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THERMIONIC FUEL ELEMENT PERFORMANCE FINAL TEST REPORT TFE VERIFICATION PROGRAM

**Prepared under
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**GENERAL ATOMICS PROJECT 3450
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MASTER

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**THERMIONIC FUEL ELEMENT PERFORMANCE
FINAL TEST REPORT
TFE VERIFICATION PROGRAM**

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1. INTRODUCTION

1.1 Objective of TFE Verification Program

The program objective is to demonstrate the technology readiness of a Thermionic Fuel Element (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 on Figure 1-1. Only six cells are shown for simplicity; a megawatt class TFE would have many more cells, the exact number dependent on optimization trade studies.

1.2 Technical Approach

The TFE Verification Program built directly on 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 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 on Fig. 1-2. Five prior programs form the basis for the TFE Verification Program:

- 1) AEC/NASA program of the 1960s and early 1970s.
- 1) 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 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 test reactor. Iterative testing was performed in which 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 to very specific designs and materials.

In parallel with 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

Figure 1-1. TFE for Megawatt Class System

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

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.

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

1.3 Organization of the Program

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 Reactor (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-VP was broken down into 7 tasks, generally corresponding to the components of a TFE which are shown in Figure 1-3 and described more fully below.

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. Also, the test approach is to first test simple TFEs and then gradually test TFEs more prototypic.

For each component, the work involved:

- 1) Component design and analyses.
- 2) Materials evaluation and selection.

Figure 1-3. H-series Thermionic Cell (Typical of 3H1)

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

- 3) Performance testing.
- 4) Life testing, both accelerated and realtime.

In addition, performance models were developed for 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. 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 assures that electrons flow from the collector of one cell to the emitter of an axially adjacent cell.

1.4.4 Sheath Insulators. The sheath insulator is a structure composed of 3 layers:

- o The inner layer is the collector.
- o The middle layer is an insulator electrically isolating the collector from the reactor coolant and structure. It must also conduct reject heat to the reactor coolant.
- o The outer metallic layer 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:

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

1.4.6 Cesium Reservoir and Interconnective 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, being 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 inch; the F series, 1.1 inches; and the H series, 0.5 inches.

A specific TFE has a 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, ANL-W and LANL.

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 TEST REPORTS OF TFE VERIFICATION PROGRAM

Report Title	Document No.
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 and Interconnective Components Final Test Report	GA-A21595
TFE Performance Final Test Report	GA-A21596
TFE Design Package	GA-A21597
Fabrication Process Specifications	GA-A21734

1.7 Post Irradiation Examinations at WHC in FY-94

TFEs will be shipped from GA to WHC in 1994 for additional PIE in the WHC hot cells. The GA hot cell was not available for this activity. The results of the WHC PIE were not available for this final report so a supplementary report will be issued by WHC in FY-95 (Ref. 1-6).

1.8 TFE Design Package

The design analyses and detailed drawings used to design, fabricate and test TFEs are contained in a TFE Design Package Report, GA-A21597 (Table 1-2).

1.9 Fabrication Process Specifications

Fabrication process specifications used to fabricate TFEs and TFE components are contained in Fabrication Process Specifications - Final Report, GA-A21734 (Table 1-2).

2. OBJECTIVES OF THE TFE TEST PROGRAM

2.1 Function of the TFE

The function of the TFE is to convert fission heat to electricity in a manner that allows the resulting power to be easily drawn off and sent to the payload.

2.2 Requirements of the TFE

2.2.1 Performance Requirements

Performance requirements for the TFE, shown in Table 2-1, were derived from those for a megawatt class thermionic system. System and TFE design were reported in Conceptual Design Report, GA-A21590 (see Section 1.6).

2.2.2 Design Requirements

Design requirements necessary to give the desired performance are shown in Table 2-2.

2.3 Goals of the Test Program

The goal of the TFE test program was to demonstrate that prototypic TFEs can be fabricated from well modeled components, and that their performance was as predicted when operated in a prototypic thermionic reactor environment.

2.4 Test Logic

2.4.1 Definition of the TFE Test Specimen

The first step in defining the test specimen was to complete its design, using the data from Section 2.2 as a starting point. This design was modified as appropriate as data from the test program were obtained. The data of interest came not only from TFE testing in TRIGA but also from the component development programs discussed in Section 1, the results of which are reported in the final test reports listed in Section 1.6.

The test specimen can be defined with reference to its components:

Thermionic cell:

- * Tungsten emitter: see GA-A21594.
- * UO₂ pellets
- * Insulator seal: see GA-A21592
- * Sheath insulator: see GA-A21593
- * Fission product trapping components
- * Thermal shields

- * Fuel holddown spring

Intercell components:

- * Alignment components
- * Top and bottom adapter components

Cesium reservoir assembly (see GA-A21595):

- * Cesium supply
- * Tubes for charging cesium into the reservoir

TFE:

- * One or more cells
- * Intercell components
- * Cesium reservoir
- * Enclosing sheath
- * Emitter and collector electrical leads

Instrumentation:

- * Current and voltage probes
- * Thermocouples
- * Fission gas volume with gauging

In addition, the test vehicle includes a primary and a secondary containment.

2.4.2 Test Strategy

The test specimens were as close to the baseline TFE defined in Table 2-1 and Table 2-2 as practicable. The deviations are shown in Table 2-3.

The test logic was a step-by-step development of the fabrication processes beginning with a single cell TFE and progressing to a 6-cell TFE with progressively more prototypical components. The test matrix is defined in the next section.

TFE-1H1 had a single cell integrated into a sheath tube with appropriate end fittings. These end fittings consisted of a liquid cesium reservoir, fission gas vents and electrical current leads.

TFE-1H2 incorporated a graphite-cesium reservoir into the TFE along with a sheath insulator made from alumina rather than yttria. Yttria had been used in 1H1 because it was known to be more stable under irradiation than alumina. The move to alumina was made for two reasons:

- * It proved to be difficult to make good yttria sheath insulators; and,
- * Alumina sheaths appeared to have irradiation stability that met requirements.

TFE-1H3 was designed to investigate TFE performance when the fission products were allowed to mix with the cesium in the interelectrode gap. The data would show the extent and timing of any degradation. A fission product trap was included within the cell to trap all of the solid and condensable fission products so that only noncondensable fission products entered the cesium space to affect cell performance.

TFE-3H1 and TFE-3H5 were both 3-cell TFEs and addressed the development of the intercell region. The central cell was isolated from the end fittings and was therefore typical of cells in the interior of a thermionic reactor. Fission gas venting in a multicell environment could be studied.

TFE-6H1 was a 6-cell TFE that addressed alignment issues in fabrication, and was considered to essentially be of prototypical length.

TFE component changes in this evolutionary strategy, shown on Table 2-5, were:

- * Niobium replaced tantalum as the emitter end cap to reduce the amount of Ta in the core, which is a significant neutron poison.
- * Tungsten replaced tungsten/rhenium as the fuel pedestal material because the latter appeared during irradiation to chemically interact with the fuel and degrade the emitter.
- * An improved emitter alignment component was adopted for compatibility with a stronger emitter end cap configuration.

2.4.3 Test Matrix

The test matrix for TFEs is summarized on Tables 2-4 and 2-5.

2.4.4 TRIGA Test Reactor

TRIGA Mark F was the test reactor of choice for testing TFEs for several reasons:

- * The Mark F could be operated continuously, the test time being close to 100% of the maximum possible time.
- * Test articles could be easily inserted into the reactor.
- * Test instrumentation could be easily inserted into the reactor, with test data examined on-line.
- * Prototypic temperatures and power densities could be obtained.

- * The fast fluence was close to real time for thermionic power systems.
- * A neutron radiography capability was available.

Table 2-1
PERFORMANCE REQUIREMENTS FOR TFEs

Emitter power density	2.72 W(e)/cm ²
Efficiency	9.3%
Electrical output	
Per TFE	662 W(e)
Fast fluence (average, 7 years)	$2.7 \times 10^{+22}$
Burnup (average 7 years)	4.1 a/o
Axial reflectors	Within TFE
Cesium reservoir	Graphite
Location	Within TFE

2.5 Performance Assessment

The assessment of TFE performance relies heavily on an accurate estimate of emitter temperature. The methods used for the TFE Verification Program were developed by Rasor Associates, Inc. and are described in Appendix A.

The subsequent performance evaluation is based on an analysis of current-voltage curves. This analysis is also discussed in Appendix A.

Table 2-2
DESIGN REQUIREMENTS FOR TFEs

Emitter temperature	1800 K
Collector temperature	1000 K
Optimum diode gap	30 mil-torr
Interelectrode gap	10 mils
Emitter	
Material	CVD tungsten
Inner W layer	From WF_6
Thickness	.028 inch
Outer W layer	From WCl_6
Thickness	.012 inch
Work function	4.78 eV
Diameter	0.5 inch
Thickness	0.040 inch
Length	2.0 inch
Emitter stem	
Material	CVD tungsten
Length	0.48 inch
Thickness	0.020 inch
Collector material	Niobium
Emitter current density	7 amps/cm ²
Fuel	
Enrichment	93%
Length within emitter	1.83 inch
Volume within emitter	As needed for zoning
Sheath insulator	Trilayer
Insulator seal	Trilayer

Table 2-3
COMPARISON OF TFE TEST SPECIMEN WITH BASELINE CONDITIONS

DIFFERENCES FROM BASELINE SPECIFICATION	
Design Parameters	
Fuel enrichment	As needed for test (32 gms/emitter; $\leq 63\%$ enrichment)
Fuel volume within emitter	About 100%
Cesium reservoir	Developmental
Insulator seals	Litton taper
Test Parameters	
Fast Fluence	$.1 \times 10^{+22}$ per year
Burnup	.6 a/o per year

Table 2-4
TFE TEST MATRIX SUMMARY

TFE ID	Number of Cells	Cs Reservoir	Purpose
1H1	1	Liquid	Verification of reference cell design performance and fabrication processes. Sheath integration.
1H2	1	Graphite	Verification of integral cesium reservoir design, performance.
1H3	1	Liquid	Study effect of fission products mixing with cesium.
3H1	3	Graphite	Intercell process development. Fission product control.
3H5	3	Graphite	Backup to 3H1. Introduction of prototypic components outside cell.
6H1	6	Graphite	Verification of long-TFE fabricability.

Table 2-5
TFE TEST MATRIX - DETAIL

	1H1	1H2	1H3	3H1	3H5	6H1
<u>TFE Components</u>						
Sheath Insulator Ceramic	Y ₂ O ₃	Al ₂ O ₃	Al ₂ O ₃	Al ₂ O ₃	Al ₂ O ₃	Al ₂ O ₃
Insulator Seal Ceramic Configuration	Al ₂ O ₃ Litton	Al ₂ O ₃ Litton	Al ₂ O ₃ Litton	Al ₂ O ₃ Litton	Al ₂ O ₃ Litton	Al ₂ O ₃ Litton
Fuel Pedestal/Cover Material	W-26Re	W-26Re	W-26Re	W-26 Re	W	W
Emitter Cap Material	Ta	Nb	Ta	Nb	Nb	Nb
Emitter Alignment	Conical Washer	Slotted Spring	Conical Washer	Slotted Spring	Slotted Spring	Slotted Spring
Volatile Fission Product Trap	None	None	Al ₂ O ₃	Al ₂ O ₃	Al ₂ O ₃	Al ₂ O ₃
Cesium Reservoir	Liquid	POCO CZR-2	Liquid	POCO CZR-2	POCO CZR-2	POCO CZR-2
Dummy Cell at Bottom	Long	Long	Short	None	Short	None
Emitter Lead	Nb	Nb	Nb	Nb/Mo	Nb/Mo	Nb/Mo
<u>Containment Components</u>						
Number of Thermocouples	12	12	12	16	16	18
Fission Product Gauging	No	No	No	Yes	Yes	Yes
Collector Temperature Control	Heater	Heater	Heater	Gas Gap	Gas Gap	Gas Gap

3. FABRICATION DEVELOPMENT

3.1 Test Specimen Description

TFEs for in-core testing were made up of a string of thermionic converters with additional portions above and below the string. The number of converters in the TFE-VP was 1, 3 or 6 depending on test objectives. The portions of the TFE above and below the string also depended on test requirements.

The TFE was enclosed in a primary and a secondary containment to meet TRIGA licensing requirements.

These major elements of the test article are described below.

3.1.1 Converter String

The H-series emitter is 0.5 in. in diameter and 2.0 in. long. The emitter cylindrical wall thickness is 0.040 in., and the emitter bottom thickness is 0.060 in. designed to accommodate a converter-to-converter alignment spring (which is discussed further below). At the top end of the emitter is the emitter stem, which serves as both electrical lead to the emitter and as thermal choke for the emitter. The stem is 0.020 in. thick and 0.48 in. long. The tungsten emitter is fabricated in two layers. The inner, thicker layer is chemically vapor deposited from WF_6 . This is the structural layer of the emitter, and it also makes up the emitter stem. The outer 0.012 in. of the emitter is deposited from WCl_6 , which provides the oriented emission surface. The emitter is diffusion bonded to a tantalum transition piece at the top end.

Inside the emitter is the nuclear fuel. Three annular pellets of UO_2 total 1.83 in. in length. A tungsten-26% rhenium pedestal holds the fuel off the emitter bottom for the purpose of maintaining lower and more uniform emitter bottom temperatures than if the fuel were in contact with the bottom. Above the fuel there are four tungsten-26% rhenium discs alternating with formed wire spacers which serve as thermal radiation shields to reduce axial heat loss from the fuel and to inhibit fuel vapor transport. A tungsten-26% rhenium fuel holddown spring locates the fuel and internal parts in place during fabrication and encapsulation. This was not a flight-qualified fuel holddown component. Above the spring is a tantalum component to radially and axially locate the spring.

The fuel space is closed with a tantalum cap welded into the transition piece. There are three 0.012 in. inside diameter fission product vent tubes located in the transition piece. The tubes are made of polycrystalline high purity alumina and pressed into radial holes 0.026 in. in diameter in the transition piece. These vent tubes provide a passage for fission product gases from the fuel cavity inside the emitter to the annular space outside of the ceramic-to-metal seal and the emitter transition piece.

Opposite the emitter is the collector, and between them is the interelectrode gap, which is filled with low pressure cesium vapor. The radial interelectrode gap is 0.010 inch. Cesium is supplied to each converter through six 0.026 in. diameter axial holes in the transition piece which provide passages between the converters in the string.

The collector is part of a trilayer structure which is fabricated by gas pressure bonding. It is made up of a 0.030 in. thick niobium inner layer, which is the current carrying collector, an intermediate alumina insulator layer 0.016 in. thick, and an outer niobium layer 0.019 in. thick, which is also called the inner sheath. The trilayer outside diameter is 0.65 in. The inner sheath is slotted parallel to its longitudinal axis at places around the outside diameter to a depth of 0.008 in., 0.015 in. wide, to form axial fission product gas passages from one converter to the next. There are no slots in the trilayer of the bottom converter in a string, since there is no converter below it to produce gas.

The converter insulator seal, also called a Litton seal, is a subassembly comprised of a 0.054 in. thick by 0.025 in. wide ceramic (insulator) ring with niobium skirts brazed to it. The upper niobium skirt is thinned to 0.015 in. and formed into a convolution with a depth of 0.030 in. and a minimum radius of 0.010 in. This convolution compensates for the differential thermal expansion between the seal and the unbonded section of the outer sheath tube. The seal is welded between the fueled emitter subassembly and the trilayer to make up the converter unit.

The individual converters are welded end-to-end connecting the emitter transition of one converter to the collector of the converter above it and completing the electrical series connection. This weld also seals the interelectrode (cesium) space from the fission product space. Figure 3-1 shows the converter-to-converter region in detail. TFE-3H1 is shown for perspective. At the top of each converter the emitter fuel volume is closed with a cap made of a trilayer sandwich of niobium, alumina and niobium. An alignment device mates to the electrically isolated upper portion of the emitter cap and also to the bottom of the next emitter, providing support for that emitter and to assure alignment of the interelectrode gap. The alignment device for 3H1 is a short tube with two slots cut 180° apart transverse to the tube axis so as to create a spring.

A 0.003 in. thick plasma-sprayed alumina coating is applied over the outside of the seals and transition pieces after the converters are welded together. The assembly of converters is then put into a 0.020 in. thick niobium-1% zirconium outer sheath tube which has an inner coating of nickel. The radial clearance to the tube is 0.0005 to 0.0007 in. The assembly is subsequently wrapped with tungsten wire and heated to 1500 K, at which temperature the inner sheath and outer sheath tubes are forced into contact by the differential expansion of the largely niobium TFE structure and the tungsten wrap. A nickel-niobium braze is accomplished which bonds the converter string into the outer sheath tube. The tungsten wire wrap is removed and the final TFE outside diameter is 0.69 in.

Figure 3-1. Converter to Converter Region

3.1.2 Below the Converter String

In the TFE-1HX series and in TFE-3H5, a dummy cell is located below the bottom converter, within the outer sheath tube, and welded to the collector of the bottom converter as another converter would be. The typical converter-to-dummy region is shown in Figure 3-2. The dummy provides a seal to insulate the bottom converter-collector potential from the outer sheath tube potential. It also:

- * Seats the alignment washer and insulator for the bottom emitter;
- * Conducts the TFE current from the bottom collector;
- * Seals the interelectrode space at the bottom;
- * Provides a backup seal for the sheath tube bond of the bottom trilayer from the fission product space; and
- * Provides a shoulder for welding the outer sheath tube.

Figure 3-2 also illustrates the bottom of the TFE with the dummy cell. A niobium end piece is welded to the dummy collector lead after TFE sheath tube bonding and final processing. A copper end piece is brazed to the niobium and then welded to a copper bus tube that carries the TFE current back to beyond the top end of the test article.

3.1.3 Above the Converter String

Above the converter string are the TFE stem region, the cesium reservoir and the gaseous fission product plenum chamber. The electric current is drawn from the top of the emitter of the top most converter by a hollow niobium lead. The cesium communicates between the reservoir and the converter through the center of the lead. The fuel volume of the converter string is connected to the fission product plenum by a tube. The region between the converter string and the cesium reservoir is called the TFE stem.

Figure 3-3 shows the detail of the bottom of the stem region. Between the emitter lead and the top most emitter transition piece is the lead trilayer. This is a short piece of the same structure as the collector trilayer in the converters and is bonded to the outer sheath tube. This component is required to mechanically locate the top-most emitter, which otherwise would be supported only on the convolution of its ceramic-to-metal seal.

Outside of the emitter lead the fission product space is enclosed by a stem sheath structure consisting of an expansion joint, to accommodate differential thermal growth, and an insulator seal. This stem sheath structure is welded at the bottom to the top of the TFE outer

Figure 3-2. Bottom TFEs Showing Short Dummy Cell

Figure 3-3. Converter-To-TFE Lead Region

sheath and at the top to the cesium reservoir. The insulator separates the sheath potential from the reservoir structure which is electrically connected to the emitter potential. The reservoir design is discussed in more detail in the next section.

Above the TFE, the solid niobium emitter lead is welded to a solid copper electrical bus, which passes through the primary containment hard seal. Outside of the converter string and TFE stem and reservoir assemblies is the electrical lead, a copper bus tube connected to the collector of the bottom converter. This collector bus tube continues upward to the hard seal where there is a transition to a solid copper bus, which passes through the seal.

3.1.4 Fission Product Trap

In the reference TFE, a fission product trap is included in the top of each emitter. The purpose of the trap is to react with and retain within the emitter fission product species that could react with other TFE materials, such as the plasma sprayed polycrystalline Al_2O_3 insulation on the outside of the insulator seal, or plateout on fission product vent tubulation within the TFE. A third reason for trapping fission products is to limit the contamination of the cesium space if at any time an insulator seal should crack.

The design shown in Figure 3-4 is based on the thermionics program in the 1960s and 1970s, specifically for TFE-6F5, which proved effective in out-of-pile testing at that time. The trap consists of layered disks of molybdenum coated with plasma sprayed polycrystalline Al_2O_3 within a tantalum housing. The Al_2O_3 coatings and Mo metal will react with most of the fission product elements that are volatile in the range of emitter-to-collector temperatures. The trap provides 3 to 4 sq cm of reactive surface in a volume of 0.3 cc.

The trap for TFE-1H3 is shown in Figure 3-5 in comparison with TFE-1H1 which did not have a trap. All TFEs fabricated in the program had such a trap except TFE-1H1 and TFE-1H2.

3.1.5 Cesium Reservoir

In the TFE there is complete separation of the interelectrode cesium volume from the fission product space. A schematic of the piping for the cesium vapor and the fission product gases is shown on Figure 3-6. In the event of a leak between the two volumes, a result, perhaps, of a crack in an insulator seal, the cesium would gradually flow into the external fission gas collection chambers. To minimize the consequences of such a leak, the TFE design includes a port tube in the fission product system, located below the cesium reservoir and operating at a higher temperature than the reservoir. The port tube does not restrict passage of fission product gases but restricts severely the passage of cesium vapor. If a leak occurs between the two volumes, cesium would be lost at a very slow rate.

The cesium reservoirs are welded niobium structures, more details of which are provided in Section 3.4 and later.

Figure 3-4. Fission Product Trap Design

Figure 3-5. TFE-1H3 With Fission Product Trap
TFE-1H1 Without Fission Product Trap

Figure 3-6. Piping Schematic Cesium Reservoir and Gaseous Fission Products

3.2 Test Vehicle Description

The test vehicle incorporates the test specimen in a double container of austenitic stainless steel, with the inner primary containment leak tight to less than 2×10^{-8} std cc/sec of helium. The test vehicle is incorporated into the TRIGA core in place of a 1.5 inch diameter fuel element. All instrumentation penetrations of the primary containment are leak tight to 1200 K. Heat rejection to the TRIGA reactor water coolant must not exceed the threshold for nucleate boiling.

A schematic of the lower sections of the test vehicle is shown on Figure 3-7 for a 1-cell TFE and Figure 3-8 for the 3-cell and 6-cell TFEs. The outer of the two containment tubes shown extends to above the top of the reactor pool, a distance of about 7.5 m. It is closed 2.5 m above the core with a hard seal. The overall test vehicle is shown schematically on Figure 3-9.

The primary containment is filled with approximately one-half atmosphere of helium. A tube extending to the top of the pool permits the gas in the secondary containment volume to be changed during the test, if desirable, to optimize component temperatures.

Between the converter and the containment tubes for the 1-cell TFEs is a filler block which incorporates a pair of heater coils. The collector temperature is controlled by adding heat to the coils on the filler block as well as by changing the gas mixture in the secondary containment.

For the 3-cell and 6-cell TFEs, however, a collector gas gap built into the primary containment is used to control the collector temperature. This scheme reduces the instrumentation congestion in the TFE but more importantly reduces the risk potential associated with routing high voltage heater wires to the bottom of the TFE. The thickness of the gas gap is designed for desired collector temperature, and the gas composition can be changed during operation if fine tuning of the collector temperature is necessary.

Heaters are also used to control the cesium reservoir temperature. And in addition, in TFE-1H1, two stainless steel clad heater cables are wrapped around the cesium reservoir stem to trim the temperature of the top of the TFE. For TFE-3H1 and other TFEs (as well as TFE-1H2), heaters are wrapped around the pinchoff tubes at the end of the TFE. These heaters are not shown on Figure 3-8.

In summary, several design variables are used to give desired component temperatures, specifically:

- 1) The uranium enrichment.
- 2) The axial location of the TFE within the TRIGA core.
- 3) The heater power to the collector and reservoir heaters.
- 4) Thickness and composition of fill gas in the collector gas gap.

Figure 3-7. Test Vehicle Schematic
TFE-1HX

Figure 3-8. Test Vehicle Schematic
TFE-3HX and TFE-6H1

Figure 3-9. Test Vehicle Schematic

- 5) The gas composition within the secondary containment.
- 6) The width of the various gaps shown in Figures 3-7 and 3-8.

Current leads link the TFE to the load located outside of the reactor. These bus bar tubes are designed for 150 amps of continuous electric current. A third lead is attached to the outer sheath potential to allow drawing current across the sheath insulators. Current in this lead is only a few milliamperes.

Gaseous fission products that evolve from TFE operation are channeled to the annular space in the cesium reservoir stem region outside the emitter lead and inside the enveloping sheath assembly. Through passages in the cesium reservoir block, tubes lead out of the TFE and into an external fission gas collection chamber, a one liter stainless steel vessel which was initially evacuated. It is estimated that the pressure from noble fission product gases after 20,000 hours from a one cell TFE would be about 18 mbar.

3.3 Generic Fabrication Experience

3.3.1 Fabrication Facilities

The following fabrication facilities were developed for this program.

Chemical cleaning-electro chemistry. Chemical hoods and ultrasonic cleaning equipment were needed to clean TFE components prior to degassing and assembly operations. Electro-polishing and electro-plating capabilities were also necessary.

Electron beam welder-clean room complex. A class 100,000 clean room with class 100 work areas was adjacent to the EB welder with a controlled entry to the welder working volume. The EB welder was a 25 kW Leybold-Hereaus machine equipped with Allen Bradley CNC control. This facility was necessary to prevent electrode contamination and to achieve high quality welds.

CVD tungsten facility. Equipment for the deposition of tungsten by hydrogen reduction of WCl_6 and WF_6 was used for emitter fabrication.

Degassing furnaces. Several ultra-high vacuum furnaces were necessary to degas TFE components prior to assembly.

Brazing and metallizing. Furnaces and vacuum tables for ceramic-to-metal seal assembly and vacuum brazing of TFE components were necessary.

UO₂ fuel fabrication. Fabrication of UO₂ fuel pellets was performed in a special processing hood.

Plasma spray facility. Equipment for plasma spraying sheath insulators and other components was established. Sol-gel techniques were used to prepare pure starting powders.

Leak detection equipment. Leak detection equipment with a capability of 10^{-11} std cc/sec of helium was assembled.

Final processing equipment. An ultra-high vacuum system was fabricated for TFE final processing. This final processing station is described in more detail in Section 3.3.2.

A large quantity of other equipment was necessary for in-process control, quality control and nondestructive and destructive testing.

3.3.2 Final Processing Station

An ultra-high vacuum system for final degassing, sheath tube bonding and cesium loading was assembled, as shown schematically on Figure 3-10. Separate pumping systems were used to exhaust the fission product volume leading to the fuel cavity, the cesium space and the TFE external envelope, i.e., the main vacuum chamber in Figure 3-10.

3.4 TFE-1H1

3.4.1 Component Definition

Fabrication development specific to TFE-1H1 is described below, with reference to the components listed on Table 2-5, which displays the detailed TFE test matrix. All of the items on Table 2-5 will be discussed in this section. In later sections dealing with other TFEs only items which are different than those found in TFE-1H1 will be discussed.

Sheath insulator material. Yttria (Y_2O_3) was used as the insulator material for the collector trilayer for TFE-1H1. Yttria is resistant to fast neutron damage, much better than alumina, and its electric insulating properties are adequate. Hence, it was the initial ceramic of choice for sheath insulators.

It was observed during the development program for sheath insulators, however, that alumina trilayers could be reliably fabricated and that their irradiation resistance was acceptable. Moreover, the electrical insulating properties of alumina were much superior to those of yttria. Hence, for subsequent TFEs, alumina was used in fabricating the sheath insulators.

Insulator seals. The Litton taper seal with alumina as the ceramic was used for all TFEs. This seal was developed by Litton during the thermionics programs of the 1960s and 1970s; it is a strong seal with a data base of good experience out to at least 10^{22} nvt.

Figure 3-10. Final Processing Station

Fuel pedestal/cover material. The fuel pedestal was made of a tungsten-26% rhenium alloy. Pure tungsten was used for TFE-3H5 and TFE-6H1 for reasons described in Section 3.8.

Emitter cap material. The emitter cap for TFE-1H1 was made of tantalum. As described in Section 3.1.1, this was replaced with a niobium cap for TFE-3H1.

Emitter alignment. The emitter alignment component for TFE-1H1 was a conical tungsten-26% rhenium alignment washer, .010 inches thick and 0.30 inches in outside diameter. As shown in Figure 3-11, the washer was located between a button on the bottom of the emitter and an alignment insulator. The alignment insulator was a recessed alumina disk sitting in recess machined into the tantalum emitter cap.

This design is different than that described in Section 3.1.1 which was used for TFE-1H2.

Fission product trap. TFE-1H1 did not have a fission product trap within the emitter. Fission products that escaped from the fuel and were mobile could move out of the fission product port and into the collection chamber.

Cesium reservoir. The reservoir design was discussed in brief in Section 3.1.5. TFE-1H1 had a liquid cesium reservoir, a schematic view of which is shown on Figure 3-12. The fission product port tube was located just below the liquid reservoir where it would run approximately 50 K above the reservoir. The tube was .002 in. inside diameter and 1.12 in. long; this would limit cesium loss in the event of an internal TFE leak to less than 1 gm per 30,000 hours.

Dummy cell. A long dummy cell was used for TFE-1H1, as shown on Figure 3-13. This should be contrasted to the short dummy cell discussed in Section 3.2 which was adopted at a later date to simplify the design.

Emitter lead. Niobium was used for the bus bar tubes for TFE-1H1.

Instrumentation. The test instrumentation used in TFE-1H1 is shown on Table 3-1.

The thermocouples were ceramic-insulated, Inconel-clad, floating junction, chromel-alumel thermocouples, 1.0 mm in diameter.

Current leads linked the TFE to the load located outside of the reactor. These bus bars were designed for continuous duty of 150 amps.

Three voltage probes were located to permit measurement of the emitter potential, the collector potential and the outer sheath potential.

Figure 3-11. Emitter Alignment for TFE-1H1

Figure 3-12. Liquid Cesium Reservoir Detail For TFE-1H1

Figure 3-13. Long Dummy Cell for TFE-1H1

Table 3-1
LOCATIONS OF THERMOCOUPLES AND PROBES - TFE 1H1

Thermocouple Number	Location	Purpose
12	Top of Cs heater block	Monitor heater power
11	Top of Cs reservoir block	Estimate reservoir (top) end loss
10/9	In Cs reservoir block at approximately liquid level	Temperature for Cs pressure and heater feedback
8	TFE stem just below reservoir	Estimate reservoir bottom end loss
7	TFE stem seal	Monitor seal
6	TFE stem between seal and cell	Estimate cell top end loss and feedback to step heater
5	TFE outer sheath opposite emitter lead trilayer	Infer temperature of emitter lead trilayer
4	In filler block at emitter midplane	Filler temperature
3/2	TFE outer sheath at emitter midplane	Collector temperature and TRIGA reactor trip signal on high temperature
1	TFE outer sheath opposite dummy	Estimate cell bottom end loss
Voltage Probe #1	Bottom of dummy cell at bus tube connection	Estimate collector voltage
Voltage Probe #2	Cs reservoir block	Estimate emitter voltage
Voltage Probe #3	TFE stem adaptor just above joint to sheath	Sheath voltage
Current Probe	TFE stem adaptor just above joint to sheath	Impose voltage differential from sheath to collector

A third current lead was attached to the outer sheath to allow drawing current across the sheath insulators. Current in this lead, however, was only a few milliamperes.

Fission product gauging. No gauging was installed to monitor fission product gas accumulation in the collection chamber.

Collector temperature control. The collector temperature in TFE-1H1 was controlled directly by a heater block, as outlined in Section 3.2.

3.4.2 Electrical Schematic

An electrical schematic for TFE-1H1 is shown in Figure 3-14.

3.5 TFE-1H2

3.5.1 Component Definition

The areas in which TFE-1H2 are different from TFE-1H1 are described below.

Sheath insulator material. As discussed in Section 3.4.1, the ceramic material in the sheath insulator for TFE-1H2 and for all subsequent TFEs was Al_2O_3 .

Figure 3-14. Electrical Schematic: TFE-1H1

Emitter cap material. The emitter cap in TFE-1H2 was made of niobium instead of tantalum as in TFE-1H1 and 1H3. Niobium is less of a neutron poison than tantalum and system design is improved when tantalum is removed from the core.

Emitter alignment. The emitter alignment for TFE-1H2 was the short slotted tube described in Section 3.1.1 and shown on Figure 3-1.

Cesium reservoir. The reservoir in TFE-1H2 was made of POCO-CZR2 graphite, formed into an annulus 12.9 mm (0.51 in.) in outside diameter, 1.3 mm (.051 in.) thick and 50 mm high. The volume was 2.4 cc which held 1.5 g of cesium. A schematic of this reservoir is shown on Figure 3-15.

The port tube for TFE-1H2 was .002 in. in diameter and 0.5 in. long, and would pass about 1 g of cesium in 20,000 hours if there was an internal TFE leak. The tube temperature is 950 K.

Cesium was loaded from a liquid cesium reservoir into the graphite reservoir at a cesium pressure of 2.3 torr and a graphite temperature of 746 C. This corresponded to the formation of a second stage compound at a specific loading of 461 mg Cs per gram of carbon.

I-V sweeps were made at several temperatures with the liquid reservoir valved off; the evaluated results are shown on Figure 3-16. The cesium pressure at a temperature of 746 C (1019 K), which was the loading temperature, is less than the loading pressure of 2.3 torr. This is because the graphite temperature shown on Figure 3-16 is an average of 4 thermocouple readings and, hence, was not as well defined as the loading temperature.

The data of Figure 3-16 are consistent with the data obtained during the design, fabrication and test activities of the TFE Verification Program.

Instrumentation. The instrumentation used for TFE-1H2 is shown on Table 3-2. It was similar to that used for TFE-1H1.

3.5.2 Electrical Schematic

An electrical schematic for TFE-1H2 is shown on Figure 3-17. The electrical path identified by (*) was an intentional short across the dummy cell insulator seal. This fabrication step was taken to seal a leak in the insulator seal. The electrical path identified by (#) was a collector short to ground caused by the design of the ceramic spacer.

Figure 3-15. Graphite Cesium Reservoir Detail for TFE-1H2

Figure 3-16. Cesium Pressure vs Graphite Temperature
Arrhenius Plot for TFE-1H2

(Cs Loading: 461 mg Cs/g C)

Table 3-2
LOCATIONS OF THERMOCOUPLES AND PROBES - TFE 1H2

Thermocouple Number	Location	Purpose
12	Top of TFE top heater	Heater feedback
11	On pumpout tubes inside graphite annulus	Monitor
10	Top of Cs reservoir	Monitor
9/8	Reservoir envelope/heater at midpoint	Cs heater feedback
7	Emitter lead adaptor	Monitor potential "cold" point
6	TFE stem between seal and cell	Estimate cell top end loss
5	TFE outer sheath opposite emitter lead trilayer	Lead trilayer monitor
4	In filler block at emitter midplane	Filler heater feedback
3/2	TFE outer sheath at emitter midplane	Collector temperature and TRIGA reactor trip signal on high temperature
1	TFE outer sheath opposite dummy	Estimate cell bottom end loss
Voltage Probe #1	Top of dummy cell under alignment insulator	Estimate collector voltage
Voltage Probe #2	Cs reservoir block	Estimate emitter voltage
Voltage Probe #3	TFE stem adaptor just above joint to sheath	Estimate sheath voltage
Current Probe	TFE stem adaptor just above joint to sheath	Impose voltage differential from sheath to emitter and collector

3.6 TFE-1H3

3.6.1 Component Definition

The areas in which TFE-1H3 was different from TFE-1H2 and TFE-1H1 are described below.

A hole was drilled through the envelope which normally separates the fission gases from the cesium vapor. This was accomplished by adjusting the location of the holes which normally carry fission gases out of the emitter to the axial vent grooves to instead deposit fission gases on the outboard side of the seal. This simulated a cracked seal.

Emitter alignment. A conical washer was used for emitter alignment, as in TFE-1H1 but in contrast to TFE-1H2.

Fission product trap. TFE-1H3 had a fission product trap as described in Section 3.1.4. The purpose of testing TFE-1H3 was to determine TFE performance when fission product gases were allowed to mix with the cesium in the interelectrode space. Hence, it was important to trap the non-volatile fission products and keep them within the TFE.

Cesium reservoir. TFE-1H3 used a liquid cesium reservoir so that the results of its irradiation could be directly compared to TFE-1H1.

Figure 3-17. 1H2 Electrical Schematic

Dummy cell. A short dummy cell, shown in Figure 3-2, was adopted for TFE-1H3 and for subsequent TFEs to shorten the length of the TFE and to reduce the electrical loss in the dummy. The change had no significant effect on component temperatures or thermal end losses.

Instrumentation. The test instrumentation used in TFE-1H3 was the same as shown for TFE-1H1 in Table 3-1.

3.6.2 Electrical Schematic

The electrical schematic used in TFE-1H3 was the same as shown for TFE-1H1 on Figure 3-14.

3.7 TFE-3H1

3.7.1 Component Definition

The areas in which TFE-3H1 was different from prior TFEs are described below.

Emitter cap material. The emitter cap for TFE-3H1 was made of niobium instead of tantalum which was used for TFE-1H1 and 1H3.

Emitter alignment. The emitter alignment component for TFE-3H1 was the same as for TFE-1H2, i.e., a slotted tube.

Cesium reservoir. The reservoir design for TFE-3H1 was the same as that for TFE-1H2.

The Cs-graphite reservoir was loaded using the same equipment and techniques use for TFE-1H2. The loading pressure and temperature were 2.3 torr and 746 C, respectively. The resulting Ahrenius plot is shown in Figure 3-18.

This plot is to the right and higher than the comparable plot for TFE-1H2 shown on Figure 3-16. The graphite in the reservoir of TFE-1H2 was in the form of several short sections of tube which together radially filled the available volume and axially filled the volume to within 0.2 inches. The graphite tubes for TFE-3H1 were individually the same size but there was more volume both radially and axially to accomodate expansion that occurred during cesium loading. This expansion volume, however, also limited thermal contact between the graphite and the surrounding reservoir housing, and as a result there is more uncertainty in the graphite temperature. The resulting inference is that TFE-3H1 was actually loaded at a slightly lower temperature than TFE-1H2, giving rise to a slightly higher loading and, as a result, a somewhat higher cesium pressure at the same temperature.

Dummy cell. TFE-3H1 did not have a dummy cell at the bottom of the TFE. The design at the bottom is shown schematically in Figure 3-19.

Figure 3-18. Cesium Pressure vs Graphite Temperature
Ahrenius Plot for TFE-3H1

Figure 3-19. Bottom of TFE-3H1 With No Dummy Cell

Emitter lead. Niobium was used for the bus bars for TFE-3H1.

Instrumentation. The test instrumentation used in TFE-3H1 is shown on Table 3-3.

Table 3-3
LOCATIONS OF THERMOCOUPLES AND PROBES - TFE 3H1

Thermocouple Number	Location	Purpose
16	Cesium volume pumpout tube	Temperature of cold surface
15	Top of TFE in lead cap	Temperature of cold surface
14	Bottom of cesium reservoir block	Cs reservoir temperature
13/12	Reservoir midplane	Cs reservoir temperature
11	Top of cesium reservoir block	Cs reservoir temperature
10	Transition between sheath tube and stem seal	Stem seal temperature
9	Top of lead trilayer	Temperature moniotr
8	Collector heat rejector	Collector temperature
7/6	Sheath tube, top cell	Collector temperature
5/4	Sheath tube, middle cell	Collector temperature
3/2	Sheath tube, bottom cell	Collector temperature
1	Bottom of bottom cell collector	Monitor
Voltage Probe #1	Bottom of bottom cell collector	Collector voltage
Voltage Probe #2	Cap above stem seal	Emitter voltage

Fission product gauging. Gauging was installed to monitor fission product gas accumulation in the collection chamber. A schematic of this instrumentation is shown on Figure 3-20. Two gauges were used were covered the range of interest and also fit within the limited space available in the test capsule. A Pirani gauge will register from 1×10^{-3} torr to 3 torr. A second gauge was an all-welded diaphragm instrument with output from the variable reluctance of a magnetic circuit which includes the diaphragm; it provides readings from 6.5×10^{-2} torr to 6.5 torr differential pressure. The pressure of the reference side of the diaphragm could be varied so that the range of the differential gauge could be extended considerably above an absolute pressure of 6.5 torr.

3.7.2 Electrical schematic

An electrical schematic for TFE-3H1 is shown in Figure 3-21.

3.8 TFE-3H5

3.8.1 Component Definition

Cesium reservoir. The Cs loading point for TFE-3H5, 3 torr Cs at a graphite temperature of 670°C, was chosen to provide a high loading and, thereby, reduce the demand upon the reservoir heaters. At this lower temperature the paschen breakdown curves were erratic and the pressure-temperature isosteres were unreliable. The data were only employed as a

Figure 3-20. TRIGA Test Vehicle for TFE-3H1 With Fission Gas Chamber Pressure Gauges

TRIGA Containment Tubes and Pool

Figure 3-21. Electrical Schematic: TFE-3H1

guideline in the startup of TFE-3H5 and the actual Cs pressure was inferred from the dynamic I-V curves.

Fuel pedestal material. The fuel pedestal for TFE-3H5 was made of pure tungsten, in contrast to the tungsten-rhenium used for the earlier TFEs. As explained in Section 5.2, a chemical reaction between rhenium and the UO₂ fuel with its fission products was observed during the operation of TFE-1H1. TFE-3H5 was the first device in which the fabrication status permitted a change.

Dummy cell. TFE-3H5 had a short dummy cell so that the sheath insulator could be tested with an externally applied voltage. A schematic picture of the dummy cell is shown in Figure 3-22 in comparison with the other TFE bottom designs. TFE-3H5 had two insulator seals to minimize the risk of helium leakage into the interelectrode space.

Emitter lead. A niobium clad molybdenum electric lead was fabricated for TFE-3H5. The composite structure, which was made by hot isostatic pressing, was a simple change for the all-niobium lead used in the other TFEs. The use of molybdenum reduced electric resistive losses in the lead by approximately 50%.

Fission product gauging. The gauging for TFE-3H5 was essentially the same as for 3H1.

Instrumentation. The instrumentation for TFE-3H5 was the same as for TFE-3H1, shown in Table 3-3, except for the addition of voltage probe #3 and the current probe shown, cf, on 1H1 in Table 3-1.

3.8.2 Electrical Schematic

An electrical schematic for TFE-3H5 is shown on Figure 3-23.

3.9 TFE-6H1

3.9.1 Component Definition

Fission product port. Experience with the irradiation testing of TFE-1H3 and TFE-3H1 gave some indication that some fission product species might have migrated to the end of the capillary port tube and condensed in such a way as to prevent fission gas from escaping from the fuel cavity. In the case of TFE-1H3, the port was positioned near the top of the emitter and thus was accessible for the condensation of fission product compounds. For TFE-3H1, the port was located within the cesium reservoir block to keep the temperature of the port above the condensation temperature of the cesium. To protect the capillary tube in TFE-6H1, a fission product baffle was installed over the end of the tube, and the tube was withdrawn into a cooler region above the cesium reservoir block. The baffle was filled with niobium wool to intercept and condense fission product compounds. This arrangement is shown schematically on Figure 3-24.

Figure 3-22. TFE Design Dummy Cell (TFE Bottom)

TRIGA Containment Tubes and Pool

Figure 3-23. 3H5 Electrical Schematic

Figure 3-24. 6H1 Fission Gas Port

Collector temperature control. The collector temperature in TFE-6H1 was controlled indirectly by a gas gap, as outlined in Section 3.2.

Fission product gauging. The gauging for TFE-6H1 was essentially the same as for TFE-3H1.

Instrumentation. The test instrumentation for TFE-6H1 is given in Table 3-4.

3.9.2 Electrical Schematic

The electrical schematic for TFE-6H1 is the same as shown in Figure 3-21 for TFE-3H1 with the addition of 3 cells.

Table 3-4
LOCATION OF THERMOCOUPLES AND PROBES - TFE-6H1

Thermocouple Number	Location	Purpose
17	Emitter lead trilayer	Monitor
16	Cs pumpout	Monitor
15	Emitter lead cap	Monitor
14	Top of Cs reservoir housing	Monitor
13/12	Axial midplane of Cs reservoir housing	Cs reservoir temperature and control
11	Bottom of Cs reservoir housing	Monitor
10	Stem seal	Monitor
9	Sheath tube opposite emitter lead trilayer	Monitor
8A/8B	Collector heat rejector (collector bus) opposite cell 5	Radial heat loss
7	Sheath tube at center of cell 6 (top cell)	T_c at center of cell 6
6	Sheath tube at center of cell 5	T_c at center of cell 5
5	Sheath tube at center of cell 4	T_c at center of cell 4
4	Sheath tube at center of cell 3	T_c at center of cell 3
3	Sheath tube at center of cell 2	T_c at center of cell 2
2	Sheath tube at center of bottom cell 1 (bottom cell)	T_c at center of cell 1
1	Bottom transition to collector bus	Bottom end loss
Voltage Probe #1	Bottom transition to collector bus	Collector voltage
Voltage Probe #2	Between emitter trilayer and Cs reservoir	Emitter voltage

4. IN-REACTOR TESTING

4.1 TRIGA Mark F Test Facility

4.1.1 Reactor Facility Description

The Mark F operates at a steady state power level of up to 1500 kW. The reactor has a water reflected core suspended in a shroud from a carriage, which allows the insertion of large test devices in the pool. The core can be moved within the large water pool. Vital statistics for the Mark F are as follows:

* Fuel:	UZrH fuel rods
* Active core length:	38 cm
* Thermal flux below 0.4 ev:	3×10^{13} n/cm ² /sec
* Fast flux above 10 kev:	2.8×10^{13} n/cm ² /sec
* Scheduled shutdowns:	One per year for fuel inspection

Special capabilities include:

- * Direct access to core from above.
- * Neutron radiography capability within the reactor pool.
- * Flux trap test positions.
- * Auxiliary out-of-core test positions.
- * Data acquisition system can be tailored to test program.
- * Core easily reconfigured.

The fuel elements in the Mark F are arranged in rings, the A ring being at the center of the core and the B, C, rings out farther on the radius. A schematic of this structure is shown on Figure 4-1. When a TFE is to be loaded into the core, a TRIGA fuel element is removed and a TFE inserted in its place. A TFE inserted in Ring A will, generally, operate at a higher power than one inserted in Ring D.

4.1.2 Neutron Radiography Facility Description

Neutron radiography was one of the major non-destructive test methods used to follow TFE radiations. The procedure followed was as follows:

- 1) Indium and dysprosium foils were placed in back of the TFE test article which was then exposed to a collimated beam of neutrons for about 2 hours. The indium foils detected the fast neutrons and the dysprosium detected the thermal neutrons. The irradiation time was determined by the materials and thickness of the test article.
- 2) Each foil was then immediately placed between two sheets of film, Industrial X SR-5 (Kodak), and allowed to "soak" for 24 hours. This length of time would allow the

Figure 4-1. TRIGA Mark F Core Layout

short lived isotopes to decay and give a sharp image.

- 3) The film was then developed and read. The accuracy with which an emitter diameter can be measured by neutron radiography is less than 0.001 inch, typically 0.0005 inch.

4.1.3 Description of Operations

Operation of TRIGA Mark F reactor is governed by NRC license and by extensive operating procedures which have been tested over the years and proven to be safe and efficient.

Reactor shutdowns. Shutdowns occurred for one of three reasons:

- 1) Unplanned shutdown from a scram signal. Scram signals could arise from many sources, including loss of off-site power, loss of cesium, malfunction of the power supply driving current through the TFE and sudden rise in temperature of one of the TFE components. An unscheduled shutdown would lead to an evaluation of the cause and its correction.
- 2) Planned shutdown to, for example, load another test article into the reactor. Generally when this happened, neutron radiographs would be taken of all the test articles.
- 3) Planned shutdown as required by license. At least one shutdown a year was required by the TRIGA facility operating license for maintenance, operator training purposes, facility inspection, etc. During this shutdown, neutron radiographs would generally be taken of all test articles.

Reactor startups. All reactor startups followed a procedure designed to quickly bring the emitter to near its design operating temperature, typically reached after about 20 minutes at about 40% full power. The cesium pressure and TFE current were then adjusted to provide electron cooling and, at the same time, maintain operation in the "obstructed mode" portion of the dynamic response of the converter(s) as the power was increased.

The rapid rise to power prevented fuel redistribution into the small gap between the fuel pellet and the emitter which was created when the fuel cooled down from operating temperature. If this were to happen, further temperature increases could cause strains in the emitter from the different thermal expansion coefficients between the UO₂ and the tungsten emitter.

4.2 TFE Test Configuration

4.2.1 TFE Instrumentation

Tables 3-1 to 3-4 list the thermocouple and voltage probe locations for the various TFEs. The signals from these probes were recorded automatically by the data acquisition system. In addition to the instrumentation shown in the tables, the secondary containment pressure was recorded and, where applicable, the potentials on CP1 and VP3 were recorded also. For TFE-3Hx and TFE-6H1, the pressures recorded by the pirani gauge and the differential gauge on the fission product plenum chamber were recorded. A third pressure gauge kept a record of the pressure in the reference chamber of the differential fission product gauge.

4.2.2 Electrical Test Circuit

The equivalent lumped-parameter electrical circuit of TFE-1H2 is shown in Figure 4-2, which is an extension of Figure 3-17. With only minor differences, it also represents the other TFEs. The resistances r_1 through r_4 represent the electrical resistance of leads for the various electrical probes, i.e., the resistance of the 20 ft lead wire that extends from the top of the TFE to the top of the capsule. These resistances are each slightly over 1Ω . Resistances r_{10} and r_{11} are the bus bars for the emitter and collector, respectively, and are about $2.75\text{ m}\Omega$ each. The remaining resistors that are drawn with full lines represent distributed internal resistances, e.g. r_6 and r_7 which are the resistances of the collector and emitter electrodes. The values of these resistors r_5 through r_9 and r_{17} , r_{18} are less than $1\text{ m}\Omega$. The 'ghosted' resistors r_{13} through r_{16} represent internal insulators, e.g. collector trilayer, lead trilayer and seal. In the as-built condition, these resistors are greater than $10\text{ k}\Omega$. In the event of a short, they could drop towards zero.

The electrical performance of the TFE is derived from the measurement of the current flowing in the emitter-collector bus circuit through r_{10} and r_{11} and the voltage measured between nodes three and one with voltage probes VP1 and VP2. Under special circumstances, VP3 and CP may also be utilized. As long as no internal shorts have occurred, as would be the case if any of the four insulators depicted by r_{13-16} failed, the current and voltage measurements just described are unambiguous. However, failure modes can create situations requiring careful analysis. If r_{16} , which represents the stem seal, becomes shorted some fraction of the measured current will flow through the sheath, bypassing the converter. On the other hand, if r_{14} , representing the collector trilayer, becomes shorted the effective internal series resistance of the TFE becomes less. A detailed circuit analysis, in conjunction with the measured voltages at all three nodes in Fig. 4-2 can usually assist in interpreting unusual behavior of the TFE.

The point design of the TFEs is based on a current of 140 amperes at a single-cell voltage of 0.49 volts. This corresponds to an output impedance of $3.5\text{ m}\Omega$. The combined impedance of the emitter and collector bus bars is $5.5\text{ m}\Omega$. This value cannot be reduced appreciably in the TRIGA tests because of the 20 ft depth of the reactor core in the water

Figure 4-2. Electrical Circuit for TFE-1H2

pool. The excess resistance of the bus bars is counterbalanced by a driving power supply in series with the converter(s), as indicated schematically in Fig. 4-3. The presence of the power supply does not alter the thermionic performance of the cell; it is merely an electronic means of reducing the load resistance into which the cell is operating.

The effect can be illustrated by superimposing the load lines with and without the driving power supply schematically on the I-V characteristic of the TFE, as in Fig. 4-4. In the absence of a driving power supply, the direct current (d.c.) operating point of the TFE will be at the intersection of the I-V curve and the load line defined by the total external and internal resistance of the TFE, the total resistance (ΣR) including not only the bus bars, but all cabling, internal lead resistances, etc. In order to raise the load line up to pass through the design operating point, the driving power supply must provide a voltage in series with the TFE that has the value V_{dps} , where

$$V_{dps} = I_o(\Sigma R - R_o)$$

with

$$R_o = \frac{V_o}{I_o}$$

In the present case, $R_o = 3.5 \text{ m}\Omega$.

4.2.3 On-Line Data Acquisition

The data acquisition system is displayed schematically in Figure 4-5. Its principle components are the HP 3497A data logger and the HP 9816 computer. The data logger consists of a digital multimeter (DVM), multiplexer, buffer and controller. The data logger receives an instruction message from the computer, makes the appropriate measurements, stores the data in the buffer, then sends the data to the computer when requested to do so. The data may then be displayed on the CRT, printed in hard copy, or transferred to disks.

The computer is driven by data acquisition and display software and is normally instructed to collect data from all channels every minute. This 'minute' data is collected in volatile RAM and is overwritten every 8 hours. Once every hour, the system is instructed to transfer the real-time data from all channels to the external disk drive, as well as to the RAM. The 'hour' data in RAM is overwritten every week. When circumstances warrant, the computer can be instructed to copy the 'minute' data from RAM to the disk. Except for such occasions, however, the archival record consists of 'hour' data.

The computer is programmed to convert the output of the DVM into appropriate units for each data channel. Thus a raw voltage signal is converted into units of temperature, volts, amperes, torr etc. Each channel is compared with preset (by the TFE test engineer) limits. If the data value for any channel falls outside these preset limits, visual and audible warning signals are sent to the TRIGA control console.

Figure 4-3. Electrical schematic of the TFE, bus bars, cables and driving power supply

Figure 4-4. Generic I-V curve for a TFE. The driving power supply overcomes the internal resistance of the test vehicle to achieve the design load line of the test article.

Figure 4-5. Data Acquisition System

In addition to tabular display of current data, the software also permits any data channel to be displayed in a strip chart mode. Three time intervals are available for these displays. Minute data for the two previous hours or the eight previous hours, or hour data for the previous week can be shown in a strip chart. These are not 'live' displays, however, and must be updated manually to keep the data current. Hard copies of the strip charts, as well as the tabular data can be obtained at any time.

4.2.4 I-V Sweep Circuit

The sweep voltage for the TFE is transformer-coupled to the circuit as indicated in Figure 4-6. The sweep power supply delivers a pulse of variable width at intervals of 1 or 2 seconds, or continuously, as selected by the operator. Each pulse contains one or more 60 hz sine waves. Since the duration of the pulses is short, there will be no change in the dc operating conditions of the converter, e.g., emitter temperature, while the I-V characteristic is being recorded. The power supply also provides a trigger signal for a digitizing oscilloscope that can display TFE current and voltage versus time, or TFE current vs voltage.

Any I-V curve can be archived on permanent media by transferring its voltage and current time-files to a HP9816 computer dedicated for this purpose. In addition, this computer runs the program UNIG (Reference 4-1) with which the TFE emitter temperature can be estimated by comparing the saturated unignited current with that calculated by UNIG for various values of T_{emitter} , see Appendix A.

4.2.5 Thermal Control

Section 3 contains the details of the gas gaps and heater blocks employed in the various capsules to control the temperature. All TFEs were provided with electric heaters for the reservoirs, whether they were liquid cesium or Cs-graphite. The 1H series of TFEs also had electric heaters on the collector. TFE-3H1, TFE-3H5 and TFE-6H1 did not have electric heaters, but the thermal resistance in the collector thermal circuit included a gas gap. The composition of the gas mixture in this gap afforded a measure of control of the collector temperature. In addition to being able to control the composition of gas in the collector gas gap, the composition of the gas in the secondary containment could also be varied. This feature applied to all capsules, and was frequently employed to raise or lower the temperature of all components of the TFE (with the exception of the emitter).

In addition to varying the heater power or gas composition, the temperatures could be altered to some extent by changing the location of the TFE within the core. As was the case with 6H1, this included relocating the TFE to a flux trap, surrounded by three water voids in the core.

Figure 4-6. The sweep voltage power supply is transformer coupled to the TFE-DPS circuit

4.2.6 Emitter Temperature Control

The emitter temperature is controlled primarily by the thermal input from the fuel (proportional to the reactor power) and electron cooling (proportional to the electron current). The gas gaps have little influence on the emitter temperature; they primarily affect the collector temperature which has only a small effect on the radiative loss from the emitter. In operation the emitter temperature is inferred from the ignition current and the driving power supply is adjusted as necessary to maintain a value of $T_e \sim 1800$ K. If T_e should be ≥ 1800 K when the current reaches 140 A the reactor power is reduced instead of increasing the current further.

In the late stages of testing, some of the TFEs in this program had moved out of the power quadrant and estimates of T_e were subject to large uncertainties. A different judgement was made in each case concerning the amount of electron cooling to maintain.

4.3 TFE Performance Evaluation

The procedures used to evaluate on-line TFE performance are described in Appendix A. The data from these evaluations are presented in Section 5 for each TFE.

5. TEST HISTORY

5.1 TFE-1H1

5.1.1 Chronology

Table 5-1
SUMMARY OF TFE-1H1 TESTING

Test Start Date	September 15, 1988
Test End Date	December 21, 1990
Hours In-core	17,166
Estimated Burnup, % FIMA	1.13
Estimated Fast Fluence, nvt	6.4×10^{20}
Current (Voltage) at Startup, Amp(Volt)	137 (0.45)
Reason for End of Test	Loss of Output

5.1.2 Performance Evaluation

Two unusual incidents occurred before significant operation of TFE-1H1 occurred. During the installation of the secondary containment, a sudden decrease in the resistance between the sheath tube and the emitter bus was detected. This occurred after the final weld was made on the secondary containment tube. The result was that the scheduled test of the sheath insulator at high voltage could not be performed. This was not deemed to be important enough to warrant disassembly and repair of the short circuit that occurred during the weld.

The second incident occurred during the initial rise-to-power of TFE-1H1. The collector reached its design value of 1070 K at 800 kW (TRIGA power), without any external power to the collector heaters. The cesium reservoir, on the other hand, was at 590 K, 10 K or about 0.5 torr below design value, with the reservoir heater at full power. A decision was made to change the secondary containment gas from 50%He/50%Ar to one with a higher percentage of He, so that the collector would not reach 1070 K until full power was achieved. After the changeover, the reservoir cooled as well as the collector, with the result that the converter lost cesium and, consequently, electron cooling. The driving power supply tried to maintain the converter current, with the result that full voltage was applied to the converter, about 25 V. For a few seconds, a high power cesium arc must have existed inside the converter. Also, during that time, it is estimated that the emitter temperature rose to 2100 K, and the collector temperature rose to 1300°C momentarily. When normal operation was resumed, the unignited portion of the I-V curve was altered in a fashion consistent with a shunt resistance of 250-400 mΩ. Although this apparent shunt resistance had little effect on the converter output at the design point, it had to be included for accurate

estimation of the emitter temperature, based on the unignited mode saturation current.

Figure 5-1 shows the TFE current and the cell voltage throughout the test history of TFE-1H1. The cell voltage is calculated from the sum of the measured lead voltage and the product of the current and the calculated internal lead resistance of 2.109 m Ω . For the first 8000 hours, TFE-1H1 was located in the E ring of the TRIGA reactor core (see Fig. 4-1), and the average reactor power was 1300 kW. At the end of that period TFE-1H3 was installed, and TFE-1H1 was moved into the F ring. From 8000 to 11,200 hours, it remained in the F ring and the average reactor power was about 1450 kW. At 11,200 hours, TFE-1H2 was installed in the TRIGA core, and TFE-1H1 was relocated in the E ring. From 11,200 to 17,166 hours, the TFE remained in the E ring and the reactor power was about 1200 kW.

From startup to 8000 hours, the TFE delivered 140 amperes (7 amp/ cm²), at a voltage near 0.4 v. From 8000 to 11,200 hours, the current was lowered to reduce the electron cooling, since less heat was generated. The voltage increased during this period to as much as 0.55 v. After the shutdown to install TFE-1H2 in February 1990 (at 11,200 hours), a slow degradation was observed in the output voltage of TFE-1H1. The operating point moved out of the power quadrant at about 12,000 hours, as indicated by cell voltage passing from positive to negative values (see Fig. 5-1). On October 30, 1990, after about 16,500 hours (not shown in Fig. 5-1), the reactor power was lowered to 700 kW for diagnostic purposes. After the subsequent return to full power, the I-V sweep of TFE-1H1 was purely resistive (5.32 m Ω) and remained that way until the TFE was removed from the core after 17,166 hours.

In GA-A20335, Semiannual Report for Period Ending September 30, 1990, several mechanisms are discussed, each of which could contribute to the degradation in the output of TFE-1H1 after 11,000 hours. These include instrumentation difficulties, error in determining the cesium pressure, emitter swelling, fission product gas in the interelectrode space, internal short circuit, and collector work function changes. As discussed in GA-A20335, there are reasons to discount all these mechanisms with the exception of the collector work function changes.

An explanation for the degradation based on a change in the collector work function, ϕ_c , was based on evidence of an interaction between the fuel and the emitter clad in the vicinity of the W-25%Re heat shields at the bottom of the emitter. Emitter thinning was observed in neutron radiographs. A similar effect was seen in the case of the UFAC fueled emitter tests (Ref. 5-1), where a liquid phase was detected where the UO₂ came into contact with the heat shields. It appears likely that uranium migrated through the clad, then evaporated onto the adjacent collector. The work function of bare uranium is about 0.8 eV lower than that of Nb, and it is estimated that uranium will adsorb very little Cs compared to Nb. The contamination of the collector will cause the cesiated work function to change from about 1.8 to 3.2 eV, as a result. This $\Delta\phi_c$ will cause the output voltage to change by approximately 1.0v, as shown by a MASTERPC calculation (Ref. 4-1). Though the voltage was observed to shift by about 1.5v, this seems to be in reasonably good agreement with a MASTERPC analysis.

TFE-1H1 Performance

Figure 5-1. Time Dependence of Current and Voltage for TFE-1H1

The operational history of TFE-1H1 is highlighted by the following events:

- o A welding accident during secondary encapsulation.
- o A cesium runaway during cooling-gas change out at full power.
- o Possible interaction of the fuel with the W-25% Re heat shields at the bottom of the emitter, leading to emitter thinning and possible contamination of the collector surface.

5.2 TFE-1H2

5.2.1 Chronology

Table 5-2
SUMMARY OF TFE-1H2 TESTING

Test Start Date	March 13, 1990
Test End Date	March 6, 1992
Hours In-Core	14,000
Estimated Burnup, % FIMA	1.44
Estimated Fast Fluence, nvt	1.4×10^{21}
Current (Voltage) at Startup, Amp (Volt)	128 (0.2)
Reason for End of Test	Internal Short Circuit

5.2.2 Performance Evaluation

One unusual incident occurred with TFE-1H2. On June 8, 1991, after about 8,900 hours of operation, the heater on the end heater block failed. This caused the Cs reservoir to cool down by approximately 40°C. Since the driving power supply was trying to maintain constant current, the converter was forced into the saturation region while full power supply voltage was applied. For a short period of time, more than 1 kilowatt was absorbed internally in a plasma arc or other discharge. When the voltage and current returned to near-normal values, the I-V characteristic was ohmic ($\approx 1.7 \text{ m}\Omega$), and it remained that way for the remainder of the test.

Figure 5-2 displays the cell voltage and TFE current for the first 8,800 hours of TFE-1H2 operation. This TFE remained in the D ring of the TRIGA core throughout. The cell voltage in Figure 5-2 has been corrected for an internal lead resistance of 2.109 mΩ. From startup until the incident of June 8, 1991, the output voltage remained in the range 0.45 ± 0.05 volts, at a current of 140 amps.

Figure 5-2. Time Dependence of Current and Voltage for TFE-1H2

Subsequent to the incident of June 8, the I-V curve was a straight line, indicating a resistive component. However, it did not pass through the origin, as it would have had there been no voltage generated internally. A lumped-parameter equivalent circuit of TFE-1H2 was developed and analyzed. A detailed description is presented in GA-A20804, Semiannual Progress Report for the Period Ending September 30, 1991. It was found that the voltage probe measurements made at the top of the capsule were best matched by postulating a short circuit across the emitter lead trilayer, and assuming that the converter itself was performing in a normal fashion with this short circuit acting as the load resistor. It was not possible, of course, to characterize its performance accurately, since it was isolated by a short circuit.

Two attempts made to remove the internal short circuit in TFE-1H2 are described in GA-A21210, Semiannual Progress Report for the Period Ending September 30, 1992. In the first attempt, a d.c. current of 300 amps was forced through the TFE. The temperatures of all thermocouples were monitored. A temperature maximum occurred opposite the emitter lead trilayer, but the short circuit did not clear. Next, a series of 80 current pulses were applied. These pulses were about 6 msec in duration and the amplitude was about 4000 amps at 14 v. Again, a temperature maximum occurred at the emitter lead trilayer, and, again, the attempt to clear the short circuit failed.

The operational history of TFE-1H2 is highlighted by the following event:

- o A cesium runaway and associated arc when a heater failed and the reactor scram circuitry was bypassed for diagnostic purposes. This event at 8,800 hours of operation produced a short circuit within the capsule.

5.3 TFE-1H3

5.3.1 Chronology

Table 5-3
SUMMARY OF TFE-1H3 TESTING

Test Start Date	August 11, 1989
Test End Date	April 20, 1992
Hours In-Core	20,020
Estimated Burnup, % FIMA	1.11
Estimated Fast Fluence, nvt	2.4×10^{21}
Current (Voltage) at Startup, Amp (Volt)	84 (.42)
Reason for End of Test	Loss of Output

5.3.2 Performance Evaluation

Figure 5-3 shows the cell current and lead voltage of TFE-1H3 during its testing period. For the first 4300 hours of operation, the TFE delivered 6.5 amps/cm² at a voltage of 0.55 volts. TFE-1H2 was inserted in the core at about 4350 hours. The rearrangement of the TRIGA core at that time reduced the heat generation at the location of TFE-1H3 in the B ring, which caused the emitter temperature to drop. To bring the emitter temperature back up, the electron cooling was decreased (the cell current was reduced from ≈ 130 amps to ≈ 70 amps in Fig. 5-3). At about 13,000 hours of operation, the I-V curve for the TFE moved out of the power quadrant without overt cause. Although the cell voltage for the rest of the test period was between 0.1 and 0.4 volts, there was no TFE current. The converter was operating in the unignited mode for the last 7000 hours of the test.

As in the case of TFE-1H1, the I-V characteristic of TFE-1H3 moved gradually out of the power quadrant over a period of about 1,000 hours, after approximately 12,000 hours of operation. Prior to the gradual shift out of the power quadrant, though, the behavior of these two TFES was different. The power output of TFE-1H1 remained relatively constant at 58 watts, whereas TFE-1H3 dropped in output from about 40 watts to nearly 20 watts from 4400 hours to 12,000 hours. This 50% decrease in output is in large part due to the fact that the electron cooling was steadily reduced to maintain the emitter temperature. No decrease in power was detected prior to rearrangement of the TRIGA core at 4350 hours.

The slow decline in output prior to 12,000 hours may be due to a different mechanism than the rapid (by comparison) change that was observed subsequently. One possibility is emitter cooling due to the buildup of fission gas in the cesium space. The change in current from 70 A at 6000 hours to 45 A at 12,000 hours corresponds to a decrease in electron cooling of about 70 watts. In 12,000 hours the partial pressure of Xe would be approximately 5 torr. As reported in GA-A20804, Semiannual Progress Report for the Period Ending September 30, 1991, Xe gas conduction at this pressure could be about 80 watts at the observed emitter and collector temperatures. Thus the slow decline in output is probably due to emitter cooling arising from fission gas buildup.

The gradual shift of the I-V curve out of the power quadrant after 12,000 hours is conditionally associated with a collector work function change, as discussed in the case of TFE-1H1. The validity of this mechanism will be established when the PIE is completed.

The operational history of TFE-1H3 is highlighted by the following events:

- o Possible interaction of the fuel with the W-25% Re heat shields at the bottom of the emitter, as with TFE-1H1.
- o Thermionic performance degradation due to (intentional) buildup of fission gases within the interelectrode (cesium) space.

TFE-1H3 Performance

Figure 5-3. Time Dependence of Current and Voltage for TFE-1H3

5.4 TFE-3H1

5.4.1 Chronology

Table 5-4
SUMMARY OF TFE-3H1 TESTING

Test Start Date	May 3, 1991
Test End Date	March 19, 1993
Hours In-Core	14,167
Estimated Burnup, % FIMA	1.03
Estimated Fast Fluence, nvt	1.6×10^{21}
Current (Voltage) at Startup, Amp (Volt)	64(1.45)
Reason for End of Test	Reservoir Heater Failure

5.4.2 Performance Evaluation

The performance of TFE-3H1 is shown in Figure 5-4. The I-V curve moved out of the power quadrant at about 10,000 hours. The rate of degradation was somewhat faster than observed with TFE-1H3. If the degradation in performance was due to a leak between the fission gas and cesium spaces so that the build up of Xe could cause the emitter to cool as was postulated for TFE-1H3, then the rate of degradation should have been 3.7 times as fast, based on the estimated thermal power generated in each TFE. On the other hand, neutron radiographs taken at about 4500 hours showed a suggestion of a crack in the emitter of the middle cell which could indeed allow fission gas into the cesium space.

Before the loss of the reservoir heaters, TFE-3H1 displayed a tendency to go into output oscillations, with a period in the range of minutes. It was the type of behavior that is frequently associated with the distillation of cesium from one location to another and back again.

TFE-3H1 was the first TFE which was instrumented to measure the pressure buildup in the fission gas plenum chamber. Figure 5-5 shows the experimental result; the straight line segments are drawn through the points, and correspond to the rate of increase shown. The rate of increase corresponding to the estimated power generation in the UO_2 fuel and a 100% release rate is 4.5×10^{-7} torr/sec. During the period from about 3800 hours to 5550 hours, the observed release corresponds very nearly to a 100% release of fission product Xe and Kr from the fuel, followed by accumulation in the fission gas plenum. Before and after this interval the accumulation rate is very much smaller. One possibility is the presence of a partial 'plug' in fission gas port capillary tube that is located between the fuel and plenum. If this were the case, the pressure in the plenum should continue to increase even during periods of shutdown, until the pressure was equalized across the capillary tube. During the

Figure 5-4. Time Dependence of Current and Voltage for TFE-3H1

Figure 5-5. Fission Gas Pressure Buildup in Plenum Chamber for TFE-3H1

shutdown for neutron radiography and fuel inspection in April 1992 (at about 7500 hours in Fig. 5-5) the plenum pressure was monitored continuously. The anticipated increase during this 2-week period, based on the presumed leak rate, was only about 1-2%. The uncertainty in the measurement was between 1 and 2 percent due to factors like temperature variations in the pool water so that no conclusion could be drawn from the results.

If the low gas accumulation rate was due to partial plugging of the fission gas port, then the gas pressure within the fueled emitters would be considerably higher than that in the plenum until equilibration had occurred (after shutdown). Based on the relative volumes, temperature differences and gas release calculations, the pressure over the fuel at removal from the core could have been as high as 2 atms. It would have immediately dropped to about .67 atm because of the lowering of the temperature in the primary containment volume. Ultimately, the pressure in the fuel volume (including the plenum) should equilibrate at about 25 torr. The pressure in the plenum will be measured in PIE.

The operational history of TFE-3H1 is highlighted by the following events:

- o Failure of cesium reservoir heaters.
- o Possible plugging of the fission product port.

5.5 TFE-3H5

5.5.1 Chronology

Table 5-5
SUMMARY OF TFE-3H5 TESTING

Test Start Date	September 28, 1992
Test End Date	October 22, 1993
Hours In-Core	8,041
Estimated Burnup, % FIMA	0.77
Estimated Fast Fluence, nvt	9.3×10^{20}
Current (Voltage) at Startup, Amp (Volt)	125 (1.45)
Reason for End of Test	Testing Terminated

5.5.2 Performance Evaluation

The performance of TFE-3H5 is shown in Figure 5-6. Throughout the testing period the output was nearly constant at 220 watts (~ 0.57 V/cell, 6.5 A/cm²). The test was terminated only upon the end of the TFE-VP TRIGA testing on October 22, 1993. The accumulation of fission gas is shown in Fig. 5-7. The experimental rate of pressure increase is 8×10^{-8}

TFE-3H5 Performance

Figure 5-6. Time Dependence of Current and Voltage for TFE-3H5

3H5 fission gas generation

Table 5-7. Fission Gas Pressure Buildup in Plenum Chamber for TFE-3H5

torr/sec, which is 15% of the estimated generation rate of 5.42×10^{-7} torr/sec. Once again this suggests that there may be a constriction in the tubulation connecting the fuel with the plenum. The plenum pressure of TFE-3H5 will also be checked in PIE.

The operational history of TFE-3H5 is highlighted by the following event:

- o Possible plugging of the fission product port.

5.6 TFE-6H1

5.6.1 Chronology

Table 5-6
SUMMARY OF TFE-6H1 TESTING

Test Start Date	April 2, 1993
Test End Date	October 22, 1993
Hours In-Core	4,316
Estimated Burnup, % FIMA	0.07-0.25*
Estimated Fast Fluence, nvt	5.1×10^{20}
Current (Voltage) at Startup, Amp (Volt)	79 (2.17)
Reason for End of Test	Testing Terminated

*The burnup for each cell in this TFE was estimated, and the min-max values are listed.

5.6.2 Performance Evaluations

Figure 5-8 shows the current and voltage of TFE-6H1 during the first 3200 hours of testing. The TFE output was low at startup, and degraded slowly during the first 1500 hours of operation. A strong axial gradient in the thermal power profile existed for this TFE. The power profile was skewed such that the emitter temperature of the top cell was probably below 1000 K, as determined by calorimetry. This top cell became part of the load of the remaining 5 cells and is the probable reason that the output voltage never exceeded about 2.2 volts, instead of an anticipated voltage in the vicinity of 3.0 volts.

At 3400 hours, the TFE was relocated into a flux trap formed by three symmetric water voids in the TRIGA core. Furthermore, the lower core grid plate was modified at this time to allow TFE-6H1 to be lowered beyond the core centerline for diagnostic purposes. When the TFE was lowered to centerline, the temperature profile became symmetric, but both ends were quite cold. The measured collector temperatures were used in conjunction with the

Figure 5-8. Time Dependence of Current and Voltage for TFE-6H1

temperature of the collector heat rejector as a calorimeter to calculate the total heat flow from emitter to collector. These values were set equal to the heat flow due to electron cooling and radiation and the resulting equations were solved for the emitter temperature. The results for three different times in the test are given in Table 5-7. Prior to 3400 hours, the top cell (No.6) was below 1000°C; the thermionic performance of the remaining cells varied from good to fair. When the TFE was lowered in the core (September 22, 1993), both end cells were too cold for thermionic performance.

Table 5-7
CALCULATED EMITTER TEMPERATURES (K) FOR THE CELLS OF TFE-6H1

Date	Hours	T _{e1}	T _{e2}	T _{e3}	T _{e4}	T _{e5}	T _{e6}
May 11, 1993	937	1622	1823	1755	1616	1406	732
August 9, 1993	2973	1553	1850	1812	1695	1509	925
September 22, 1993	3596	1148	1526	1692	1692	1628	1123

The slow degradation of the output of TFE-6H1 may be related to the presence of the cold cells. These cells are likely to be operating in the saturation region, where the output voltage is a more sensitive function of the electrode condition, due to the absence of a sheath potential. These cold cells could undergo larger swings in voltage than the hotter cells that are operating in the obstructed mode.

Another factor that may contribute to the degradation of the output is the possible presence of hydrogen in the interelectrode space. Russian work has shown that the vibrational modes in diatomic molecules can soak up sufficient energy from the interelectrode plasma to greatly increase the plasma drop (decrease the voltage output). The Russian work predicts that the output voltage of a six-celled device, e.g. TFE-6H1, could drop by an amount $\Delta V = 0.8 \times (H_2 \text{ pressure in torr})$. A possible source of H_2 is the acetone that was used as a thinner for the epoxy material comprising the soft seal in the secondary containment. The acetone would have to pyrolyze at the estimated temperature of 150 to 200°C, forming methyl radicals, which would have to decompose and diffuse through the primary containment walls and the niobium sheath tube/trilayer assembly to reach the interelectrode space. Estimates of these various processes were made with the result that a 1% conversion of acetone into CH_3 radicals would be sufficient to produce the observed degradation in performance. The interelectrode gas will be analyzed for H_2 in the PIE. Acetone was detected in the secondary containment gas.

GA-A21511, Semiannual Progress Report for the Period Ending September 30, 1993, contains a description of both the method by which the emitter temperatures were estimated and the calculation of the hydrogen effects.

Figure 5-9 shows the rate of accumulation of fission gas in the plenum of TFE-6H1. The approximate slope of the data corresponds to a release rate from the fuel of 15%. Conversely, it may simply be the manifestation of a flow constriction of about the same size as that in TFE-3H5 and TFE-3H1.

The operational history of TFE-6H1 is highlighted by the following events:

- o Strong axial power gradient due to length of TFE.
- o Possible plugging of fission product port.

5.7 Summary of In-Reactor Testing

5.7.1 Summary of Testing History

Table 5-8 gives a summary of the testing history of the six TFEs tested in the TFE-VP. Table 5-9 is a guide to the particular semiannual report which contains more detailed narrative for each TFE than is contained in this final report.

Table 5-8
SUMMARY OF TFE TESTING

	TFE-1H1	TFE-1H2	TFE-1H3	TFE-3H1	TFE-3H5	TFE-6H1
Test Start Date	September 15, 1988	March 13, 1990	August 11, 1989	May 3, 1991	September 28, 1992	April 2, 1993
Test End Date	December 21, 1990	March 6, 1992	April 20, 1992	March 19, 1993	October 22, 1993	October 22, 1993
Hours In-Core	17,166	14,000	20,020	14,167	8,041	4,316
Estimated Burnup, % FIMA	1.13	1.44	1.11	1.03	0.77	0.07-0.25
Estimated Fast Fluence, nvt	6.4×10^{20}	1.4×10^{21}	2.4×10^{21}	1.6×10^{21}	9.3×10^{20}	5.1×10^{20}
Current (Voltage) at Startup: Amp (Volt)	137 (0.45)	128 (0.2)	84 (.42)	64 (1.45)	125 (1.45)	79 (2.17)
Reason for End of Test	Loss of output	Internal short circuit	Loss of output	Reservoir heater failure	Testing terminated	Testing terminated

6H1 Fission Gas Generation

Figure 5-9. Fission Gas Pressure Buildup in Plenum Chamber for TFE-6H1

Table 5-9
DETAILED NARRATIVE DESCRIPTIONS OF THE TESTING HISTORY OF TFEs

Report Number	TFE-1H1	TFE-1H2	TFE-1H3	TFE-3H1	TFE-3H5	TFE-6H1
GA-A19666	Startup					
GA-A19876	8,000 hours		Startup			
GA-A20119	11,500 hours	Startup	4,800 hours			
GA-A20335	15,070 hours; analysis	3,937 hours	8,323 hours			
GA-A20493	End of test	6,900 hours	11,289 hours			
GA-A20804		Short; 10,855 hours	Status and analysis; 15,901 hours	Startup		
GA-A20911	Status Summary	Status summary; 14,000 hours; end of test	Status summary; 19,500 hours	Analysis; 7,000 hours		
GA-A21210		Repair attempts	Test ended; gamma scan attempt	Output oscillations; 11,100 hours	Startup	
GA-A21326			End of test; 14,167 hours	End of test; 14,167 hours	Status; 3,718 hours	
GA-A21511					End of test; 8,041 hours	Startup and end of test; analysis of temperature profile, H ₂ effects; 4,316 hours

5.7.2 TFE Life Testing Review

A significant number of TFEs have been built and tested in the TRIGA reactor. Table 5-10 summarizes data from the 1960s and 1970s (see Section 1.2). The data there show that:

- 1) Uranium oxide is the fuel of choice for TFEs.
- 2) A low value for the ratio of emitter diameter to thickness is necessary for long life potential. The data indicate this ratio should be $1.1/.080 = 13.75$, or lower.

Table 5-11, derived from Section 5, shows similar data for the TFE Verification Program. For most of these TFEs, the lifetime was determined by problems with the test instrumentation or test vehicle.

Figure 5-10 shows graphically TFE lifetime performance. The data are arranged in the order in which the testing was initiated. The solid vertical arrows indicate that the test was on-going when the program was terminated. The hours of operation shown for the H series TFEs are the hours before the onset of a decline in performance.

One materials problem which appeared to affect lifetime was the use of W/Re pedestal within the emitter. This was corrected in TFE-3H5.

A possible design problem which requires further study in PIE is the size of the fission gas port for channeling fission gases out of the emitter. If this is a problem, it is easily corrected. No other life limiting design or materials issues were identified.

Table 5-10
TFE PERFORMANCE SUMMARY: THERMIONICS PROGRAM ENDING JANUARY, 1973

TFE	Number Cells	Fuel	Emitter Diameter (in)	Emitter Thickness (in)	Emitter Temperature (K)	Burnup (a/o)	Watts/cm ²	Hours Operation	Test Ended	Failure Mode
2E1	2	UO ₂	.625	.040	1800	1.1	6	12,500	1-72	Interelectrode short
2E2	2	Carbide	.625	.040	1800	1.4	6	11,100	1-73	None
2E3	2	Carbide	.625	.040	1700	0.4	4	3,700	3-71	Envelope leak
1F1	1	UO ₂	1.1	.040	1800	0.3	4	8,600	9-72	Interelectrode short
1F2	1	Carbide	1.1	.040	1900	0.3	5	6,400	5-72	Emitter swelling
1F3	1	Carbide	1.1	.040	1850	0.1	4	3,400	9-72	Emitter crack
1F4	1	Carbide	1.1	.040	1900	0.3	5	4,900	1-73	None
2F1	2	Carbide	1.1	.080	1850	0.4	3	8,000	11-72	Emitter crack
2F2	2	Carbide	1.1	.080	1800	0.2	5	5,600	1-73	Emitter crack
2F3	2	UO ₂	1.1	.080/.040	1800	0.2	6	3,000	1-73	None
6F1	6	Carbide	1.1	.040	1950	0.2	2	6,400	5-72	Emitter crack
6F2	6	Carbide	1.1	.040	1850	0.3	3	7,700	9-72	Emitter crack
6F3	6	UO ₂	1.1	.080	1750	0.3	3	8,100	1-73	None
6F4	6	Carbide	1.1	.080	1700	0.1	4	3,000	1-73	None
6F5	6	Carbide	1.1	.040	1800	0.1	4	1,400	1-73	None

Table 5-11
TFE PERFORMANCE SUMMARY: TFE VERIFICATION PROGRAM

TFE	Number Cells	Fuel	Emitter Diameter (in)	Emitter Thickness (in)	Emitter* Temperature (K)	Burnup (a/o)	Watts/cm ²	Hours Operation	Hours Power Operation	Test Ended	Failure Mode
1H1	1	UO ₂	.50	.040	1800	1.1	2.8	17,166	12,000	12-90	UO ₂ /Re interaction Loss of cesium
1H2	1	UO ₂	.50	.040	1800	1.4	3.3	14,000	8,800	3-92	Loss of cesium
1H3	1	UO ₂	.50	.040	1800	1.1	3.3	20,020	13,500	4-92	UO ₂ /Re interaction Fission gases with Cs
3H1	3	UO ₂	.50	.040	1800	1.0	1.95	14,167	9,000	3-93	Cesium heaters
3H5	3	UO ₂	.50	.040	1800	.8	4.0	8,041	8,041	10-93	None
6H1	6	UO ₂	.50	.040	1800	.1-.3	1.25	4,316	4,316	10-93	None

*The emitter temperature was maintained at about 1800 K whenever possible by adjusting the driving current, hence the magnitude of electron cooling.

TFE TEST HISTORY

Figure 5-10. TFE Test History

6. PIEs PLANNED AT WHC IN FY-94 AND FY-95.

As pointed out in Section 1.7, TFEs will be shipped from GA to WHC in 1994 for additional PIE in the WHC hot cells. The results of the WHC PIE were not available for this final report but will be issued by WHC in FY-95.

Each TFE will be disassembled in the WHC hot cell and the following examinations will be performed:

- 1) Sample primary system gas. This will determine whether there are any leaks between the secondary and primary containments, or whether any welds have cracked which would allow cesium to leak out of the interelectrode space. It will also determine if there is hydrogen in the system. Acetone was used in fabricating the secondary containment and there is some concern that acetone vapor could have been thermally decomposed by the hot primary containment, liberating hydrogen which could then have permeated into the primary containment and possibly into the TFE.
- 2) Sample the interelectrode gas. This will determine whether any insulator seals have cracked which would allow cesium volume and to the fission product volume to communicate. Loss of cesium or entry of fission gases into the interelectrode space could seriously degrade thermionic performance. Measurements will also be made for hydrogen.
- 3) Sample the fission gas. This would determine the effectiveness of the fission product trap in trapping condensable fission products.
- 4) Perform electrical measurements. Electrical measurements will be made to determine if there are any electrical shorts in the TFE or elsewhere in the test vehicle. The integrity of the various insulators will be evaluated.
- 5) Evaluate graphite-cesium reservoir. The condition of the graphite-cesium reservoir will be determined by visual examination and dimensional measurements, and the mass will be measured.

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- 1-6 Personal communication (1994), Leo Lawrence, Westinghouse Hanford Company.
- 4-1 For a discussion of converter performance models, see GA-A21591, "Converter Performance Final Test Report," Prepared by Rasor Associates, Inc., March 1994.
- 5-1 GA-A21594, "Fueled Emitter Final Test Report," June 1994.

APPENDIX A

TFE EMITTER TEMPERATURE AND PERFORMANCE DIAGNOSTICS

A.1 Indirect Emitter Temperature Measurement

In-core tests of Thermionic Fuel Elements (TFEs) seek to determine converter performance and the extent of emitter fuel swelling. In order to evaluate both of these factors, it is crucial to know the emitter temperature accurately. Since a direct temperature measurement is virtually impossible, indirect methods based on analysis of the volt-ampere characteristics of a thermionic cell are used. A method has been developed for accurately determining emitter temperature based on fitting calculated results to the unignited mode (diffusion mode) portion of the I-V curve.

A.1.1 Background

During the 1960s and early '70s methods were developed to infer the emitter temperature from various features of the volt-ampere characteristic of a thermionic cell. An illustration of the typical form of the I-V curve is shown in Fig. A-1. There are two modes present: the low-current diffusion, or unignited mode; and the high-current arc, or ignited mode. The most useful diagnostics depended on either the unignited mode saturation current or the current at which ignition occurs. These current levels theoretically depend only on the emitter temperature, cesium pressure and interelectrode gap. An additional diagnostic was developed which employed the output voltage of the lower current portion of the ignited mode. This method had the disadvantage that it was strongly dependent on collector temperature and work function as well as any series resistance in the experimental design.

For the TFE Verification Program a diagnostic was sought which would be more accurate and comprehensive than using a single point on an I-V curve. The method involves fitting the entire unignited mode portion of the I-V curve with a calculation from an accurate computer model. The unignited mode has several advantages for emitter temperature diagnostics. Under typical conditions for TFE tests the unignited mode is in the "electron-rich" regime, where the emitter work function has virtually no effect on the I-V curve. The physics of the unignited mode is simple enough that an accurate model can be produced. The unignited mode current is extremely sensitive to small changes in emitter temperature. Finally, the relatively low current of this mode minimizes the voltage drop due to any series resistance. This enables the H-series TFE design to have voltage sensing leads far from the actual cell without degrading the diagnostic.

A highly accurate computer model of the unignited mode was developed for emitter temperature diagnostics. This is the MASTERPC (MASTER Planar Converter) program.

Figure A-1. I-V Curve Emitter Temperature Diagnostics

A.1.2 MASTERPC Unignited Mode Model

In MASTERPC numerical solutions are obtained for the transport equations and boundary conditions. The cesiated emitter work function is calculated from the emitter temperature cesium pressure and bare work function using the Rasor-Warner formulation. In the electron-rich mode used for temperature diagnostics the volt-ampere curve is relatively insensitive to emitter work function, so that this quantity need not be known precisely. The cesiated collector work function is calculated from an analytical fit to measurements on planar thermionic converters with the same electrode materials as the H-series cells.

It has proven to be essential to retain volume ionization, recombination and radiation terms in the formulation in order to accurately match I-V curves at high emitter temperatures. These terms have usually been ignored in descriptions of the unignited mode. A comparison between calculated J-V curves with and without these terms is shown in Fig. A-2. It is found that for emitter temperatures above about 1700 K, where there is no distinct saturation region in the J-V curve, ion formation in the interelectrode space causes a significant increase in current as the voltage approaches the ignition point.

MASTERPC is described in detail in GA-A21591 (see Table 1-2).

Figure A-2. Effect of Volume Ionization on the Unignited Mode

A.1.3 Comparison with Experimental Data

A comparison between calculated and experimental volt-ampere characteristics in the electron-rich, unignited mode is shown in Fig. A-3. The experimental curve was obtained from the PD-6 variable-spacing planar converter (Refs. 1-4 and 1-5). The emitter is duplex tungsten and the collector is niobium, as in the H-series in-core test converters. The cesium reservoir temperature, interelectrode spacing, and emitter temperature for this case were chosen to match the operating conditions of TFE-1H1. Excellent agreement is obtained between calculated and experimental results. The ionization/recombination terms included in MASTERPC enable the ignition behavior of the I-V curve to be accurately calculated in both the forward and reverse directions. Comparisons at low (800 K) and high (1150 K) collector temperatures are shown in Figs. A-4 and A-5. The high degree of accuracy indicates that the variation in collector work function with temperature and the effects of back emission are treated correctly.

The effect of emitter temperature over a range from 1600-1800 K is shown in Fig. A-6. Again, a high degree of accuracy is obtained.

A match to experimental data from TFE-1H1 is shown in Fig. A-7. Here the emitter temperature is used as a fitting parameter. The experimental curve has been compensated for a series resistance of 1.2 milliohms, due to the resistance of the electrodes and current leads in the device. This has only a small effect on output voltage at unignited mode current levels. A very good match is obtained at an emitter temperature of 1745 K.

Figure A-3. Comparison Between MASTERPC Calculation and PD-6 Data

Figure A-4. MASTERPC Compared to PD-6 Data at Low Collector Temperature

Figure A-5. MASTERPC Compared to PD-6 at High Collector Temperature

Figure A-6. Match Between Calculated Results and PD-6 Emitter Temperature Family

Figure A-7. MASTERPC Fit to TFE-1H1 In-Core Cell Data

Cylindrical converters, such as the H-series cells, have significant axial temperature gradients. Experimental results comparing planar and cylindrical converters as well as computer calculations indicate that the volt-ampere curve is a function of the average emitter temperature, with very little effect due to the gradient. It is the average temperature, therefore, which is measured by the technique of I-V curve matchings.

A.1.4 Implementation

Two independent systems, each with its own microcomputer, are employed. One system records, displays, and stores all thermocouple, DC voltage and DC current readings from the H-series cells in the reactor. Time histories of all measured parameters over periods ranging from two hours to one week can be displayed on this system. The other system reads dynamically-swept I-V curves using a digital oscilloscope. This computer displays, stores, catalogues, retrieves, and compares these I-V curves. It is also equipped to perform real-time emitter temperature diagnostics using the UNIG unignited mode program. This is similar to, but much more approximate than, MASTERPC. In particular, ionization and radiation phenomena are neglected in UNIG. In practice, UNIG was used to obtain first estimates of emitter temperature (good to within about ± 50 K) and MASTERPC was later used to obtain more precise values.

The ability to fit unignited mode I-V characteristics with calculated curves, coupled with a sophisticated data acquisition and analysis system, provides a very useful and accurate way to determine emitter temperatures in in-core thermionic experiments.

A.2 TFE Performance Diagnostics

The diagnostics described below are primarily used to understand and evaluate changes in TFE performance with time. Changes in a number of operating parameters can result in a variations in the output voltage from a TFE. Coupled with unknown values for emitter temperature and, in some cases, cesium pressure these present a challenge for performance diagnostics based on I-V curve analysis. In order to distinguish various effects, the unique ways each parameter affects the I-V curve must be identified.

A.2.1 Emitter Temperature

The effect of emitter temperature on the I-V curve is illustrated by Fig. A-8, which presents experimental data from the PD-6 variable-spacing planar converter. The current from this device has been scaled by the 20 cm² electrode area of the H-series cells. Changing emitter temperature results in the following observable features:

- A significant shift in voltage for the portion of the I-V curve below the "knee". The rate of decrease is about 0.2 volts per 100 K, with voltage decreasing when the emitter temperature decreases and increasing when temperature increases.
- Decreasing temperature increases the saturation current as well as the current at which the "knee" of the I-V curve occurs. Increasing emitter temperature has the opposite effect.
- A significant increase in the current of the unignited mode with increasing emitter temperature, as discussed in the previous section concerning emitter temperature diagnostics. This is due to increased formation of positive ions at the emitter surface.
- The ignition voltage increases with increasing emitter temperature. At high enough emitter temperatures the ignition and deignition voltages become identical, so that the hysteresis between modes disappears.

A.2.2 Collector Temperature

The outer sheath temperature is measured during all H-series experiments. This differs from the collector temperature by the temperature drop through the sheath trilayer. Normally the difference is a small amount; however, the possibility of trilayer debonding with a consequent high collector temperature must be considered in diagnosis of anomalous TFE performance.

Figure A-8. Effect of Emitter Temperature on I-V Characteristics

Typical behavior is shown in Fig. A-9. Collector temperature effects are:

- Output voltage increases overall as collector temperature increases to an optimum of about 1000 K, then falls again as the temperature continues to increase. The value of the optimum temperature depends somewhat on the cesium pressure. The optimum comes about in the following way. As the collector temperature increases up to about 1000 K the collector work function decreases as the ratio T_C/T_R rises. The lower collector work function results in a corresponding increase in output voltage. Above about 1000 K, back emission becomes significant and the decrease in collector work function levels off, resulting in a decrease in output voltage. Above a T_C/T_R ratio of about 2 (about 1200 K for the case shown in Fig. A-9) the collector work function increases again, adding to the performance loss due to back emission.
- The effect is nearly a simple shift in voltage, although the I-V curves become steeper in the below-knee region as collector temperature increases above the optimum.
- The knee current and saturation current are nearly unaffected.
- The unignited mode current is nearly unaffected. The unignited mode is shifted in voltage in nearly the same way as the ignited mode.
- Negative current at elevated output voltages increases in both the unignited and back-ignited modes (not shown in Fig. A-9).

Figure A-9. Effect of Collector Temperature

A.2.3 Cesium Pressure

Figure A-10 indicates the trends involving cesium pressure.

- The minimum barrier index (point of closest approach to an ideal diode I-V curve) goes through a maximum at a value of pressure times spacing of about 15-20 mil torr. Voltage decreases significantly for cesium pressure higher than optimum.
- The knee current and saturation current increase significantly with increasing cesium pressure. The position of the knee becomes indistinguishable at high cesium pressure.
- The unignited mode current decreases with increasing cesium pressure (there is actually an optimum cesium pressure lower than the minimum 1 torr shown in Fig. A-10).

Figure A-10. Effect of Cesium Pressure

A.2.4 Emitter Bare Work Function

The bare work function of the emitter can change due to the presence of contaminants. These could be UO_2 or fission products such as barium, strontium or selenium leeching through the emitter cladding. Experimental data showing the effect of bare work function independent of changes in cesium pressure or electrode temperature are difficult to obtain; however, calculational results (using TECMDL and MASTERPC together) are shown in Fig. A-11. These indicate:

- Output voltage below the knee is nearly unaffected by changes in bare work function.
- The knee current and saturation current decrease significantly with decreasing bare work function.
- The unignited mode current is virtually unaffected in this range.

Figure A-11. Calculated Effect of Bare Emitter Work Function

A.2.5 Collector Work Function

Contamination can cause an increase in the cesiated collector work function. Calculational results indicate that for most conditions, raising the collector work function produces an equal decrease in the voltage of the I-V curve, both in the ignited and unignited modes. However, when back emission becomes higher than about 10% of the forward current (due to either a low collector work function or high collector temperature) then the voltage is no longer affected by changes in the collector work function. This is due to formation of a space charge layer at the collector which electrically shields the surface.

A.2.6 Series Resistance

The effect of series resistance on the observed I-V curve is shown by the example in Fig. A-12. Series resistance produces a voltage drop which is proportional to the output current, causing the I-V curve to "lay down". If the knee is indistinct, this can appear like a decrease in bare emitter work function, as can be seen by comparing $R_s = 1\text{ m}\Omega$ in Fig. A-12 with 4.8 eV in Fig. A-11. Because of its low current, the unignited mode is nearly unaffected.

Figure A-12. Effect of Resistance in Series with the TFE

A.2.7 Parallel Resistance

Resistance in parallel with the TFE (a partial short-circuit) results in a loss of current which is proportional to the output voltage. This is shown by the example in Fig. A-13. The unignited mode is shifted to the negative current quadrant, and may not appear at all on the display if the AC sweep amplitude is limited. An unambiguous indicator of parallel resistance is the presence of negative current in the I-V curve even at low collector temperatures, when back-emission is expected to be negligible. In order to evaluate the parallel resistance it is absolutely essential to be able to observe the slope of the current-voltage characteristic in the negative current quadrant.

A.2.8 Gas in the Interelectrode Space

Four different ways for gas to enter the interelectrode gap have been proposed:

- As xenon or krypton fission gas entering through a rupture in the emitter clad or stem.

Figure A-13. Effect of Resistance in Parallel with the TFE (Partial Short-Circuit)

- As helium entering from the primary containment through cracked metal-to-ceramic insulators (requires a failure of two components).
- As carbon monoxide or dioxide from an inadequately-outgassed graphite cesium reservoir.
- As hydrogen permeating the TFE, resulting from thermal pyrolysis of known residual hydrocarbons in the secondary containment.

Uncertainty as to the gas composition, added to a lack of available experimental data, makes it very difficult to diagnose a gassy converter.

Gas has two independent effects:

- At a given thermal power level, the emitter temperature will drop due to increased thermal conduction in the interelectrode space. This is especially true for light gasses such as hydrogen or helium. The performance consequences of a decrease in emitter temperature are discussed above.
- Scattering or absorption of energy by gas molecules results in increased arc drop. There are some experimental results which quantify this for xenon¹, hydrogen², and CO³.

A.3 DIAGNOSTICS OF MULTIPLE, SERIES-CONNECTED TFEs

TFEs 3H1, 3H5, and 6H1 contained multiple thermionic cells in a series string. The overall I-V characteristic from these TFEs results from summation of the voltages from several cells having different emitter and collector temperatures. Experimental and calculational data were used to identify those features of such a complex I-V curve which could be used for diagnostics.

A.3.1 Emitter Temperature Diagnostics with Multiple Cells

Figure A-14 shows the unignited mode portion of I-V curves representative of three emitter temperatures (1600, 1700, and 1800 K) taken from the PD-6 planar converter. The curve formed by the series summation of voltages from each of the three curves is also shown. The "upswept" portion of the curve exhibits distinct "spikes" or kinks associated with the ignition currents of each of the individual cells. Such spikes are observed in measured I-V curves from multicell TFEs. In combination with MASTERPC, the current level at each spike was used to determine an emitter temperature for each cell.

A.3.2 Collector Work Function Determination

Back emission diagnostics can be used to estimate the collector work function for individual thermionic cells. For a multicell TFE with a spread of emitter and collector temperatures this diagnostic becomes more complicated. Figure A-15 shows calculated I-V curves for a case from TFE-3H1. As was true in Fig. A-14, the series summation shows kinks associated with unignited mode saturation in each individual cell. For the lowest temperature cells, these levels are closely associated with the back emission levels from each cell. The highest temperature cell does not have a kink, due to the very high level of back emission from this cell, and therefore no determination of its collector work function can be made.

Figure A-16 compares the calculated series-summation from Fig. A-15 with data from TFE-3H1. The degree of agreement is very good. In this case, the values for collector work function determined by the diagnostic are within the normal range for the given conditions.

Figure A-14. Series Summation of I-V Curves From PD-6 at Three Different Emitter Temperatures

Figure A-15. Series Summation of Calculated I-V Curves with Three Different Collector Temperatures and Levels of Back Emission

Figure A-16. Comparison of Series Summation of Figure A-15 with TFE-3H1 Back-Emission Data

A.4 REFERENCES

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