970s under the Atomic Energy Commission (AEC) and the National Aeronautics and Space Administration (NASA) sponsorship. This technology development resumed in 1983 with the Department of Defense (DoD), NASA, and the Department of Energy (DOE) support for the SP-100 program, and it is continuing in the current DOE/SDIO-sponsored Thermionic Fuel Element (TFE) Verification Program. The aim of this program is to demonstrate the technology readiness of a TFE designed for service in a megawatt-class reactor with a full power life of 7 years. Accordingly, the TFE concept for this class of reactors is a cesium-vapor diode, operating in the ignited mode.

The system design effort represented herein resulted in a TFE design and component designs that are the basis for the test program of the TFE Verification Program. Performance requirements were also, of course, derived from the system design.

While the parametric discussions focus on the 2 MW(e) system, additional data is included to demonstrate that this thermionic system concept scales well over the output power range of 500 kW(e) to 5 MW(e) without having to change the basic TFE design approach.

This document presents work sponsored by DOE under Contract DE-AC03-86SF16298 and is the final milestone under Task 2 of the Statement of Work.

2. APPLICABLE DOCUMENTS

2.1. GENERAL

This system design description (SDD) is the top-level document in the TFE verification program technical document tree (shown in Fig. 1). This document provides the system basis for the parameters reflected in the reference TFE specification (Document 908955) which defines the TFE used in the 2 MW(e) reactor design and serves as the basis for the test program.

3. DESCRIPTION

3.1. SYSTEM FEATURES

The 2 MW(e) thermionic space power system arrangement is similar to that shown in Fig. 2. The arrangement is similar to most space nuclear power systems: the thermionic reactor is the system element outermost from the payload, followed by a radiation shadow shield, the main radiator, and finally the boom, which maintains a discrete separation distance between the reactor and payload. The reactor converts nuclear heat directly into low-voltage dc electric power and transmits this output to a low-voltage power conditioner situated directly behind the shield. The low-voltage power conditioner reconfigures the power to accommodate both the payload and housekeeping needs.

The radiation shadow shield has the shape of a conical frustum and is interposed between the reactor and the balance of system to create a radiation-protective shadow for sensitive equipment. The shield attenuates both neutron and gamma radiation generated by the reactor source to tolerable levels at the equipment locations.

TFE Verification Program Technical Document Tree

Fig. 1. TFE verification program technical document tree

Fig. 2. Space power system concept

The reactor is cooled by electromagnetically pumped liquid metal, lithium, circulating in a closed heat transport loop that couples the reactor to the main radiator. The coolant loop is concerned only with the low-temperature, heat rejection end of the thermionic power conversion process, permitting the entire reactor coolant system to operate at temperatures within existing liquid metals technology. In addition to the electromagnetic pump, the coolant loop also contains a coolant expansion reservoir and reactor decay heat removal provisions.

The main radiator is a cone-cylinder arrangement with heat rejection carried out by thermal radiation on the outer surface. The radiating surface consists of a large array of heat pipes brazed to a heat exchanger in the coolant loop. The system reject heat is conducted from the liquid metal coolant across the heat exchanger wall into the evaporator sections of the heat pipes. The heat pipes ensure efficient distribution of the reject heat over the radiating surface.

The use of Nb-1Zr refractory alloy throughout the system and the diodic operating characteristics of the heat pipes in the radiator make the thermionic system inherently capable of surviving laser threats without requiring shutdown of the reactor. Vulnerable elements of the system are protected by the radiator, neutron shield, and reactor control elements. These inherent system survivability advantages are available at no increase in system mass.

Table 1 presents the vital statistics of the 2 MW(e) system, and Fig. 3 shows the overall energy balance.

3.2. REACTOR DESCRIPTION

The general arrangement of the 2 MW(e) reactor conceptual design is shown schematically in Fig. 4 and Table 2 summarizes its key features. Except for its size, the reactor concept and configuration are similar to those of the SP-100 in-core thermionic reactor design, calling for a

TABLE 1
SUMMARY OF 2 MW(e) SYSTEM FEATURES

Net electrical power	2010 kW(e)
System efficiency	8.9%
System full-power lifetime	7 yr
Shield cone half-angle	12 deg
Payload diameter x separation	5 x 25 m
Reactor	
Reactor thermal power	22.5 MW(t)
Reactor coolant	Lithium
Coolant flow rate	48.5 kg/s
Coolant pump input power	25.1 kW(e)
Shield	
Dose plane limits	
Neutrons	1×10^{13} nvt
Gammas	5×10^5 rad (si)
Gamma shield thickness	7.87 cm
Neutron shield thickness x diameter	61.5 cm x 1.31 m
Reflector wing thickness x diameter	46.5 cm x 1.54 m
Reflector wing weight	198 kg
Scatter wing thickness x diameter	36.9 cm x 2.07 m
Scatter wing weight	446 kg
Radiator	
Reject heat	20.3 MW(t)
Effective surface temperature	1020K
Emissivity	0.85
Area	426 m ²
PC radiator area	43.7 m ²
System mass	
Reactor	8,720 kg
Shield	2,803
Coolant loop	1,788
Main radiator	6,390
PC and shield	1,230
PC radiator	262
Power cables	509
Structure and miscellaneous	791
<hr/>	
Total system	22,490 kg

*HYDRAULIC FEEDBACK INTO MAIN RADIATOR LOOP TREATED AS NEGLIGIBLE.

Fig. 3. 2 MW(e) system energy balance diagram

Fig. 4. Reactor schematic

TABLE 2
SUMMARY OF REACTOR FEATURES

Reactor diameter, cm	127
Reactor length, cm	149
Core diameter, cm	102
Core length, cm	100
Side reflector thickness, cm	11 (including 2.5 cm poison)
End reflector thickness, cm	10 (including 2 cm poison)
No. of TFEs	2849
Fuel	UO ₂ , 93% enriched
Burnup, a/o	4.1 average; 5.3 peak
Fuel fraction/void fraction	0.24/0.103
Fluence, nvt	2.7×10^{22} (average); 3.5×10^{22} (peak)
Emitter temperature, K	1800
Collector temperature, K	1070
Output voltage	≈ 15
Current, amp	140
Coolant inlet temperature, K	950
Coolant exit temperature, K	1050
Coolant velocity, m/s	1.4
Coolant pressure drop, MPa	0.02

close-packed array of TFEs to be housed within a Nb-1Zr reactor vessel that is headered to route the lithium coolant flow in one axial pass over the elements.

The thermionic converters, which contain the nuclear fuel, are fashioned in the form of cylindrical fuel rods that are close-packed within the core. Each such TFE contains thermionic converters stacked electrically in series in a manner similar to a multiple-battery flashlight. Axial reflection of neutrons is accomplished by incorporating axial sections of neutron reflecting material at both ends of each TFE. The TFE electrical leads penetrate the reactor vessel at one end only and are externally converted in parallel to busbars which deliver the reactor electrical output to the power conditioner. The TFEs are electrically clustered in groups of seven to produce a seven-fold reduction in the number of penetrations in the vessel.

Reactivity control is provided by an array of control drums surrounding the reactor vessel, acting in conjunction with a set of in-core rods. The control drums contain BeO reflector material with B_4C poison segments. Although reactor control analysis is beyond the scope of the conceptual design effort, it should be noted that the 2 MW(e) reactor is well beyond core criticality limits and can readily accommodate additional control rods with minimal envelope impact.

Several coolant headering schemes are possible for the 2 MW(e) reactor. Figure 5 shows one such approach: the coolant enters the vessel through radial nozzles penetrating the vessel side wall; makes a single, axial heat transfer pass over the TFEs; enters a plenum outside the TFE bundle; and leaves the reactor through a central opening in the vessel head. Heat fluxes within the reactor are governed by the thermionic power conversion process and are, therefore, much lower than those encountered in typical liquid-metal fast reactors. This low heat flux and high liquid metal heat transfer coefficient in the reactor core combine with the high thermal conductivity of the TFE outer sheath to minimize circumferential thermal gradients in the TFEs even when they are

Fig. 5. Reactor elevation view

closely pitched. Temperature distributions in the reflector control drums and the reflector filler pieces mounted outside the reactor vessel are controlled by installing multifoil insulation on the outside of the vessel to limit heat flow into the drums, permitting the heat generated in the BeO reflector material, the B₄C neutron absorber material, and the niobium cladding material to be radiated to space. Figure 6 provides a section plan view through the reactor, showing the closely-pitched TFEs, the vessel wall, and the surrounding control drums and filler pieces.

The reactor vessel and coolant-exposed internals are an electron beam-welded, all-Nb-1Zr alloy assembly. The electrical lead from each TFE cluster is welded into a flat tubesheet head at one end of the reactor vessel, but the cluster is allowed to move axially to accommodate differential thermal growth. The other ends of the TFE clusters are stabilized radially by a grid plate that is perforated to pass the coolant flow while helping to redistribute it. Differential axial expansion is expected to be small, since the coolant is exposed only to Nb-1Zr alloy and the temperature gradients are small. The cylindrical wall, flat tubesheet head, and ellipsoidal head on the reactor vessel are sized to contain the anticipated peak coolant pressure.

The features of the TFE and the individual thermionic converters which go into its assembly are presented in the reference TFE Specification, General Atomics (GA) Document 908955.

The arrangement of a typical 7-element TFE cluster is shown in Fig. 7. Each individual thermionic converter within a TFE can be viewed as an assembly of concentric cylinders. Proceeding from the center outward, the key elements in each converter are the highly-enriched UO₂ fuel pellet; the oriented-tungsten emitter; and the outer trilayer, consisting of a niobium collector, ceramic insulator, Nb-1Zr outer layer. The nuclear reaction heats the emitter, which also serves as the fuel cladding, producing thermionic emission of electrons that travel across

Fig. 6. Reactor section view

Fig. 7. TFE cluster arrangement

a small radial gap to the collector. The voltage difference developed between the emitter and collector drives the electrons through the external load. The ceramic insulator electrically isolates the collector from the TFE Nb-1Zr sheath, preventing the individual converters from shorting to the coolant. The converters within each TFE are series-connected to build up the voltage over the length of the TFE, which can then be connected to its neighbors in a series-parallel arrangement that produces both the required reactor output voltage and the circuit redundancy used to achieve high reliability in the reactor design. The reactor output voltage selection is bounded by the minimum needed for efficient low-voltage dc power conditioning (typically about 15 V dc) and by the maximum consistent with ceramic insulator lifetime considerations.

3.3. REACTOR SAFETY FEATURES

The megawatt class thermionic reactor has inherent safety features similar to those of the thermionic SP-100 reactor. The emitter, tri-layer, and sheath provide multiple containment of the nuclear fuel within the TFE. This not only provides fuel retention for launch, orbit, and reentry scenarios but also enhances the nuclear safeguard capability of the reactor. Fuel retention is further enhanced by the high temperature strength of the refractory alloys used in the core construction. The heat flux to the coolant is about one-tenth that of a typical sodium-cooled breeder reactor, reducing core temperature gradients. The more uniform temperature profiles combine with the thick emitter cladding to minimize rod bowing or flow obstructions. The comparatively low core power density provides inherent passive cooling capability in the reactor. If a sudden loss of coolant occurs, internal core temperatures are maintained below the melting point by passive radiation heat transfer from the reactor vessel to space. Core heat removal reliability is high because diverse, ac-powered and thermoelectrically driven EM pumps ensure the required amount of reactor coolant circulation without the need for mechanical check valves and because

the relatively low reactor coolant temperature provides ample piping system design margin. The reactor in-core control rods, which are fully inserted and locked until the desired orbit is achieved, assure reactor subcriticality for all suborbital events. In addition to being an independent and diverse shutdown system, the rods provide end-of-life shutdown capability.

4. SYSTEM TRADE-OFFS

4.1. TECHNICAL APPROACH

The technical approach used to identify the 2 MW(e) reactor concept can be characterized as follows:

1. Perform system-level trade-offs to determine initial TFE features and reactor scalability trends.
2. Refine these results and identify the 2 MW(e) reactor general arrangement with primary emphasis on characterizing the features and performance of the TFE.

System parametric data were generated with in-core, a flexible in-core thermionic space nuclear power system code initially developed by Space Power, Incorporated and updated to incorporate the following nuclear and thermionic modifications:

- Nuclear modifications
 - Six group diffusion theory.
 - R-Z two-dimensional synthesis.
 - Three axial by 3 radial fuel zones/quadrant.

- Thermionic modifications
 - Emitter stem optimization.
 - Emitter deformation prediction.
- As a result of these enhancements, the following capabilities are now available with the code:
 - Obtain axial and radial power profiles in core.
 - Determine thermionic operating conditions in each fuel zone.
 - Predict emitter distortion in each fuel zone.
 - Shift fuel among zones to minimize emitter distortion.

A flow chart showing how these modifications were integrated into the thermionic reactor model is shown in Fig. 8.

System specific mass was the parameter used to optimize the concept design. For the classical reactor-shadow-shield-radiator arrangement discussed in Section 3.1, the following assumed system parameters were considered representative:

Radiator mass	15 kg/m ²
Coolant	Lithium
Shield cone half-angle	12 deg
Power conditioning	96% efficient - 0.3 kg/kW(e)

The radiator mass assumption is very dependent on radiator configuration and orbital environment.

The TFE which emerged from the system studies is defined in Table 3, along with the rationale for the specification.

"INCORE" PROGRAM WITH NEUTRONICS

Fig. 8. "In-core" program with neutronics

TABLE 3
TFE DEFINITION

Parameter	Nominal Value	Rationale
Emitter temperature	1800 K	Tradeoff between long life (low temperatures) and high performance (high temperatures)
Emitter diameter	0.5 in.	Small diameters are favored at 2 MW(e). Fabricability considerations limit diameter to 0.5 in. or more. Criticality considerations at 500 kW appear acceptable at 0.5 in.
Interelectrode gap	0.01 in.	Fuel swelling considerations suggest larger gaps. Performance improves with small gaps. 0.01 in. is a compromise which accommodates fuel swelling over a 7-year lifetime.
Fuel enrichment	93%	Fuel zoning is accomplished by emitter length and central hole volume. Only one enrichment is desired for fabrication plant.
TFE output voltage limit	15 V	Higher voltages put greater stress on the sheath insulator.
Emitter work function	4.9 eV	Achievable with oriented tungsten.
Emitter length	2.0 in.	Emitter diameter-to-length ratio of 1/4 gives acceptable current density and low unfueled volume.
Emitter thickness	≥ 0.040 in.	Small emitter thicknesses are desirable from the criticality point of view. Larger thicknesses yield longer life. 0.040 in. appears to meet lifetime requirements.
Emitter current density	7 amp/cm ²	The tendency of system mass to optimize at current densities higher than 7 amp/cm ² must be traded off against reduced lifetime resulting from increasing the energy density of the fuel. The present values of 7 amp/cm ² gives acceptable emitter distortion.

4.2. SYSTEM TRADE-OFFS

Figures 9 through 13 are parametric surveys at the 2 MW(e) output power level showing how the system specific mass reacts to change in the important thermionic parameters. The results indicate that the reference TFE design points are near optimum for low specific mass. Within the study constraints, some of the more important trade-offs and trends exhibited are:

1. Emitter diameter - System specific mass benefits from improving emitter surface-to-volume ratio, reducing the size of the reactor needed for a given power output.
2. Optimum emitter and collector temperatures - Thermionic output improves with higher emitter temperature. At a given emitter temperature, the optimum collector temperature results from a trade-off between thermionic performance and radiator size.
3. Optimum emitter L/D - For a given emitter diameter, the optimum emitter length corresponds to a length-to-diameter ratio (for the emitter) of about four. The trade-off is cell electrical losses against parasitic intercell length.
4. Interelectrode gap - Specific mass is reduced for small inter-electrode gaps. However, below about 0.010 in., the sensitivity is small.
5. Current density - Emitter current densities in the 10 amp/cm² range minimize system mass but increase emitter swelling, which in turn reduces lifetime. A current density of 7 amp/cm² gives acceptable system lifetime.

Fig. 9. Effect of emitter temperature and diameter

Fig. 10. Effect of collector temperature

Fig. 11. Effect of current density and aspect ratio

Fig. 12. Effect of diode gap

Fig. 13. Effect of current density on emitter deformation

The specific mass data do not, of course, reflect spacecraft integration criteria. Nevertheless, they show the low specific mass for megawatt class thermionic power systems. While these results are based on using lithium for the reactor coolant, it is important to note that falling back to NaK-78 may offer dormancy advantages that outweigh its 1 to 2 kg/kW(e) system mass penalty.

4.3. ALTERNATE DESIGN OPTIONS

Two side studies were pursued in support of the 2 MW(e) reactor design effort. An alternate emitter stem approach was reviewed as a possible backup for improving reactor core compactness, and the merits of using oxygenated electrodes for improving thermionic performance and/or lifetime were considered. The results of these investigations are summarized below.

4.3.1. Alternate Emitter Stem Study

Thermal analysis and materials compatibility assessments indicate that utilizing Mo-Re stem designs in tungsten emitters is a backup design option. This would result in improved thermionic performance with a shorter and thicker stem. There appears to be no chemical compatibility problem between Mo-Re and UO_2 fuel, as long as the temperature is held below 1873 K. It is possible that fission gas formed from condensed UO_2 may enter the stem material by fission recoil, but this effect should be limited to a depth of only a few microns.

Pursuing Mo-Re stems as the primary design approach is not warranted at this time because the stem length is governed by the insulator seal envelope.

4.3.2. Oxygenation Option

(LATER)

5. SCALABILITY

(LATER)

(INTENTIONALLY OMITTED)

APPENDIX B:

REFERENCE THE SPECIFICATION

GA 1485 (REV. 10/82)

TITLE	REFERENCE TFE SPECIFICATION	☒ R & D ☐ DV & S ☐ DESIGN	APPROVAL LEVEL <u>2</u>
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QUALITY ASSURANCE LEVEL	SAFETY CLASSIFICATION	SEISMIC CATEGORY	ELECTRICAL CLASSIFICATION
NA	NA	NA	NA

CONTINUE ON GA FORM 1485-1	NEXT INDENTURED DOCUMENTS 908954
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1. SCOPE

This document provides a technical description of the reference thermionic fuel element (TFE) designed to serve as the basic element of in-core-thermionic space nuclear reactors in the output electric power range of 500 kW(e) to 5 MW(e). A point design at 2 MW(e) is used to make system trade studies and define an optimized TFE. The reference TFE and its associated operating requirements provide the technical guidance for the TFE Verification Program.

2. APPLICABLE DOCUMENTS

2.1. GENERAL

This specification currently occupies the second indenture level of the TFE Verification Program Document Tree, as shown in Fig. 1. The supporting documentation includes the technical data bases for the individual task categories in the TFE Verification program.

Figure 1

908955/2

TFE Verification Program Technical Document Tree

3. DESCRIPTION

3.1. FUNCTION

The TFE serves both as a nuclear fuel element and as a power conversion device in the in-core-thermionic reactor. Each TFE contains several series-connected thermionic converters, which convert heat directly into electricity. The thermionic power conversion process entails the emission of electrons from a hot metallic electrode heated by the nuclear fuel and migration of these electrons across a gap to a colder metallic electrode cooled by the reactor liquid metal coolant. A voltage difference is developed between the two electrodes to drive the electrons through an external payload or space craft.

3.2. KEY FEATURES

Figures 2 and 3 illustrate the physical arrangements of the TFE and an individual thermionic converter, respectively. The key components are identified by item number in Fig. 3, and their functions are summarized in Table 1.

3.3. DESIGN REQUIREMENTS

The reference TFE is designed to comply with the form, fit, and functional requirements of the 2 MW(e) reference reactor design addressed in SDD 908954. Envelope, weight, and opening conditions can be derived from the TFE design definition data provided in the following

Fig. 2. TFE schematic

Fig. 3. Thermionic converter details

TABLE 1
TFE AND CONVERTER FUNCTIONS

Item	Component	Primary Function	Secondary Function(s)
1	Fuel (UO_2)	Fission	- Heat emitter - Release fission gas
2	Emitter (W)	Emit electrons	- Contain/restrain fuel - Conduct heat and electricity - Separate Cs and fission gas
3	Collector (Nb)	Collect electrons	- Conduct heat and electricity - Separate Cs and fission gas
4	Insulator seal (ceramic/Nb)	Separate CS and fission gas	- Electrically insulate emitter and collector
5	Sheath insulator	Electrically insulate converters	- Conduct heat
6	Sheath (Nb-1 Zr)	Isolate converters and reactor coolant	- Maintain emitter-collector alignment
7	Insulation coating (ceramic)	Electrically insulate converters from sheath tube (backup function)	--
8	Radiation shield (W)	Intercept thermal radiation from fuel to intercell region	
9	Hold-down spring (W-25 Re)	Retain fuel pellets within emitter cup during fab, handling and launch	

TABLE 1 (Continued)

Item	Component	Primary Function	Secondary Function(s)
10	Cap (W) + transition (Ta) assembly	Provide series electric connection between converters	<ul style="list-style-type: none"> - Provide fission product channel - Provide Cs channel - Separate Cs and fission products - Guide hold-down spring - Guide emitter end restraint
11	Emitter end restraint	Structurally support fueled emitter assembly	<ul style="list-style-type: none"> - Maintain emitter-collector alignment

section. Technology criteria for identifying the reference TFE design include the following considerations:

1. Projected performance shall be based upon experimental data.
2. Maximum voltage across the insulators shall be less than 50 V at the TFE operating condition.
3. The reference TFE operating environment and dimensional stability shall be consistent with a 7 yr lifetime.
4. Where appropriate, the reference TFE design features will be selected to reduce technical risk, consistent with the overall program goal of verification.

3.4. DESIGN DEFINITION

Nominal performance and dimensional parameters for the reference TFE and the individual converter are summarized in Table 2.

TABLE 2
TFE DESIGN DEFINITION

PERFORMANCE

Overall TFE:

Output electrical power (We)	782
Efficiency	8.9
Max voltage	5.9
U235 burnup (a/o)	4.1 avg., 5.3 peak
Fluence (nvt)	2.7×10^{22} avg., 3.5×10^{22} peak

Converter:

Converter power (Wt/We)	658/65.2
Thermal power/length (wt/cm)	137.8
Emitter power Flux (We/cm ²)	3.22
Diode current density (a/cm ²)	7.0
Thermionic work function (eV)	4.9
Emitter temperature (K)	1800
Collector temperature (K)	1070
Cesium pd (mil-torr)	20
Converter output voltage	0.49
Converter current (amp)	140

CONFIGURATION

Overall TFE:

TFE length (active core) (in.)	39.6
TFE length (overall)	TBD
Sheath tube o.d. (in.)	0.694
Lead o.d. (in.)	0.875
Lead length (in.)	4
Converters per TFE	12

Converter:

Emitter o.d. x L x t (in.)	0.5 x 2.0 x 0.040
Emitter stem L x t (in.)	0.45 x 0.020
Diode gap (in.)	0.010
Trilayer t: Collector	0.028
Insulator (in.)	0.016
Outer cylinder	0.028

TABLE 2 (Continued)

Fuel specification	93% enriched UO_2 ; variable volume fraction
Intercell axial space (in.)	0.74
<u>MASS</u> (kg per TFE)	
Emitters	0.74
Trilayers	0.65
Fuel	0.65
Connectors & Misc.	<u>0.29</u>
TFE Total	2.33

REFERENCE DATA: TFEs per 2 MWe reactor = 2849
 (Other reactor and system data
 can be found in document 908954)

**DATE
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END

 