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TFE VERIFICATION PROGRAM

SEMIANNUAL REPORT

FOR THE PERIOD ENDING SEPTEMBER 30, 1990

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

DATE PUBLISHED: JANUARY 1991

GENERAL ATOMICS

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1. INTRODUCTION

1.1 OBJECTIVE OF PROGRESS REPORT

The objective of the semiannual progress report is to summarize the technical results obtained during the latest reporting period. The information presented herein will include evaluated test data, design evaluations, the results of analyses and the significance of results.

1.2 TFE VERIFICATION PROGRAM GOAL

The program objective is to demonstrate the technology readiness of a TFE suitable for use as the basic element in a thermionic reactor with electric power output in the 0.5 to 5.0 MW(e) range, and a full-power life of 7 years.

1.3 TECHNICAL APPROACH

The TFE Verification Program builds 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 addresses this concern.

The general logic and strategy of the program to achieve its objectives is shown on Fig. 1-1. Five prior programs form the basis for the TFE Verification Program:

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

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

Figure 1-1

LOGIC TO DEMONSTRATE TECHNOLOGY READINESS OF MEGAWATT CLASS TFE

The approach to be followed is to design a TFE that will meet the reliability and lifetime requirements for the 2 MW(e) conceptual reactor design, and initiate component testing in a fast reactor. The demonstration of a 7-year component lifetime capability will be through the combined use of analytical models and accelerated, confirmatory tests. Iterative testing will be performed where the results of one test series will lead to evolutionary improvements in the next test specimens.

The TFE components will undergo screening and initial development testing in ex-reactor tests. Several design and materials options will be considered for each component. As screening tests permit, down selection will occur. It is necessary to rapidly make baseline design and materials selections to make optimum use of irradiation testing.

In parallel with ex-reactor testing, and fast reactor component testing, components will be integrated into a TFE and tested in the TRIGA. Realtime testing of partial length TFEs will be used to test support, alignment and interconnective TFE components, and to verify TFE performance in-reactor with integral cesium reservoirs. Realtime testing will also be 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 will rest primarily on the accelerated component testing results, as correlated and extended to realtime by the analytical models developed.

The fast reactor testing of fueled emitters will be calibrated by verifying the accuracy of emitter temperature predictions through complementary analysis and ex-reactor and in-reactor diagnostic tests. Instrumented sheath insulators will be tested in a fast reactor with an applied voltage.

A test of prototypic TFEs will be run in a fast reactor as a verification of the basic TFE design. This design may be upgraded based on the final component testing results.

The deliverables of the program are:

- 1) Conceptual design of a megawatt class power system including component specifications and a system description.
- 2) Thermionic components with verified performance.
- 3) TFE demonstration in a fast reactor.
- 4) Fabrication process specifications.
- 5) Verified performance models.

2. CONCEPT DESIGN TASK

2.1 OBJECTIVE

Task 2 provides the design guidance for the TFE Verification Program. The primary goals of this task are:

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

2.2 TECHNICAL APPROACH

The technical approach being taken in the concept design effort can be characterized as follows:

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

2.3 System Definition Update

The description of the 2 MW(e) thermionic power system that was used to define the reference TFE for the program was reported in Ref. 1. This was recently updated and the results are shown below.

A major improvement made in the current work was to use an improved model of the thermionic performance of the unit cell. This reflects the results of ongoing work at Rasor Associates.

Table 2-1 summarizes current system parameters along with the prior data. Table 2-2 summarizes the related TFE design. The major results of the update are as follows:

- 1) The specific mass increased slightly, from 11.3 to 12.1 kg/kW(e).
- 2) The optimum collector temperature was reduced to about 1000 K. System efficiency increased slightly as a result. The optimum cesium pressure at a spacing of 10 mils increased to 3 torr. (Conversely, the gap could be increased slightly keeping the cesium pressure at 2 torr.)

The scalability of the design is shown on Fig. 2-1. System specific mass varies from about 14 kg/kW at 500 kW to about 12 kg/kW at 5000 kW.

The sensitivity of mass to current density is shown on Fig. 2-2. The optimum is 7 to 8 amperes per sq. cm.

As shown on Fig. 2-3, the optimum collector temperature is a little less than 1000 K.

The optimum product of the cesium pressure in torr and the interelectrode gap spacing in mils is about 30. This is shown on Fig. 2-4. For a 10 mil gap, the cesium pressure would then be about 3 torr; for a 15 mil gap, 2 torr.

Mass sensitivity to the (fueled) length to diameter ratio of the cell is shown on Fig. 2-5. The optimum is about 5. For a diameter of 0.5 inch, the emitter length should be about 2.5 inches.

TABLE 2-1
2 MWe SYSTEM PARAMETERS

	Prior Data (Ref. 1)	Changes in Current Data
Net electrical power	2010 kWe	
System efficiency	8.9%	9.3%
Lifetime @ full power	7 years	
Shield cone half-angle	12°	
Reactor thermal power	22.5 MW(t)	21.5 MW(t)
Coolant	Lithium	Lithium
Number of TFEs	2849	3021
Heat rejection	20.3 MW(t)	
Radiator temperature	1020 K	
Radiator area	426 m ²	
System mass	11.3 kg/kW	12.1 kg/kW

References

- 2-1 GA-A19412, TFE Verification Program Semiannual Report for the Period Ending October 31, 1988 (Published January 1989).

TABLE 2-2
TFE DESIGN DEFINITION

	<u>Prior Data</u> <u>(Ref. 1)</u>	<u>Changes In</u> <u>Current Data</u>
PERFORMANCE		
Overall TFE:		
Output electrical power (We)	782	662
Efficiency	8.9	9.3
Maximum voltage	5.9 (15)	
U-235 burnup (a/o)	4.1 avg, 5.3 peak	
Fluence (nvt)	2.7x10 ²² avg, 3.5x10 ²² peak	
Converter:		
Converter power (Wt/We)	658/65.2	594/55.2
Emitter power flux (We/cm ²)	3.22	2.72
Diode current density (a/cm ²)	7.0	
Thermionic work function (eV)	4.9	4.9
Emitter temperature (K)	1800	
Collector temperature (K)	1070	1000
Cesium pd (mil-torr)	20	30
Converter output voltage	0.49	
Converter current (amp)	140	
CONFIGURATION		
Overall TFE:		
TFE length (active core)(in)	39.6	
TFE length (overall)	TBD	
Sheath tube o.d. (in)	0.694	
Lead o.d. (in)	0.875	
Lead length (in)	4	
Converters per TFE	12	
Converter:		
Emitter o.d. x L x t (in)	0.5x2.0x0.040	
Emitter stem L x t (in)	0.45x0.020	
Diode gap (in)	0.010	
Trilayer t: collector	0.028	
insulator (in)	0.016	
outer cylinder	0.028	
Fuel specification	93% enriched UO ₂ ; variable volume fraction	
Intercell axial space (in)	0.74	

Figure 2-1

Reactor Performance Scalability

Emitter dia 0.5 in

Figure 2-2

System Mass vs Current Density

For Power Output = 2MWe

Emitter dia. = 0.5 in

Figure 2-3

System Mass vs Collector Temperature

For Power Output = 2MWe

Emitter dia = 0.5 in

Figure 2-4

System Mass vs Cell PD For Power Output = 2MWe

Emitter dia = 0.5 in

Figure 2-5

System Mass vs Cell L/D Ratio

For Power Output = 2 MWe (With Varying J)

Emitter dia = 0.5 in

3. CONVERTER PERFORMANCE TASK

3.1 OBJECTIVE

The objective of the converter performance task is to establish accurate converter performance models which have been correlated to observe test data. The data base will be developed from near prototypic converters using emitter and collector materials of interest over the full range of anticipated operating parameters. Part of the data base will include off-design and non-ideal operation of the converters. The resulting models will be used to determine the optimum converter configuration (materials, additives, spacing, etc.) for use in the prototypic TFE and reactor design.

A thermionic reactor is composed of a large array of thermionic cells, each of which has a unique input power, emitter temperature, and operating current density. In addition, individual cells will vary in performance over the system lifetime due to changing operating conditions caused by fuel burnup and variations in operating power requirement, or losses of some of the cells. Thus, the design and performance prediction of a thermionic reactor require an extensive data base on prototypical cell performance over a wide range of operating conditions.

The data and models will also be used in the startup of the TFEs in TRIGA and the FFTF and also in the startup of thermionic reactors. The observed current-voltage data during startup can be related to system temperatures through the ex-reactor correlations.

3.2 TASK DESCRIPTION

The current test matrix is shown on Tables 3-1 and 3-2.

Planar Converter-1 (PC-1) is a planar (variable spacing) converter with a tungsten $\langle 110 \rangle$ emitter, a niobium collector and a graphite cesium reservoir external to the converter. The emitter has a small cavity for accepting a fuel pellet of depleted uranium oxide. The test strategy is to first obtain comparative maps with uranium oxide present. The converter with the UO_2

TABLE 3-1
EX-REACTOR PLANAR CONVERTER TEST PROGRAM

Emitter	Collector	Cs		Rationale for Test
		Reservoir		
PC-1	Duplex W	Nb	Graphite	Performance map with graphite-cesium reservoir.
PC-2	Duplex W	Nb Tilted	Pool	A verification of the model which relates converter output to emitter distortion.
PC-3	High Strength Emitter	Nb	Pool	Establish data base on performance with high strength emitter
PC-1 (Mod)	Duplex W	Nb	Graphite	UO ₂ in contact with the emitter. When compared to PC-1, differential data on the UO ₂ effect will be available. Conduct a life test.

TABLE 3-2
EX-REACTOR CYLINDRICAL CONVERTER TEST PROGRAM

	Emitter	Collector	Reservoir	Life Test	Rationale
CC-1	Duplex W	Nb	Graphite	No	Performance map with reference electrodes and reservoir.

installed is designated PC-1 (Mod). The uranium oxide is separated from the interelectrode space by a relatively thin layer of tungsten. At the operating temperature of the emitter, 1800 K to 2000 K, the oxygen from the uranium oxide will migrate into the interelectrode space and change the performance of the converter.

PC-1 (mod) will be used to measure the long term performance of the converter with the combined effects of oxygen and cesium from a cesium-graphite reservoir. Both PC-1 and PC-1 (Mod) will be built in FY-91 with testing of PC-1 (Mod) to be carried into later years.

4. INSULATOR SEAL TASK

4.1 OBJECTIVE

The overall objective of the insulator seal task is to develop and validate the performance of an insulator seal for use in the thermionic fuel element reference design. In particular, the objectives are:

1. Produce designs for the insulator seal.
2. Develop required fabrication processes for insulator seals and document the process specifications.
3. Fabricate insulator seals for ex-reactor and in-reactor testing.
4. Verify the performance characteristics and lifetimes associated with insulator seals by means of ex-reactor and in-reactor testing. Perform postirradiation examination of the seal specimens and use the test results to improve the seal design.
5. Develop an analytical model of the performance and lifetime of the insulator seal and validate the model with test data.

The insulator seal must provide electrical isolation between adjacent collectors while maintaining a leak-tight seal separating the cesium vapor of the interelectrode space from the fission products. This is shown schematically in Fig. 4-1. The current design requirements are listed below:

1. Insulator temperature	Maximum 1150°K
2. Nominal fast fluence, E>0.1 Mev	2.3×10^{22} n/cm ²
3. Maximum applied voltage	0.63 volts
4. Operating environment	2-3 torr Cs and fission gases
5. Leak tightness (unirradiated)	$\leq 1 \times 10^{-8}$ standard cc/s
6. Electrical resistance	>10 ohms (1150°K)
7. Lifetime	≥ 7 years.

Figure 4-1. Thermionic cell showing insulator locations

4.2 TASK DESCRIPTION

The insulator seal task consists of five subtasks:

1. Seal design. Seal designs consistent with the TFE requirements are to be developed. Designs to be considered are the taper seal, the butt seal and trilayer seal.
2. Fabrication development. Select appropriate insulator materials. Develop appropriate bonding techniques for each insulator material selected. Fabricate insulator seal specimens for ex-reactor and in-reactor testing. Prepare and issue process specifications. Insulator materials to be considered are alumina (Al_2O_3), yttria (Y_2O_3) and YAG ($\text{Y}_3\text{Al}_5\text{O}_{12}$).
3. Ex-reactor testing. Perform ex-reactor tests to evaluate the effects of thermal cycling, cesium compatibility, applied voltage and material interdiffusion on insulator seal performance and lifetime.
4. In-reactor testing. Perform in-reactor tests and the related postirradiation examinations to determine seal mechanical stability, electrical resistance and hermeticity after exposure to fast neutron fluences.
5. Modeling. Develop and validate analytical models to predict seal lifetime and performance.

4.3 DESIGN AND MATERIALS DOWN-SELECTION

The seal design has been down-selected to include only the taper design. Table 4-1 gives an overview of the down-selection process for the seal insulator. The trilayer seal design is still a viable alternative, and its development will be part of the sheath insulator task (Task 5). While the trilayer seal design is different from the sheath insulator design, the technology is identical for the two insulators. The seal designs which have been studied are shown on Fig. 4-2.

TABLE 4-1
SEAL INSULATOR DESIGN DOWN SELECTION

	<u>Butt</u>	<u>Trilayer</u>	<u>Taper</u>
1986-87	UCA-1	UCA-1	UCA-1, 1H1
1988-89		UCA-2	UCA-2, 1H2, 1H3
1989-90			UFAC-3, 3H1, 3H5
1990-91		UCA-3	UCA-3, 6H1

Figure 4-2 - Insulator seal designs

The insulator materials currently being developed as seals are single crystal alumina, the reference insulator material, polycrystalline alumina and polycrystalline YAG. Initial PIE results of UCA-2 single crystal YAG taper seal test samples indicate that YAG has good neutron damage resistance and requires additional testing. YAG exhibits considerably less swelling than alumina, and will therefore be developed as a backup to alumina.

4.3.1 Fabrication Development

Postirradiation examination of UCA-1 taper insulator seals showed that the niobium skirt had partially peeled away from the single crystal alumina, the weak area being through the insulator and not at the braze interface. It was concluded that this weakness was due to a combination of factors:

- Fabrication induced microcracks.
- Residual stresses from the high temperature metallizing and brazing.
- Swelling of the niobium and alumina during irradiation.

Improvements in the fabrication procedure are being implemented to solve the first two problems:

- Reduce the microcracking by minimizing the machining of the seal after metallizing and brazing. Cleanup of the insulating gap is now done by diamond lapping rather than diamond grinding.
- Reduce fabrication residual stresses by using a lower temperature metallizer and braze alloy. Two new braze alloys, niobium-zirconium and titanium-vanadium, were identified to yield ductile compositions in the 1300°C to 1750°C temperature range. Niobium-zirconium and titanium-vanadium have melting temperatures 100°C and 250°C lower than the standard niobium-vanadium braze. The two selected brazes are undergoing tests for wetting, bond strength, and compatibility with alumina, YAG, niobium and cesium. A new metallizer composition is also under investigation. The metallizing temperature of this new composition is 200°C lower than the standard tungsten-yttria metallizer. The new metallizer is being tested for compatibility with the braze alloys, alumina and YAG insulators, and cesium.

4.4 EX-REACTOR TESTING

Accelerated testing is underway on a single crystal alumina taper seal. After 85 days at 1273 K the seal has an electrical resistance of 1.6×10^8 ohms. The resistance as a function of time is shown in Fig. 4-3. The applied potential will be increased from the nominal 1 volt to 10 volts after the sample accumulates 90 days of testing. The initial activation energy was calculated to be 2.7 eV. The sample is not being exposed to cesium vapor during electrical testing due to lack of leak tightness of the test assembly.

4.5 IN-REACTOR TESTING

4.5.1 UCA-1

The postirradiation examination of UCA-1 samples has been completed.

SINGLE CRYSTAL TAPER INSULATOR SEAL RESISTANCE VS TIME

Figure 4-3. Resistance as a function of time at 1273 K for a single crystal taper seal.

Irradiation testing began on September 11, 1986 and was completed on October 10, 1987. The insulators were irradiated for approximately 341 effective full power days (EFPD) and received estimated peak fast fluences between 3.0 and 7.2×10^{22} nvt at a temperature of about 1110 K. The test matrix and PIE results for the insulator seals in UCA-1 are shown in Table 4-2.

TABLE 4-2
UCA-1 INSULATOR SEALS

Configuration	S/N	Irradiation Temperature	Fluence $\times 10^{22}$ nvt	1070 K Resistance	He Leak Rate Std. cc/sec
Taper alumina	L-1	1126 K	3.9	4.93×10^7	.5
Taper alumina	L-2	1110 K	3.1	5.20×10^7	.5
Taper alumina	L-3	1159 K	7.2	4.30×10^7	.1
Butt	B-1	1094 K	3.0	2.0×10^5	1.5
Butt	B-2	1114 K	4.1	5.0×10^6	1.5
Butt	B-4	1156 K	7.1	Not tested	Not tested
Yttria trilayer	T-1	1113 K	3.0	1000	1.2×10^{-8}
Yttria trilayer	T-2	1113 K	3.0	1280	1.5
Yttria trilayer	T-3	1170 K	7.2	350	1.5

4.5.2 UCA-2

UCA-2 is the second in the series of in-reactor component testing. Irradiation testing in FFTF was completed on January 8, 1989. The insulators were irradiated for approximately 335 effective full power days (EFPD) and received estimated fast fluences between 3.8 and 5.5×10^{22} nvt at a temperature of about 1130 K. The test matrix and PIE results for the insulator seals in UCA-2 are shown in Table 4-3. Improved He leak tightness for the seals is expected for the UCA-3 samples which will implement several new fabrication procedures. Three seals (S/N 003, S/N 001, and S/N 280B) have been selected for metallographic examination which will start at the end of September.

TABLE 4-3
UCA-2 INSULATOR SEALS

Configuration	S/N	Irradiation Temperature	Fluence 10 ²² nvt	1070 K Resistance	He Leak Rate Std. cc/sec
Taper alumina	003	1115 K	4.4	1.0 x 10 ⁸	.5
Taper YAG	001	1162 K	5.5	4.6 x 10 ⁴	1
Yttria trilayer	297B	1138 K	3.8	1595	1 x 10 ⁻²
Yttria trilayer	280B	1135 K	4.0	2257	1 x 10 ⁻²

4.5.3 UFAC-3

To gain additional fast reactor experience with insulator seals, a set of specimens was fabricated for irradiation testing in EBR-II as part of the UFAC Batch 2 program. The specimens include individual taper seal components as well as metallized and brazed taper seals, as shown in Table 4-4. Irradiation began in January 1990 and ended in September 1990, with a total of 170 EFPD and an estimated exposure of about 2.3×10^{22} nvt at 1140 K. No major changes were detected on the neutron radiographs taken of the seals during the April 1990 interim examination when the fluence was about 0.9×10^{22} nvt.

The radiographs are shown in Fig. 4-4.

TABLE 4-4
UFAC-3 Batch 2 INSULATOR SEALS TEST MATRIX

Materials	Seals	Ceramic Rings	Skirts
Alumina (SC)	1	2(1)	
YAG (PC)	2	2(1)	
Niobium			2(2)

SC Single crystal
PC Polycrystalline
(1) One ring metallized
(2) Top and bottom

**Subcapsule
YAG I**

**Subcapsule
YAG II/YAG III**

**Subcapsule
A III**

Diamond Sample

Figure 4-4. Postirradiation neutron radiographs of seal insulator samples and diamond sample irradiated in UFAC-3 capsule SC3-2 at a fast fluence of $1 \times 10^{22} \text{ n/cm}^2$

4.5.4 UCA-3

The initial test matrix for UCA-3 is shown in Table 4-5. For this test the insulator seals will be fabricated using the improved lapping technique as well as the new metallizer and braze alloys to reduce stresses and produce a He leak tight seal. Testing is scheduled to start December 1990 in EBR-II and will run for 180 EFPD at an estimated accumulated total fluence of 2.5×10^{22} nvt.

A trilayer seal configuration will also be tested in UCA-3. The trilayer design will be such that, in principle, it can be substituted for the taper seal in a converter without any modifications to the TFE. Figure 4-5 show schematics of both the trilayer seal and the taper seal.

TABLE 4-5
UCA-3 INSULATOR SEALS TEST MATRIX

Alumina			
Single crystal	Taper		6
Polycrystalline graded	Trilayer		2
Polycrystalline Nb cermet	Trilayer		2
YAG			
Polycrystalline	Taper		6

Figure 4-5. Trilayer seal and taper insulator seals

4.6 STATUS SUMMARY

The current reference seal insulator specifications are summarized below:

Reference material:	Single crystal alumina
Design:	Taper seal
Fabrication:	Braze to niobium.

The current seal insulator backups are (not in priority):

- Alumina sheath insulator design
- YAG polycrystalline taper seal
- Alumina polycrystalline taper seal.

The polycrystalline alumina taper seal has experienced over 30,000 real time test hours in the TRIGA reactor, good evidence that its lifetime is at least several years. YAG is also being carried as a backup because of its low irradiation induced swelling and good electrical properties. More fabrication development and testing, both in-reactor and ex-reactor, are needed for YAG.

A summary of the seal insulator development effort is shown on Table 4-6.

References

4-1 TFE Verification Program Semiannual Report for the Period Ending March 31, 1990, GA-20119.

TABLE 4-6
INSULATOR SEAL TECHNOLOGY STATUS

Material Design	Electrical Properties	Neutron Stability	Fabric-ability	Test Matrix (No. of Specimens)				
				UCA-1	UCA-2	UFAC-3	TFE 1H1/1H2 1H3	Fueled Emitter
Alumina Taper SC	Good	Acceptable	Good	3	1	1		
YAG Taper SC	Acceptable	Good	Good		1			
Alumina Taper PC	Good	Acceptable	Good				6	9
YAG Taper PC	TBD	Good	Good			3		
Alumina Trilayer Graded	Good	Acceptable	Good	6	2			
Alumina Trilayer Cermet	Good	Good	Good	3	2			

PC - Polycrystalline
SC - Single crystal

5. SHEATH INSULATOR TASK

5.1 OBJECTIVE AND TECHNICAL APPROACH

The overall objective of the sheath insulator task is to develop and validate the performance of a sheath insulator for use in the thermionic fuel element reference design. In particular, the objectives are:

1. Produce designs for the sheath insulator.
2. Develop fabrication processes for the sheath insulators and document the process specifications.
3. Fabricate sheath insulators for ex-reactor and in-reactor testing (uninstrumented and instrumented testing).
4. Verify the performance characteristics and lifetimes associated with sheath insulators by means of ex-reactor and in-reactor testing. Perform postirradiation examination of the sheath insulators and use the results to improve on the sheath insulator design.
5. Develop an analytical model of the performance and lifetime of the sheath insulator and validate the model with test data.

The sheath insulator must provide electrical isolation between the collector of each converter and the outer sheath tube which is in contact with the reactor liquid metal coolant. The sheath insulator must also provide good thermal conduction between the collector and the sheath tube. This is shown schematically in Fig. 5-1. The current design requirements are listed below:

1. Insulator temperature	Nominal 1070 K
2. Nominal fast fluence, $E > 0.1$ MeV	2.3×10^{22} n/cm ²
3. Maximum applied voltage	7.5 volts
4. Operating environment	Fission gases
5. Electrical resistance	> 1000 ohms (1070 K)
6. Thermal conductivity	> 0.03 W/cm-K)
7. Lifetime	≥ 7 years

Figure 5-1. Thermionic cell showing insulator locations

The technical concerns are the unbonding of the sheath insulator structure due to fast neutron induced damage, and electrolysis which could lead to low electrical resistance, and electrical breakdown. The objective of the sheath insulator task is to resolve these concerns and to develop and validate the performance of a sheath insulator for use in a prototypic TFE.

5.2 TASK DESCRIPTION

The sheath insulator task consists of five subtasks:

1. Sheath design. Sheath designs consistent with the TFE requirements are to be developed. The current design is the trilayer, consisting of an insulator layer between the niobium collector and the outer niobium sheath tube.
2. Fabrication development. Select appropriate insulator materials. Develop appropriate fabrication techniques for each insulator material selected. Fabricate sheath insulator specimens for the ex-reactor and in-reactor testing. Prepare and issue process specifications. Insulator materials to be considered are alumina (Al_2O_3), yttria (Y_2O_3) and YAG ($\text{Y}_3\text{Al}_5\text{O}_{12}$). The fabrication techniques include plasma spraying the insulator onto the niobium collector, and thermal bonding free standing ceramic tubes to the collector.
3. Ex-reactor testing. Perform ex-reactor tests to evaluate the effects of thermal cycling, applied voltage and material inter-diffusion on the sheath insulators performance and lifetime.
4. In-reactor testing. Perform uninstrumented and instrumented in-reactor tests and the related postirradiation examinations to determine the sheath insulator mechanical stability, electrical resistance and hermeticity after exposure to fast neutron fluences with and without an applied voltage.
5. Modeling. Develop and validate analytical models to predict sheath insulator lifetime and performance.

5.3 DESIGN AND MATERIALS DOWNSELECTION

Two manufacturing processes and two insulator materials are currently being evaluated. The manufacturing processes are the plasma sprayed graded trilayer being investigated at GA and the cermet trilayer being investigated at TTC. The insulator materials under investigation are alumina and yttria. Single crystal alumina trilayer, which had been under investigation, has been dropped from the program because of the difficulty of making sheaths with no cracks.

Table 5-1 gives an overview of the downselection process for the sheath insulator task since the start of the program.

TABLE 5-1
OVERVIEW OF DOWNSELECTION

Material	Test	Current Focus	Comments
Graded trilayer			
Alumina	UCA-1,2, 1H1-1,2,3	X	Crack free
Yttria	UCA-1,2, 1H1		Marginal electrical
YAG	UCA-2		Fabrication cracks
Cermet trilayer			
Alumina	UCA-1,2	X	Short free
Yttria	UCA-2		Poor electrical
YAG	UCA-1		Fabrication cracks

5.3.1 Plasma Sprayed Graded Trilayer Fabrication Development

Commerical Linde A alumina (0.3 μm average particle size) was plasma sprayed on 0.500 inch and 0.350 inch thick mandrels. Metallographical examination of the HIP'ed* mandrels revealed that the Linde A alumina sheaths are very similar in microstructure and crack count to sol-gel derived alumina. Linde A alumina can be used as a substitute for sol-gel derived alumina sheath insulators.

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*HIP: hot isostatic press.

5.3.2 Cermet Trilayer Fabrication Development

Alumina cermets with 5% and 10% niobium powder are being manufactured using the slip cast method to make samples for ex-reactor and in-reactor tests. A new supply of niobium powder had to be selected because of changes in the average particle size of the previous niobium supplier and the larger cost associated with sizing the powder to the useful 10 μ m particle size.

5.3.3 Single Crystal Alumina Trilayer Fabrication Development

Bonding of chemically polished sapphire tubes did not produce a crack free trilayer. The single crystal alumina trilayer fabrication development effort has been dropped from the program because of the difficulty of making sheaths with no cracks.

5.4 EX-REACTOR TESTING

The ex-reactor testing of the sheath insulators is done by Rasor Associates Inc. (RAI). Testing includes long term tests at the nominal operating temperature and applied potential and accelerated tests at higher temperatures and a higher applied potential.

The electrical resistance testing procedures at RAI have been modified to involve three test temperatures: the nominal operating temperature of 1070 K and two accelerated temperatures, 1170 K and 1270 K. Duration of the testing will be 150 days. Ninety days are run with the nominal potential of 7.5 volts. The remaining sixty days are run with a 30 volts (accelerated) potential. The activation energy is measured on all the samples at the start of testing and subsequently every other week. The minimum number of samples required for testing is three so one can be tested at each of the test temperatures.

Ex-reactor electrical testing of sheath insulators fabricated during FY-89 was terminated. Six sol-gel derived alumina graded sheath insulators and four sol-gel derived yttria graded sheath insulators were tested under realtime and accelerated conditions of temperature (1250, 1150, and 1050 K)

and voltage (7.5 and 30 volts). The transition from the nominal potential of 7.5 volts to the accelerated potential of 30 volts happened after 90 days of testing. The resistance as a function of time for all the alumina and yttria samples tested are shown in Figs. 5-2 and 5-3 respectively. An open circuit developed in the measuring system so the two alumina samples being accelerated to 1150 K were only tested for 60 days. Three of the four yttria samples shorted during testing. The two yttria samples being accelerated at 1250 K shorted after 30 days of testing and the sample being accelerated to 1150 K shorted four days after the applied potential was increased to 30 volts. Tables 5-2 and 5-3 show the equivalent operating time at 1070 K and 7.5 volts for the two alumina samples accelerated to 1250 K at 7.5 and 30 volts and for the yttria samples tested at 1150 K and 1050 K respectively.

TABLE 5-2
GRADED ALUMINA EQUIVALENT OPERATING TIME AT 1070 K AFTER
ACCELERATION AT 1250 K AND 7.5 AND 30 VOLTS

S/N	Activation Energy	Test Time	1250 K Resistance	Equivalent Time (1070 K)
1108	2.72/2.41 eV	154 days	6.93×10^7 ohms	43 years
1109	3.13/2.41 eV	154 days	6.60×10^7 ohms	58 years

TABLE 5-3
GRADED YTTRIA EQUIVALENT OPERATING TIME AT 1070 K AFTER ACCELERATION
OF 1150 K AT 7.5 VOLTS (S/N 1116) AND 1050 K AT 30 VOLTS (S/N 1117)

S/N	Activation Energy	Test Time	1250 K Resistance	Equivalent Time (1070 K)
1116	1.92/1.78 eV	90 days	6.35×10^3 ohms	1 year
1117	1.92/1.68 eV	154 days	2.13×10^4 ohms	1 year

GRADED ALUMINA

Figure 5-2. Ex-reactor test results for graded alumina sheath insulators: Sol gel derived alumina.

GRADED YTTRIA

Figure 5-3. Ex-reactor test results for graded yttria sheath insulators: Sol gel derived yttria.

A new set of ex-reactor sheath insulator test samples was delivered to RAI. A total of fifteen samples, six alumina cermets with 5% niobium from TTC and three graded yttria and six graded alumina from GA, are undergoing testing. The samples have been tested for a total of 43 days. The resistance as a function of time and temperature are shown in Figs. 5-4, 5-5 and 5-6 for the graded alumina, alumina cermet and graded yttria, respectively. None of the alumina samples have shown any decrease in resistance as a function of time and temperature. The graded yttria sample being accelerated to 1270 K is showing signs of degradation, while the yttria samples being tested at 1170 K and 1070 K show no indications of degradation. Testing under the current conditions will continue until a total of 90 days of testing have been accumulated.

5.5 In-Reactor Testing

UCA-1. The postirradiation examination of UCA-1 samples has been completed. Irradiation testing began on September 11, 1986 and was completed on October 10, 1987. The insulators were irradiated for approximately 341 effective full power days (EFPD) and received estimated peak fast fluences between 3.1 and 7.0×10^{22} nvt at a temperature of about 1110 K. The test matrix and PIE results for the sheath insulators in UCA-1 are shown in Table 5-4.

UCA-2. UCA-2 is the second in the series of in-reactor component testing. Irradiation testing in FFTF was completed on January 8, 1989. The insulators were irradiated for approximately 335 EFPD and received estimated peak fast fluences between 3.4 and 6.2×10^{22} nvt at a temperature of about 1130 K. The test matrix and PIE results for the sheath insulators in UCA-2 are shown in Table 5-5. The resistance values of the yttria cermets and the graded YAG sheath insulators are below the minimum required for the sheath insulators. All work on yttria cermets was stopped about a year ago because of the poor performance of this material during ex-reactor testing. The results for YAG are intriguing because the single crystal YAG insulator seal has a high resistance after irradiation while the polycrystalline YAG has a low resistance. Work on graded YAG has also stopped because of difficulties of making sheaths with few or no cracks. Five out of the ten UCA-1 sheath insulators (S/N 317, S/N 336, S/N TA8, S/N TA9 and S/N 346Z) were selected for metallographic examination which will start at the end of September.

Figure 5-4. Ex-reactor test results for graded alumina sheath insulators: currently on test.

Figure 5-5. Ex-reactor test results for alumina cermet sheath insulators: currently on test.

Figure 5-6. Ex-reactor test results for yttria sheath insulators: currently on test.

TABLE 5-4

UCA-1 INSULATOR SEALS

Configuration	S/N	Irradiation Temperature	Fluence $\times 10^{22}$ nvt	1070 K Resistance	He Leak Rate Std. cc/sec
Graded Alumina	A1-1	1109 K	3.5	3838 ohms	$>10^{-4}$
Graded Alumina	A1-2	1110 K	3.3	2000 ohms	5×10^{-5}
Graded Alumina	A1N-1	1135 K	6.9	5000 ohms	$>10^{-4}$
Graded Alumina	AA-1	1112 K	3.6	38 ohms	5×10^{-5}
Graded Alumina	AA-2	1104 K	3.2	2.3×10^6 ohms	7.5×10^{-5}
Graded Alumina	AAN-1	1114 K	3.8	313 ohms	2.6×10^{-6}
Graded Yttria	Y-1	1104 K	3.1	55 ohms	4.3×10^{-8}
Graded Yttria	Y-2	1112 K	3.7	42 ohms	1.1×10^{-7}
Graded Yttria	Y-3	1133 K	6.8	11.6 ohms	8.5×10^{-8}
Alumina Cermet	TEA-1	1090 K	3.1	Not tested	1.1×10^{-7}
Alumina Cermet	TEA-2	1137 K	7.0	Not tested	1.3×10^{-7}
Alumina Cermet	TEA-3	1111 K	3.5	Not tested	5×10^{-5}
YAG Cermet	TEYAG-1	1096 K	3.4	1210 ohms	1.5
YAG Cermet	TEYAG-2	1130 K	6.6	Not tested	1.5
YAG Cermet	TEYAG-3	1106 K	3.4	41 ohms	1×10^{-2}

TABLE 5-5

UCA-2 INSULATOR SEALS

Configuration	S/N	Irradiation Temperature	Fluence $\times 10^{22}$ nvt	1070 K Resistance	He Leak Rate Std. cc/sec
Graded Alumina	317	1114 K	3.7	8.25×10^7 ohms	6.8×10^{-5}
Graded Alumina	336	1128 K	5.8	5.13×10^7 ohms	5.4×10^{-7}
Graded Yttria	345	1117 K	3.4	4.62×10^5 ohms*	Not tested
Graded Yttria	346	1128 K	5.9	401 ohms	$<10^{-8}$
Graded YAG	333	1113 K	3.8	133 ohms	1.7×10^{-4}
Graded YAG	334	1130 K	5.6	296 ohms	1.6×10^{-4}
Alumina Cermet	TA8	1109 K	3.7	7.83×10^6 ohms	2.8×10^{-4}
Alumina Cermet	TA9	1121 K	6.0	4.40×10^7 ohms	2.9×10^{-4}
Yttria Cermet	TY2	1112 K	3.4	248 ohms	2.7×10^{-6}
Yttria Cermet	TY5	1122 K	6.2	225 ohms	1.2×10^{-4}

*The measurement was made at 873 K.

UCA-3. The initial test matrix for UCA-3 is shown in Table 5-6. Testing is scheduled to start December 1990 in EBR-II and will run for two 90 day cycles with an estimated total fluence of 2.5×10^{22} nvt.

TABLE 5-6
INITIAL UCA-3 SHEATH INSULATORS TEST MATRIX

<u>Materials</u>	<u>Polycrystalline Alumina</u>
Design	Step end
Graded	2
Cermet	2 (5 and 10% Nb)

IFAC-SI. A review meeting was held on August 15 in Reno, Nevada to review material selection for the sheath insulators, testing conditions, and needed instrumentation. The highlights of the meeting are summarized below:

- 1) Material selection with two of each type of sheaths needed
  - a) Sol-gel graded alumina
  - b) Alumina 10% niobium cermet
  - c) Alumina 5% niobium cermet
- 2) Test temperatures
  - a) 1070 K (nominal)
  - b) 1170 K (accelerated)
- 3) Test voltages
  - a) 7.5 volts (nominal)
  - b) 15 volts (accelerated)
  - c) 30 volts (accelerated)
- 4) Irradiation will consist of three 90 days cycles ($\sim 1.25 \times 10^{22}$ n/cm² per cycle). Test voltage shall change after every cycle.
- 5) Resistance will be measured both with a picoammeter and a 1000 ohms shunt resistor. Figure 5-7 is a schematic of the measuring system with all the needed instrumentation.

5.6 Status Summary

A summary of the sheath insulator development effort is shown in Table 5-7. The development priority at the moment is as follows:

Figure 5-7. Electrical schematic for the IFAC-SI instrument and control systems

TABLE 5-7
SHEATH INSULATOR TECHNOLOGY STATUS

Material	Design	Priority	Electrical Properties	Neutron Stability	Fabricability	Test Matrix (No. of Specimens)				
						UCA-1	UCA-2	TFE 1H1/1H2 1H3	Fueled Emitter	Ex- Reactor
Y ₂ O ₃ (P.C.)	Trilayer	High	Poor	Good	Good	3	4	1		23
YAG (P.C.)	Trilayer	Low	Good	Good	Difficult*	3	2			7
Al ₂ O ₃ (P.C.)	Trilayer	High	Good	Acceptable	Difficult*	10	4	2	9	34
Al ₂ O ₃ (S.C.)	Trilayer	Low	Good	Acceptable	Difficult*					2

P.C. Polycrystalline.

S.C. Single Crystal

* Not crack free

Reference: Alumina oxide, plasma sprayed graded or slip cast cermet.

Polycrystalline aluminum oxide both graded and cermet have shown good ex-reactor and in-reactor electrical properties and have survived fast neutron fluences 2-1/2 times higher than what is expected in a seven year lifetime. Polycrystalline aluminum oxide plasma sprayed graded trilayer has experienced over 30,000 real time test hours in the TRIGA reactor. Yttria was the reference material but has been dropped off as a sheath insulator material because of the poor ex-reactor electrical properties.

6. FUELED EMITTER TASK

6.1 OBJECTIVE AND TECHNICAL APPROACH

The function of the fueled emitter is to generate the heat necessary to drive the thermionic conversion process with the geometry, power densities and temperatures required by the reference TFE design, using materials compatible with both the thermionic process and reactor requirements. Specific requirements for the emitter are given in Table 6-1.

TABLE 6-1
FUELED EMITTER DESIGN REQUIREMENTS

<u>Emitter</u>	
Material	Duplex Tungsten
Outside diameter, cm	1.27
Thickness, cm	0.10
Emitter/collector gap, cm	0.025
Nominal temperature, K	1800
<u>Fuel</u>	
Outside diameter, cm	1.0
Inside diameter, cm	Variable
Enrichment, % U-235	93
Fuel length, cm	4.65
Nominal fuel burnup, atom percent	4.1
Peak fuel burnup, atom percent	5.3

The key technical concern is the emitter distortion as a result of fuel swelling over the 7-year lifetime. It is the objective of the fueled emitter task to develop and demonstrate by appropriate ex-reactor testing, in-reactor testing and analytical verification a fueled emitter capable of meeting the above design requirements.

The strategy to demonstrate the performance and lifetime of the fueled emitter is based on extensive in-reactor testing. While duplex tungsten will be the focus of most of the testing, alternate materials, particularly

the HfC strengthened materials, look very promising and will be considered. Additionally, alternate fuel forms will be evaluated which either weaken the fuel or change its swelling characteristics, thereby minimizing emitter distortion. These forms include insulated fuel, and wafered fuel.

During the current reporting period the following tasks were performed:

UFAC fast reactor irradiation program

- 1) Subassembly UFAC-1. The four accelerated pins contained in this subassembly reached the goal burnup of about 4 atom percent after 518.7 effective full power days (EFPD) of irradiation and were removed from the EBR-II core for postirradiation examination (PIE).
- 2) Subassembly UFAC-2. Irradiation of this subassembly, which contains two Batch-1 and three Batch-2 prototype emitters, continued throughout the reporting period.
- 3) Subassembly UFAC-3. Irradiation of this subassembly which contains three Batch-2 accelerated emitters and two component capsules, continued through the reporting period.

Fueled emitter lifetime modeling

Evaluation of the UFAC Batch 1 and 2 neutron radiographs (NR) continued. Emitter temperature calculations of the UFAC emitters using as built dimensions, actual EBR-II operating power profiles, and burnup measurements also continued.

(PIE) of TRIGA Capsules

Capsule 2, fabricated as part of the thermionic technology program, was transferred from the TRIGA Mark-F spent fuel pool to the GA hot cell and disassembled.

6.2 EX-REACTOR TESTING

Ex-reactor analysis has been primarily focused on the possibility that emitter distortions due to thermal ratcheting and/or bladder phenomena could be important. Early studies in the TFE program showed that both of these mechanisms are not important to the overall fuel emitter distortion. Therefore, the focus of the ex-reactor testing shifted to the investigation of the creep characteristics of the candidate emitter material.

The fabrication problems that Westinghouse AES was having in extruding bars of W HfC advanced emitter material appear to have been resolved. Using the experience gained during the unsuccessful fabrication of the UFAC Batch-2 advanced emitter material, Westinghouse successfully extruded and delivered six bars to Space Power Inc. for use as an advanced emitter material in another program. The following changes were made to the process:

- 1) The arc melted base ingots were reduced in diameter from 2 to 1.5 inches. This decreased the area reduction from about 7:1 to about 4:1 during the extrusion which lowered the stresses on the dyes.
- 2) The molybdenum coating that the ingots were encased with during the extrusion was increased from 0.030 in. to 0.150 in. The thicker coating provided more "lubrication" during the extrusion.

While these two improvements appear to have solved earlier problems, there has not been any metallographic or strength evaluation of the material up to this point. This remains to be done.

FY-91 plans for high strength emitters are being reviewed given the likely availability of desirable material.

6.3 UFAC IN-REACTOR TESTING

6.3.1 Introduction

The uninstrumented fast reactor accelerated component (UFAC) test

consists of three batches of fueled emitters that will be irradiated in EBR-II. Two of the batches are currently being irradiated while the third is planned in FY-92. The two batches on test are divided into three EBR-II subassemblies, as defined in Fig. 6-1. The EBR-II core location for these irradiations is as follows:

<u>Subassembly</u>	<u>Core Location</u>
X439	5E2 (Removed)
X440	7F1
X442	4D2

The fueled emitter identification scheme is shown on Table 6-2.

The irradiation history is shown on Fig. 6-2. EBR-II was shutdown for much of CY-89. Run 152 began on October 31, 1989, after about a six month shutdown, and extended for 30 effective full power days (EFPD). Run 153 began on January 28, 1990, commencing the irradiation of the Batch-2 specimens and extended for 63 EFPD.

The current plan for FY-91 is as follows:

- 1) UFAC Batch-1 PIE. The four accelerated emitters which have reached goal burnup will be terminally examined in the Hanford hot cells. The exams planned to be performed as part of the TFE program include photographic exams, profilometry and burnup analyses. Metallography will also be performed but as a part of the USAF thermionic program.
- 2) Interim neutron radiography examinations. Two interim examinations are planned:
  - 1) UFAC-2: Neutron radiographs will be taken after run 156 in April 1991 during the long shutdown. The peak burnup will be about 2.0 a/o and the fast fluence about 7.6×10^{22} nvt.

Test Designation	Test Content	EBR-II		Irradiation				Postirradiation Examination Status
		Subassembly Number	Core Location	Status	EFPD's*	Fast Fluence, $\times 10^{22}$ n/cm ²	Peak Burnup (at.%)	
UFAC-1	7 Batch 1 0.250 in. OD Fueled Emitters (Emitter Thickness, Temperature, Fuel Center Void)**	X439	5E2	Complete 8/87	94.5	1.5	1.0	NDE 7*** Capsules Complete 11/87
UFAC-1A	7 Batch 1 0.250 in. OD Fueled Emitters	X439A	5E2	Complete 4/88	221.5	3.6	2.1	NDE 7 Capsules Complete 7/88 DE 3**** Capsules Complete 6/89
UFAC-1B	4 Batch 1 0.250 in. OD Fueled Emitters 3 Dummy Capsules	X439B	5E2	Complete 4/90	518	7.6	4.3	NDE 4 Capsules Complete 6/90
UFAC-2	3 Batch 1 0.500 in. OD Fueled Emitters (Emitter Thickness, Fuel Center Void) 4 Dummy Capsules	X440	7F1	Complete 4/88	285	2.8	0.5	NDE 3 Capsules Complete 6/88 DE 1 Capsules Complete 6/89
UFAC-2A	2 Batch 1, 0.500 in. OD Fueled Emitters 5 Dummy Capsules	X440A	7F1	Complete 3/89	467	4.2	1.1	NDE 2 Capsules Complete 6/89
67 UFAC-2B	2 Batch 1 0.500 in. OD Fueled Emitters 4 Batch 2 0.500 in. OD Fueled Emitters (Fuel: Insulated, Wafered) 1 Dummy Capsule	X440B	7F1	In-Reactor	636	5.95	1.55	
					170	1.55	0.40	
UFAC-3	3 Batch 2 0.250 in. OD Fueled Emitters (Fuel: Insulated, Wafered) 2 Dummy Capsules 5 Cs Reservoir Samples 4 Insulator Seals	X442	4D2	Complete 4/90	63	0.9	0.6	NDE 3 Capsules Complete 5/89
UFAC-3A	3 Batch 2 0.250 in. OD Fueled Emitters 3 Dummy Capsules 3 Cs Reservoir Samples 4 Insulators Seals	X442A	4D2	Complete 9/90	170	2.3	1.55	

*EFPD, Equivalent Full Power Days.

**Test variables.

***NDE, Nondestructive examinations: visual, dimensional, gamma-scan, neutron radiography.

****DE, destructive examinations: gas sampling, radiochemical burnup, metallography.

Figure 6-1. Summary status of UFAC test series in EBR-II.

TABLE 6-2
UFAC EMITTER IDENTIFICATION SCHEME

ID Number		Diameter	Thickness	Temperature	Fuel Design	Comments
Real Time	Accelerated					
<u>UFAC BATCH-1</u>						
SU2-1		0.5	0.040	1800	15% void	Reference Design
SU2-2		0.5	0.050	1800	15% void	Thick Emitter
*SU2-3		0.5	0.040	1800	Solid	Solid Fuel
	SU1-4	0.25	0.020	1700	15% void	Reference Design/Low Temperature
	SU1-5	0.25	0.020	1800	15% void	Reference Design
	*SU1-6	0.25	0.020	1900	15% void	Reference Design/High Temperature
	*SU1-7	0.25	0.020	1800	Solid	Solid Fuel
	SU1-8	0.25	0.020	1900	Solid	Solid Fuel/High Temperature
	SU1-9	0.25	0.025	1800	15% void	Thick Emitter
	*SU1-10	0.25	0.025	1900	15% void	Thick Emitter/High Temperature
<u>UFAC BATCH-2</u>						
SU2-11		0.5	0.040	1800	15% void	Batch-1 Replica
SU2-12		0.5	0.040	1800	25% void	High Fuel Void
SU2-14		0.5	0.040	1800	-	Insulated Fuel
SU2-15		0.5	0.040	1800	-	Wafered Fuel
	SU3-16	0.25	0.020	1800	15% void	Batch-1 Replica
	SU3-17	0.25	0.020	1800	-	Insulated Fuel
	SU3-20	0.25	0.020	1800	-	Wafered Fuel

* Removed for examination at end of Run 147.

Figure 6-2

UFAC IRRADIATION SCHEDULE

- 2) UFAC-3: Neutron radiographs will be taken after run 154 in September 1990. The nonfueled capsule, SC3-2, with the Cs reservoir samples will have reached the goal fluence and will be removed at this time. In addition, NR's will be taken after run 156 in April 1991. Additional nonfueled components and possibly some diamond insulators will be inserted during this interim examination.

6.3.2 UFAC-1 Status

The four accelerated emitters which comprised subassembly X-439 attained the goal burnup after a total exposure of 518 effective full power days (EFPD) and were removed from the core for PIE. The design and the final irradiation conditions for these emitters is summarized in Table 6-3. As can be seen, the burnup for the emitters is in the range of 3.25 to 4.27 atom percents, which covers the design average burnup of 4.1 atom percent for the 2 MWe reactor design. The fast fluence, however, is in the range of 6.77 to 7.57×10^{22} n/cm² which is about three times the average fast fluence expected in the 2 MWe reactor, 2.7×10^{22} n/cm². This points up a problem with accelerated testing: it is not possible to accelerate the fluence in a manner consistent with the burnup. In the UFAC-1 case, the very large fluence may excessively degrade the materials in the fueled emitter subassembly. Separate material tests should be conducted to determine the effect on the important material properties such as creep, strength and ductility of the fast neutron fluence. This possibility will be examined in the future.

TABLE 6-3
FINAL IRRADIATION CONDITIONS IN UFAC-1

<u>Capsule</u>	<u>Emitter Surface Temperature, K</u>	<u>Emitter Thickness (Inch)</u>	<u>Fuel Form</u>	<u>Peak Fuel Burnup Atmosphere %</u>	<u>Peak Fast Fluence $\times 10^{22}$ n/cm²</u>
SU1-4	1700	.020	Annular	3.78	7.13
SU1-5	1800	.020	Annular	3.81	7.18
SU1-8	1900	.020	Solid	3.25	6.77
SU1-9	1800	.025	Annular	4.27	7.57

Neutron radiography (NR) was done to determine the conditions of the emitters prior to shipping them to Westinghouse Hanford for the destructive PIE. The NRs are shown in Fig. 6-3. A brief discussion of the individual emitters is given below.

- 1) SU1-4. This emitter has 0.25 in. diameter, 0.020 in. thickness, 15% manufactured void in the fuel, and was designed to operate at 1700 K. Analyses based on PIE results from other fueled emitters* indicated that this emitter operated at about 1550-1600 K. The NR showed that the emitter was fractured at the tungsten to tantalum transition joint. This fracture was similar to the previously observed fractures in SU1-6, SU1-7 and SU1-10.
- 2) SU1-5. This emitter has 0.25 in. diameter, 0.020 in. thickness, 15% manufactured void in the fuel, and was designed to operate at 1800 K. Analyses based on prior PIE results indicate that this emitter also operated at about 1550-1600 K. The NR showed a localized bulge in the top portion of the fueled region, about 0.25 in. below the upper heat shield. Metallography during irradiation will determine possible causes.
- 3) SU1-8. This emitter has 0.25 in. diameter, 0.020 in. thickness, manufactured solid fuel pellets, and was designed to operate at 1900 K. Analyses show that it operated at about 1600-1650 K. The NR showed the emitter to be intact.
- 4) SU1-9. This emitter has 0.25 in. diameter, 0.25 in. thickness, 15% manufactured void in the fuel, and was designed to operate at 1800 K. The analyses are showing that this emitter also operated colder than design. The NR showed the emitter to be intact.

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*See Reference 6-1, Section 6.3.5.

SUI-4 **SUI-5** **SUI-8** **SUI-9**

Figure 6-3. Postirradiation neutron radiographs of UFAC-1B

6.3.3 UFAC-2 Status

UFAC-2 continued on irradiation testing through EBR-II run 154 and is currently in run 155. The two Batch-1 and four Batch-2 emitters were irradiated for 89 EFPDs. The status of the capsules as of September 30, 1990 is shown in Table 6-4. The accumulation of burnup for these capsules is approximately realtime whereas the fluence is already more than double the 2 MWe design after only 619 days.

TABLE 6-4
STATUS OF THE UFAC IRRADIATION TESTS
THROUGH SEPTEMBER 30, 1990

<u>Assembly</u>	<u>Exposure EFPD</u>	<u>Peak Burnup Atom %</u>	<u>Fast Fluence 10²² n/cm²</u>
UFAC-2			
Batch-1	636	1.55	5.95
Batch-2	170	0.40	1.55
UFAC-3	170	1.55	2.30

6.3.4 UFAC-3 Status

UFAC-3 was removed from the reactor for the first interim examination April 1, 1990 at the end of run 153 at a peak fuel burnup of 0.6 at .% and a fast fluence of $0.9 \times 10^{22} \text{ n/cm}^2$. The capsules were removed from the UFAC-3 subassembly, visually examined and neutron radiographed at three orientations, i.e., -60°, 0°, 60° (Fig. 6-4). The radiographs were imaged for both overall structural features, and for the fuel distribution. The three emitters were intact. The plenum springs were partially collapsed suggesting operating temperatures consistent with the design emitter surface temperature of 1800 K.

The capsules were reassembled into UFAC-3A for continued irradiation in run 154. Irradiation of UFAC-3A was completed September 21 at a total exposure of 170 EFPDs of irradiation, a peak fuel burnup of 1.55 at .% and

Figure 6-4. UFAC-3 neutron radiographs after Run 153

a fast fluence of $2.3 \times 10^{22} \text{n/cm}^2$ (see Table 6-4). The capsules are to be reconstituted into UFAC-3B with irradiation to be continued December 20, 1990 in run 156.

Neutron radiographs were taken after run 153 and the results are summarized below. The NRs are shown in Fig. 6-4.

- 1) SU3-16. This emitter is a Batch-1 replica and has 0.25 in. diameter, 0.020 in. thickness, 15% manufactured void in the fuel, and is designed to operate at the nominal temperature of 1800 K. The NR shows that the emitter is intact and has a well formed central fuel cavity. The condition of the test specimen looked good.
- 2) SU3-17. This emitter has an insulated fuel configuration. The inner enriched region of fuel is surrounded by an annulus of depleted fuel. This depleted annulus will cause the central enriched fuel to operate hotter, lower its creep strength, and will act as a barrier for the emitter in reacting the swelling strains. The NR showed both the central enriched and annular depleted regions to be well formed and without any evident cracks. There appears to be some slight diffusion of the enriched fuel into the region between the depleted annular pellets. Otherwise there appears to be no diffusion of either the enriched or depleted fuel. The condition of the test specimen looked good.
- 3) SU3-20. This emitter has a wafered fuel configuration. The fuel region is subdivided into thin wafers of fuel and tungsten. The configuration will lower the overall temperature of the fuel and will cause it to run nearly isothermal with the emitter. The NR showed an equilibrium condition between the fuel and tungsten wafers without any large mass movement. Each fuel wafer appears to have a radially oriented central cavity indicating that the heat generated in the fuel is being transferred axially into the tungsten wafers and then radially out to the emitter for rejection. The condition of the test specimen looked good.

6.3.5 PIE Data Evaluation

Two activities are currently ongoing in the evaluation of the data gathered during PIE or interim NR examinations. First, all UFAC NRs taken since the program started are being reevaluated. Table 6-5 reviews the NR history for all UFAC emitters. The reevaluation will result in a consistent set of data with respect to the person doing the evaluation, the number and location of the measurements on the emitter, the use of standards and the treatment of film distortion. The current effort will include readings at five axial locations: top of fuel, 1/4, 1/2, 3/4, and bottom of fuel; and three angular locations: -60°, 0°, +60°.

TABLE 6-5

UFAC IRRADIATION PROGRAM NEUTRON RADIOGRAPHY HISTORY

Identification Number					
<u>Real Time</u>	<u>Accelerated</u>	<u>11-87</u>	<u>6-88</u>	<u>6-89</u>	<u>6-90</u>
SU2-1			X	X	
SU2-2			X	X	
SU2-3*			X		
	SU1-4**	X	X		X
	SU1-5**	X	X		X
	SU1-6*	X	X		
	SU1-7*	X	X		
	SU1-8**	X	X		X
	SU1-9**	X	X		X
	SU1-10*	X	X		
SU2-11					
SU2-12					
SU2-14					
SU2-15					
	SU3-16				X
	SU3-17				X
	SU3-20				X

* Removed for postirradiation examination on 7-88.

**Remove for PIE on 7-90.

The reanalysis of the operating history for the ten UFAC Batch-1 emitters is continuing. SPI has been asked to perform an independent review of the prior TTC analyses, based on PIE results, to verify the temperature, power, and distortion histories for these emitters. This review is currently in progress.

6.4 Postirradiation Examinations - GA Hot Cell

The GA hot cell was opened for the month of August primarily to perform postirradiation examination of Capsule 2 which was originally fabricated as part of the SP-100 Thermionic Technology Program. Components from previously disassembled Capsules 1 and 3 and insulators from Capsule 4 were also examined. Capsule 2 was originally inserted in the Mark-F reactor on January 13, 1985 and was removed from service on February 26, 1990 after 38,982 hours of irradiation. It had been stored in the spent fuel pool of the Mark F since then. All procedures followed were developed during the disassembly of Capsules 1 and 3.

To facilitate the transfer of the capsule from TRIGA to the hot cell, the upper 15 feet of the capsule was cutoff using a large diameter tubing cutter shown in Figs. 6-5 and 6-6. The lower, irradiated portion of the capsule was then inserted into a 6 ton cask and transferred to the hot cell using a 80 ton crane (Fig. 6-7). Once in the hot cell the capsule was destructively disassembled to recover the fueled emitters, the fission product plenums, and the fission product lines.

The examinations in the hot cell consisted of:

- 1) Gamma scanning of the fission gas plenums, spiral fission gas tubes, and the lower end of the capsule over the emitter region.
- 2) Visual examination of the components.
- 3) Measurement of the diameters and lengths of the emitters.
- 4) Room temperature electrical resistance measurements on the insulators from Capsule 4.

6.4.1 Gamma Scanning

Gamma scans of the fission product plenums and the fission product lines were taken. The activity of both the plenums and the lines was found

Figure 6-5. Cutting upper portion of capsule with tubing cutter

Figure 6-6. Upper portion of capsule after cutoff

Figure 6-7. Capsule being transferred to Hot Cell

to be extremely low. Initially the detector was set up so it would scan them while they were in the low level cell. However, all that was detected was background activity. The components were measured and found to have less than 2 R/hr at contact. They were put inside plastic bags and taken out of the hot cell, with thongs, and set up in the operating galley for scanning. The estimated activity is summarized in Table 6-6.

TABLE 6-6
GAMMA SCAN RESULTS FROM CAPSULE 2: RELATIVE COUNT RATE

	<u>Kr-85</u>	<u>Cs-134</u>	<u>Cs-137</u>	<u>Co-58</u>	<u>Co-60</u>	<u>Mn-54</u>
Fission product plenums	320	18	160	1	7	2
Fission product lines						
Emitter 1						
Lower spiral		6	650	4	43	7
Middle spiral		4	480	3	33	6
Upper spiral		5	250	3	19	4
Emitter 2						
Lower spiral		63	860	4	44	8
Middle spiral		57	570	4	36	8
Upper spiral		68	240	2	19	4
Emitter 3						
Lower spiral		15	670	4	43	7
Middle spiral		34	820	4	36	7
Upper spiral		9	360	2	18	4

6.4.2 Visual Examinations

The visual examination showed that the three emitters had longitudinal cracks in the fuel region not previously detected from the neutron radiographs. The operating conditions for each emitter and possible causes for the failures are discussed below.

Emitter 2.1, the uppermost in the capsule, had an external short from the very inception of the irradiation testing. The emitter, however, could be partially ignited up to August 22, 1989 or at about 34,000 hours of irradiation. The confidence in operating temperature, however, was never very high since volt/ampere (I/V) plots could not be obtained due to the short. The actual temperature could have been significantly higher than the

assumed 1750 K because of the low electron cooling component of the heat balance on the emitter.

Emitter 2.2 was one of the best performing emitters from the three capsules fabricated as part of the SP-100 irradiation program. It had the longest irradiation time, 20,255 hours, during which there was a high confidence in the 1850 K emitter temperature. This is shown in Table 6.7. The I/V curves during this time were clean and well defined yielding the high confidence in the temperature. The I/V curves slowly degraded and gave an indication of a short on about June 28, 1988 or at about 26,000 hours of irradiation. At that time, with the loss of electron cooling, emitter temperatures could have been excessive.

TABLE 6-7
EMITTER TEMPERATURES

Cell	Hours of Data	Emitter Thickness mils	Emitter Temperature K
1.2	10,000	100	1850
2.2	20,255	70	1850
2.3	16,000	70	1750
3.1	14,000	40	1750
3.2	14,000	70	1750
3.3	16,000	70	1750

Emitter 2.3 operated for 16,000 hours in which there was a high degree of confidence in the 1750 K emitter temperature. After about 19,000 hours (July 21, 1987), the I/V curves degraded and gave an indication of an open circuit, indicative of a "gassy" interelectrode spacing which was probably helium from the primary containment.

As each emitter deignited and no longer operated in the thermionic mode, electron cooling ceased. Heat transfer by radiation alone could have caused the emitter temperature to increase by as much as 300 to 400 K. A heat balance analysis showing the effect on emitter temperature of increasing the radiation cooling while lowering the electron cooling for emitter 2.2 is shown in Fig. 6-8. The figure shows that the emitter could have been

f.6-8

Figure 6-8. Capsule 2 Cell 2 Operating History

running in excess of 2000 K for a significant period even though it was still operating as a thermionic device. This could be the major cause of emitter breaches.

6.4.3 Dimansional Measurements

Diameter and length measurements were taken on the three Capsule 2 emitters and on the six emitters previously recovered from Capsules 1 and 3. The measurements were taken with an Heidenhein electronic measuring system, a linear slide, Vee block supports, and end stops (see Fig. 6-9).

The diametral measurements were made at 90 degree increments around the circumference and at 0.10 in. axial increments. The system was first calibrated using a 1.100 in. diameter gauge placed on the Vee block, as shown on Fig. 6-9. The gauge was then replaced by an emitter and the diameters measured. The raw data for a typical emitter, Capsule 2-Diode 2, are shown in Table 6-8. Similar data is available for all nine emitters. A table which shows the diameter measurements and the resulting inferred distortions at four equally spaced axial locations is shown in Table 6-9. We are planning to update the historical NR distortion data with these PIE measurements.

The lengths of the nine emitters were also determined as shown in Table 6-10. A precise definition of "length" in the hot cell was not possible so the hot cell measurements are quite approximate. The nominal, as-fabricated, length was 2.134 in.

6.4.4 Resistance Measurements on Capsule 4 Sheath Insulators

Resistance measurements were made on the sheath insulators that were recovered from Capsule 4. Two electrical leads were passed through the hot cell wall and connected to the measuring instruments as shown in Fig. 6-10. The measuring instruments were a Fluke multimeter and a General Radio resistance bridge. The Fluke output voltage was approximately 1.9 V, while General Radio was 10 volts. The samples were separated into two groups, unguarded specimens and guarded specimens.

Figure 6-9. Heidenheim's system for measuring emitter diameters and lengths

TABLE 6-8
HOT CELL MEASUREMENTS OF IRRADIATED TFE EMITTERS

Emitter Identification	Diameter in Inches		(Degrees Clockwise from 0°)	
	Position I (0°)	Position II (90°)	Position III (180°)	Position IV (270°)
Emitter #2, Capsule #2	1.09998	1.10000	1.10000	1.10000
	1.10156	1.10200	1.10232	1.10280
	1.10818	1.10518	1.10746	1.10860
	1.11256	1.10848	1.11226	1.11308
	1.11668	1.11192	1.11056	1.11744
	1.12022	1.11362	1.11152	1.12308
	1.12222	1.11450	1.11180	1.12178
	1.12328	1.11496	1.11164	1.12256
	1.12406	1.11562	1.11174	1.12340
	1.12470	1.11632	1.11186	1.12384
	1.12484	1.11648	1.11192	1.12380
	1.12472	1.11690	1.11186	1.12372
	1.12418	1.11726	1.11164	1.12308
	1.12348	1.11744	1.11138	1.12206
	1.12260	1.11762	1.11098	1.12158
	1.12178	1.11824	1.11058	1.12152
	1.12146	1.11934	1.11084	1.12268
	1.12166	1.12072	1.11140	1.12390
	1.12204	1.12208	1.12422	1.12438
	1.12204	1.12300	1.11314	1.12380
	1.11948	1.12268	1.11156	1.12110

TABLE 6-10
HOT CELL MEASUREMENTS OF IRRADIATED TFE EMITTERS

Enter Identification	Length in Inches
Emitter #1, Capsule #1	2.110
Emitter #2, Capsule #1	2.120
Emitter #3, Capsule #1	2.130
Emitter #1, Capsule #2	2.140
Emitter #2, Capsule #2	2.115
Emitter #3, Capsule #2	2.140
Emitter #1, Capsule #3	2.120
Emitter #2, Capsule #3	2.140
Emitter #3, Capsule #3	2.140

TABLE 6-9

DIAMETER MEASUREMENTS AND DISTORTIONS
AT FOUR AXIAL LOCATIONS

CAPSULE	DIODE	DISTANCE FROM BOT	0 DEGREES		90 DEGREES		180 DEGREES		270 DEGREES	
			DATA	DISTORT	DATA	DISTORT	DATA	DISTORT	DATA	DISTORT
1	1	0	1.10014	0.0	1.09992	0.0	1.09998	0.0	1.09978	0.0
		0.5	1.10174	1.6	1.10232	2.4	1.09302	-7.0	1.10058	.8
		1.0	1.10222	2.1	1.10306	2.1	1.08458	-15.4	1.10004	.2
		1.5	1.10154	1.4	1.10324	2.7	1.07468	-25.2	1.09994	-0.4
		2.0	1.10146	1.2	1.10302	2.1	1.06458	-25.4	1.09828	-1.5
1	2	0	1.10038	0.0	1.10005	0.0	1.10014	0.0	1.10001	0.0
		0.5	1.10018	-0.2	1.10078	.2	1.10058	.4	1.10084	.6
		1.0	1.10007	.3	1.10188	1.4	1.101	.9	1.10122	1.0
		1.5	1.10042	.7	1.10254	2.0	1.1012	1.1	1.10148	1.3
		2.0	1.10056	.2	1.102	2.5	1.10144	1.2	1.1018	1.5
1	3	0	1.10068	0.0	1.10052	0.0	1.1	0.0	1.10070	0.0
		0.5	1.10204	2.0	1.10274	2.2	1.10234	2.4	1.10214	2.4
		1.0	1.10308	2.4	1.10248	2.0	1.10488	0.0	1.10264	2.0
		1.5	1.10404	3.4	1.10464	4.1	1.10502	5.0	1.10294	2.2
		2.0	1.10258	1.9	1.10308	2.6	1.10214	2.1	1.1025	1.0
2	1	0	1.109988	0.0	1.1	0.0	1.1	0.0	1.1	0.0
		0.5	1.10494	5.1	1.10024	.2	1.10898	9.0	1.10102	1.9
		1.0	1.11172	11.8	1.10944	-5.0	1.10372	22.0	1.10042	.4
		1.5	1.11806	18.2	1.10892	-10.7	1.11292	12.0	1.10202	-0.4
		2.0	1.11652	26.6	1.10826	-17.4	1.109426	-5.0	1.10070	-14.0
2	2	0	1.109998	0.0	1.1	0.0	1.1	0.0	1.1	0.0
		0.5	1.11068	16.7	1.11192	11.9	1.11056	10.0	1.11744	17.4
		1.0	1.1147	24.0	1.11632	16.2	1.11186	11.7	1.12384	23.8
		1.5	1.1126	22.6	1.11762	17.0	1.11098	11.0	1.12158	21.0
		2.0	1.11948	19.5	1.12268	22.7	1.11156	11.6	1.1211	21.1
2	3	0	1.1	0.0	1.1	0.0	1.1	0.0	1.1	0.0
		0.5	1.10544	5.4	1.10932	9.2	1.10456	4.0	1.10722	7.0
		1.0	1.1012	1.2	1.10986	9.9	1.1111	11.1	1.11272	12.2
		1.5	1.10976	-2.4	1.11054	10.5	1.1118	11.0	1.11218	12.2
		2.0	1.10908	-9.0	1.1124	12.4	1.11084	10.8	1.11278	12.8
3	1	0	1.10312	0.0	1.10004	0.0	1.1	0.0	1.10002	0.0
		0.5	1.1144	11.2	1.1182	18.2	1.12210	22.2	1.12078	20.0
		1.0	1.11236	9.2	1.11406	14.0	1.11904	19.0	1.11574	15.0
		1.5	1.11942	16.3	1.12452	24.5	1.12794	27.9	1.1304	20.4
		2.0	1.11026	7.1	1.11196	11.9	1.11158	11.6	1.10902	9.9
3	2	0	1.1	0.0	1.099444	0.0	1.1	0.0	1.1	0.0
		0.5	1.10356	3.6	1.09884	4.4	1.10728	7.2	1.10444	4.4
		1.0	1.10426	4.3	1.10116	6.7	1.1110	11.0	1.1065	6.5
		1.5	1.10498	5.0	1.10246	8.0	1.1121	12.1	1.10726	7.2
		2.0	1.10442	4.4	1.09956	5.1	1.10522	5.2	1.10544	5.4
3	3	0	1.1	0.0	1.10598	0.0	1.1	0.0	1.1	0.0
		0.5	1.10524	5.2	1.1117	5.7	1.1067	5.7	1.11092	5.9
		1.0	1.10646	6.5	1.1125	6.5	1.1115	11.5	1.1054	5.4
		1.5	1.10808	8.1	1.11224	8.3	1.11492	14.9	1.1062	6.2
		2.0	1.10812	8.1	1.10730	1.4	1.12214	22.1	1.10778	7.8

Figure 6-10. Resistance measurement rig

The unguarded specimens were measured first, with the results shown in Table 6-11. Using the simple setup, the guarded specimens could only be measured using the Fluke. The results are shown on Table 6-12. As can be seen all resistances are in the Meg-ohm range, well above the 1000 ohm design value.

TABLE 6-11

UNGUARDED SPECIMEN RESISTANCE MEASUREMENTS

Sample Identification Serial Number	GR1644-A Measurements (10 VDC)	Fluke 8060A Measurement (1.9 VDC)
5561-103-2	170 K-ohm	299 K-ohm
4966-67-2	5 to 9 M-ohm*	30 to 43 M-ohm*
5561-103-4	>100 M-ohm	>100 M-ohm
4966-65-b	4.75 K-ohm	9 K-ohm
5561-103-1	2.7 M-ohm	3.48 M-ohm

Note: (*) indicated increasing values, probably capacitive.

TABLE 6-12

GUARDED SPECIMEN RESISTANCE MEASUREMENTS

Sample ID Serial Number	Point C to Point F	Point D to Point F	Point E to Point F	Point C to Point D	Point D to Point E
8978-12-D	37 M-ohms	39 M-ohms*	100 M-ohms*	80 M-ohms*	>100 M-ohms
8978-12-a	>100 M-ohms	54 M-ohms	280 to 390 K-ohms*	>100 M-ohms	50 M-ohms

Note: (*) indicates increasing reading, probably capacitive.

References

- 6-1 GA-A20119, TFE Verification Program, Semiannual Report for the Period Ending March 31, 1990, issued in July 1990.

7. CESIUM RESERVOIR AND INTERCONNECTIVE TFE COMPONENTS

7.1 OBJECTIVE

The overall objective of the cesium reservoir and interconnective TFE components task is to develop and validate the performance of cesium reservoirs and interconnective TFE components, such as intercell insulation, fission product vents and fission product traps. In particular, the objectives are:

1. Design integral cesium reservoirs and interconnective TFE components.
2. Develop required fabrication processes for integral cesium reservoirs and interconnective TFE components and document the process specifications.
3. Fabricate integral cesium reservoirs and interconnective TFE components for in-reactor and ex-reactor tests.
4. Verify the performance characteristics and lifetimes associated with integral cesium reservoirs and interconnective TFE components by means of in-reactor and ex-reactor testing.
5. Develop an analytical model of the performance and lifetime of the Cs reservoir and interconnective TFE components.

7.2 TASK DESCRIPTION

The integral cesium reservoir and interconnective TFE tasks consists of five subtasks:

1. Cesium reservoir and interconnective TFE components design.
Design integral cesium reservoir test specimens consistent with the TFE design requirements. Design test specimens of intercell insulation and interconnective TFE components such as TFE end

restraint and fission product traps, ports and tubes consistent with TFE design requirements.

2. Fabrication development. Determine integral cesium reservoir materials with the capability for storing cesium either as intercalation compounds or as sorption reservoirs. Develop systems for containing the integral reservoir material in a TFE environment. Select insulator materials such as Al_2O_3 , Y_2O_3 and YAG and develop processes for fabricating TFE end restraints and intercell insulation components. Develop materials for use as fission product traps and develop components for fission product vent and port tubes.
3. Ex-reactor testing. Perform ex-reactor tests to determine the cesium pressure of integral reservoir materials as a function of cesium loading and temperature. Examine the ability of intercell insulation coatings to reduce parasitic discharges. Determine the mechanical stability of TFE end restraints.
4. In-reactor testing. Determine the effect of fast neutron fluence on the stability of the pressure versus temperature characteristics of integral cesium reservoirs at a fixed cesium loading. Also examine the mechanical stability of prototypical TFE end restraints and intercell insulation coatings. Determine fission product release characteristics from the fuel and evaluate the effectiveness of the fission product control components and assemblies.

7.3 PROGRESS DURING PRESENT REPORTING PERIOD

7.3.1 Interim UFAC-3 PIE

HOPG/ZYH. Two HOPG samples, one cesiated and one without cesium, were irradiated to 0.9×10^{22} neutrons/cm² in EBR-II in cycle 154 and were then removed for neutron radiography. The uncesiated sample was observed to have expanded about 8% in the c-axis direction and contracted by about 3% in the

a-axis direction. The cesiated sample, by contrast, expanded by nearly 400% in the c-axis direction and contracted by about 60% in a-axis direction. Although the origin of the dimensional changes in the cesiated sample is not known, a heuristic model is suggested which has an analogue in the observed dimensional changes in oriented pure graphite as a function of crystallite size as shown in Ref. 7-1.

The HOPG samples were in the form of 11 mm diameter discs with the c-axis perpendicular to the disc face. The disc that was subsequently cesiated was 1.35 mm thick prior to intercalation. The other disc was initially 1.65 mm thick. These discs were loosely enclosed in a perforated tantalum foil liner which was placed inside a niobium canister as shown schematically in Fig. 7-1. The loading of the HOPG specimen was determined to be 295 mg Cs/g C. Both samples were x-rayed after pinchoff and it was observed that Cs intercalation caused a 50% increase in the apparent thickness of the Cs loaded sample. This is an upper limit since there was some "dishing" observed on both sides of the intercalated disc, which leads to an overestimate of the disc thickness. Third stage loading in Cs-graphite leads to an increase of 26% in the c-axis dimension, consistent with the upper limit of 50% estimated here.

The samples were irradiated to a fluence of 0.9×10^{22} n/cm² in 63 days at EBR-II. The temperature during irradiation was calculated to be in the vicinity of 1200 K. After irradiation the cans were removed from the reactor core and neutron radiographs were obtained as shown in Fig. 7-2. The uncesiated sample seen edge-on in the radiograph is about 8% thicker and about 3% smaller in diameter than it was prior to irradiation. The intercalated sample, on the other hand, was transformed from a disc into a cylinder with its axis parallel to the axis of the canister. This was verified by taking two additional radiographs at other azimuthal orientation. The observed c-axis expansion in Fig. 7-2 was about 370% and the a-axis contraction was about 62%. Note also that the elongation of the graphite cylinder exerts considerable force as evidenced by the distortion of the Ta liner.

Dimensional changes caused by neutron irradiation of Cs/graphite intercalation compounds have not been reported prior to the present work.

Figure 7-1. Schematic of the encapsulated HOPG samples

UNCESAIATED

CESIATED

Figure 7-2. Neutron radiographs of the irradiated HOPG samples on the left and corresponding cartoons depicting the form of the graphite on the right. The cylindrical and disc shaped forms were verified by additional radiographs taken at other azimuthal orientations. The sample at the top was not cesiated while the sample at the bottom was intercalated to a level of 295 mg Cs/gC.

Analogous behavior has been reported for oriented, pure graphites with different crystalline dimensions. (Refs. 7-1, 7-2) In Ref. 7-1, it was reported that the temperature and dose dependent data for c- and a-axis dimensional changes in graphite as a function of graphite crystallite size, ranging from a c-axis dimension of $L_c=40 \text{ \AA}$ to $L_c>1600 \text{ \AA}$. For irradiation to 10^{22} n/cm^2 at 1172 K, c-axis expansion of 8% is observed for the latter value of L_c , while an expansion of about 400% is observed for L_c between 170 and 800 $\text{\AA}$. The corresponding a-axis contraction is about 1% and 60% respectively. The phenomenological behavior of the uncesiated graphite is of the same magnitude as that observed for $L_c>1600 \text{ \AA}$. The present Cs/graphite neutron induced dimensional changes are in the range of those reported in Ref. 7-1 in pure graphite for $L_c \approx 500 \text{ \AA}$ (within $\approx 200 \text{ \AA}$).

The model normally invoked to describe neutron induced dimensional changes in graphite involves interlammellar diffusion of knock-on carbon atoms produced by neutron collisions. In the case of large graphite crystallites, these diffusing interlammellar species can recombine with radiation induced vacancies in the adjacent carbon planes before arriving at an interlammellar nucleation site. In the case of small crystallites the density of these nucleation sites is larger and leads to the growth of new planes of carbon atoms, with consequent c-axis growth and a-axis shrinking. Reference 7-1 quantified these effects as a function of L_c , however, as a measure of crystallinity, L_c and L_a are of the same magnitude.

In a qualitative fashion, the response of the Cs-HOPG to neutron irradiation can be discussed within the framework of the same model. For instance if a third stage GIC (graphite intercalation compound) is described by the "pleated layer" island structure of Fig. 7-3a rather than the "classical" structure of Fig. 7-3b, between every pair of graphite planes there are islands of Cs intercalant separated from their nearest neighbors by a length equal to three times the characteristic island dimension. Dimensions of these island domains as large as 400 $\text{\AA}$ have been discussed (Refs. 7-3 and 7-4). In a GIC described by the pleated layer model there are two distinct regions where a knock-on carbon atom may reside immediately following the knock-on event: in one of the intercalant islands or in the interlammellar space between islands. If it is assumed that the "shoreline"

PLEATED LAYER MODEL

CLASSICAL MODEL

Figures 7-3a and 7-3b. Pleated-layer and classical models of a third stage GIC

of the islands act as nucleation sites for diffusing carbon atoms, whether they swim or walk to the beach (i.e., whether they approach from the island side or the vacant side), then the nucleation sites are separated by a distance on the order of 400 Å or else twice that value. Following the original graphite damage model discussed above, knock-on atoms in the island regions would be likely to contribute to dimensional changes, based on island size, while those in the inter-island regions would be more likely to undergo recombination with vacancies. Furthermore, from the earlier discussion of the graphite damage data, the magnitude of the dimensional changes in the GIC are in semiquantitative agreement with the results noted in Ref. 7-1, if the GIC island dimension is associated with the L_c value in graphite. Finally, this interpretation of the present results suggests that some degree of "tailoring" of GIC's for reduced sensitivity to neutron fluence could be implemented. This possibility would arise if the size of the intercalant domains formed during GIC synthesis could be controlled.

It is to be expected that additional information about the structure of the cesiated HOPG will come from the thermodynamic data that will result when the pressure-temperature isostere is measured in PIE. For this reason the capsule containing the HOPG samples was not returned to the core for cycle 155.

POCO CZR-2. A neutron radiograph of the POCO CZR-2 samples after cycle 154 is shown in Fig. 7-4. The upper sample was loaded to 260 mgCs/gC, the lower sample was loaded to 790 mgCs/gC and the middle sample contained no Cs. The dimensional change in the latter sample is minimal while the effect of neutron irradiation on the Cs loaded POCO is quite evident in the radiograph. A likely interpretation of the radiograph is that the Cs-loaded POCO has undergone considerable breakup during irradiation. This result can be compared with the UCA-2 result at about 3 times the neutron fluence and where the graphite sample appeared to have retained its physical integrity.

In a qualitative fashion, it appears that the more heavily loaded graphite in Fig. 7-4 has undergone less crumbling than the other loaded sample. The capsule containing the POCO samples was returned to the core for continued irradiation in cycle 155. At the completion of cycle 155, the

Figure 7-4. Neutron radiograph of POCO CZR-2 samples

POCO samples will be removed for Cs pressure measurement in PIE. It must be emphasized that the viability of POCO as a reservoir candidate is not contingent in its mechanical properties, but on its thermodynamic properties. In other words, if the isostere is unaffected by the deformation seen in Fig. 7-4, the performance of an integral reservoir of this material would be certified. Furthermore, it must be recalled that PIE Cs pressure testing of the POCO CZR-2 sample in UCA-2 was successful (Ref. 7-5).

7.3.2 3H1 Cs Reservoir Loading

The Cs/graphite reservoir of TFE 3H1 was loaded with Cs. The same equipment and techniques that were used for 1H2 to determine the cesium pressure vs. graphite temperature (Ref. 7-6) were employed to characterize the reservoir of 3H1. The resulting Arrhenius plot is given in Fig. 7-5, which compares the results for 3H1 with those for 1H2. The reservoirs of both TFEs were loaded at a Cs pressure of 2.3 torr and an apparent graphite temperature of 746°C. The data of 1H2 pass through the loading point, as to be expected, while the 3H1 data lies above and to the right of the loading point. The error bars for the two sets of data are seen to overlap in Fig. 7-5: the error bars in both cases represent the range of values measured by the four thermocouples on the reservoir housing and the data points are the average values of those four readings. The agreement between the two sets of data can be improved even more if the 3H1 data is shifted by 50°K to the left (hotter), as is demonstrated in Fig. 7-6. However it is felt that the difference is due rather to a slight difference in Cs loading between the two reservoirs as described in the following:

The graphite in the reservoir of 1H2 was in the form of several short sections of tube, which together filled the available volume in the TFE to within 0.200" in length, before loading with Cs. The graphite parts that made up the reservoir of 3H1 were individually the same size as for 1H2, however, they each had a 0.130" wide separation machined axially in one wall of the tube to accommodate circumferential expansion. Furthermore, the overall length of the graphite in 3H1 was 0.650" less than the length of the reservoir volume. Thus, while the design of the reservoir in 3H1 allowed for more expansion of the graphite upon Cs loading, the thermal contact of

Figure 7-5. Cesium pressure vs temperature for 3H1 and 1H2

Figure 7-6. 3H1-1H2 comparison with 3H1 data shifted by 50°C (real temperature 50 degrees higher than thermocouple reading)

the graphite to the reservoir housing was less positive and there is more uncertainty in the actual graphite temperature. 3H1 was Cs loaded with the TFE at about 500°C, but the (3H1) pressure data of Fig. 7-5 was obtained with the TFE at about 800°C. Since the reservoir housing was in the vicinity of 800°C throughout, the largest temperature gradient would have occurred during loading, with the attendant largest error in graphite temperature. The resulting inference is that 3H1 was actually loaded at a slightly lower temperature than 1H2, giving rise to a slightly higher loading and, therefore, a somewhat higher Cs pressure at the same temperature as shown in Fig. 7-5.

7.3.3 UCA-3 Samples

The test matrix calls for five samples:

- a) one POCO CZR-2 1st stage loading,
- b) three POCO CZR-2 2nd stage, and
- c) one POCO CZR-2 3rd stage.

To date, four samples have been loaded, pinched off and are awaiting weld-back and encapsulation. One second stage sample remains to be loaded and the E-beam welding of all five remains to be performed.

The pressure-temperature isosteres for the four reservoirs that have been completed are shown in Fig. 7-7. A complete identification and characterization of the four samples is given in Table 7-1.

TABLE 7-1
UCA-3 RESERVOIR DATA
 $\ln P = \Delta H^\circ / RT - \Delta S^\circ / R$

Sample Number	Cs Loading	Entropy, ΔS°	Enthalpy, ΔH°
413D	278 mg gC	Cs/- 8.3 cal/mole-K	-22.5 kcal/mole
1247D	586 mg gC	Cs/-13.3 cal/mole-K	-24.6 kcal/mole
1300D	348 mg gC	Cs/-10.4 cal/mole-K	-23.8 kcal/mole
1301D	396 mg gC	Cs/-10.0 cal/mole-K	-23.4 kcal/mole

Figure 7-7. P-T isosteres for the UCA-3 reservoirs

References

- 7-1 Bokros, J. C., G. L. Guthrie and A. S. Schwartz, Carbon, 6, 55 (1968).
- 7-2 Price, R. J., Carbon, 12, 159 (1974).
- 7-3 Daumas, N. and A. Herold, C. R. Acad. Sci. C286, 373 (1969).
- 7-4 Solin, S. A., Novel Materials and Techniques in Condensed Matter, G. W. Crabtree and P. Vashishta, eds. Elsevier Science, 1982, p. 253.
- 7-5 TFE Verification Program Semiannual Report for Period Ending April 30, 1989, GA-A19666.
- 7-6 TFE Verification Program Semiannual Report for the Period Ending September 30, 1989, GA-A19876.

8. THERMIONIC FUEL ELEMENT

8.1 OBJECTIVE

The overall goal of the thermionic fuel element task is to demonstrate that TFEs prototypic of a 2 MW(e) thermionic space nuclear power system of seven year life can be fabricated from well modeled components, and that their performance is as predicted when operated in a prototypic thermionic reactor environment. Derivative goals include:

- 1) Produce a TFE engineering design and specifications.
- 2) Develop required TFE assembly processes, process specifications, and demonstrate manufacturing capability.
- 3) Fabricate TFEs and test them to demonstrate the processes and the integrated performance of the components.
- 4) Develop and verify a TFE model that can predict TFE performance and lifetime.

Components with demonstrated performance and which are projected to meet lifetime requirements will be used in these TFEs. The performance of one prototypic TFE will be demonstrated in EBR II. Thermionic fuel elements leading up to the prototype will undergo irradiation in the General Atomics Mark F TRIGA reactor.

8.2 TASK DESCRIPTION

8.2.1 Testing Logic

All converters tested in the TFEs will be of the baseline configuration. The balance of the test article will be as close to the baseline TFE design in geometry and performance as practicable. Test and design requirements are compared in Table 8-1.

TABLE 8-1
COMPARISON OF TFE TEST REQUIREMENTS WITH SYSTEM
BASELINE DESIGN REQUIREMENTS

	TFE Test Requirements (BOL)	Baseline Design Requirements (BOL)
Converter power density average (W/cm ²)	3.4	3.4
Current density average (A/cm ²)	7	7
Emitter temperature average (K)	1800	1800
Collector temperature average (K)	1070	1070
Sheath-collector voltage maximum (V)	+7.5	+7.5
Converter configuration	Baseline	Baseline
TFE materials	Baseline or variants for performance/ structural improvements	Section 2
Fuel enrichment (% U-235)	Variable enrichment	93; variable fuel volume fraction
Fast fluence: nominal (E>0.1 Mev)	Real time	2.7x10 ²² /7 years
Fuel burnup: nominal (a/o)	4.1	4.1
Cesium reservoir type	Variable with test	Integral graphite
TFE environment/heat sink	Helium/test reactor coolant	Liquid metal (Li)
Reflector above/below within TFE	No	Yes
Reactor vessel penetration integral with TFE	No	Yes

The separate in-reactor tests and the distinctions between them are outlined in Table 8-2. Note that tests 3H2 thru 3H4, which were originally proposed, have been deleted.

TABLE 8-2
TFE IN-REACTOR TEST SUMMARY MATRIX

TFE ID	Fuel/Emitter Collector	Cs Reservoir	Purpose	Reactor
1H1	UO ₂ /W/Nb	Pool	Verification of reference cell design performance and fabrication processes. Sheath integration.	TRIGA
1H2	UO ₂ /W/Nb	Graphite	Backup to 1H1. Verification of integral cesium reservoir design, performance.	TRIGA
1H3	UO ₂ /W/Nb	Pool	Study effect of fission products mixing with cesium.	TRIGA
3H1	UO ₂ /W/Nb	Graphite	Intercell process development. Fission product control.	TRIGA
3H5	UO ₂ /W/Nb	Graphite	Backup to 3H1. Introduction of prototypic components outside cell.	TRIGA
6H1	UO ₂ /W/Nb	Graphite	Verification of long-TFE fabricability. Consider evolutionary improvements. Verification of fission gas ventings. Increased voltages.	TRIGA
6H2	UO ₂ /W/Nb	Integral Graphite	Backup to 6H1.	TRIGA
6H3	UO ₂ /W/Nb	Integral Graphite	Verification of TFE performance in fast reactor environment.	TBD

The logic behind this test series is a step-by-step development of the fabrication processes, culminating in the fast reactor prototype. The first step is the development of the processes for a single cell, and the integration of the single cell into a TFE sheath tube with appropriate end fittings. These end fittings involve the cesium reservoir, fission gas venting and the conduction of electrical current produced. This single-cell TFE is designated "1H", where the H refers to the latest generation of thermionic cell in a megawatt class TFE, and the "1" refers to the number of cells in the TFE.

The second step is the development of the intercell region of the TFE. The test vehicle will be the 3H-series TFE which will contain three of the H-series cells welded end-to-end in an electrical series circuit. The center cell in the series is isolated from TFE end-fittings and is thereby typical of cells within the interior of a thermionic reactor. The testing of the three cell TFE also allows the study of fission gas venting in a representative multicell environment at a minimum expense.

As the last step in the testing before the fast reactor prototype test, 6H-series TFEs will be built to demonstrate the fabricability of a long TFE where axial alignment is critical. Testing of these TFEs will provide additional demonstration of fission product venting and the capability to maintain unobstructed fission gas passages.

Success in the process development will be evidenced by the observed in-reactor performance and stability.

8.2.2 TRIGA Facility

The Mark F TRIGA reactor at General Atomics will be used for most TFE testing. TRIGA is a water-moderated pool-type research reactor. The Mark F includes a neutron radiography facility located within the reactor pool for periodic nondestructive diagnostic examinations of the TFE internals. A hot cell at the site provides capability for postirradiation examination.

The TRIGA typically operates at about 1.4 MW(t). At this power level, the fast fluence is about 1×10^{21} nvt ($E > .1$ Mev) per year.

8.2.3 Task Status Summary

Eight TFEs (thermionic fuel elements) are being designed, built and tested to meet the task goal of demonstrating the fabrication process and the integrated performance of the components of the defined TFE. Seven TFEs will be tested in the TRIGA reactor; the eighth will be tested in a fast-neutron spectrum reactor, most probably EBR-II.

Of the eight TFEs, the first three are comprised of single converters and the second two- are three-converter TFEs. These five are the partial-length test articles. The final three TFEs are prototypic-length TFEs. Table 8-3 is the current matrix of planned TFE features. With each successive TFE in the program the design is intended to evolve toward a prototypic test article having the reference thermionic reactor system parameters and performance.

At present, TFEs 1H1, 1H2 and 1H3 are on test in the TRIGA reactor. TFE 3H1 is in the encapsulation process. Most components have been prepared for TFE 3H5 although a problem of tungsten microcracking caused emitter losses and schedule delays. This problem was traced to a grinding wheel inadequacy and satisfactorily resolved.

8.2.4 Design Description

The TFE design has been described in previous semiannual reports (Refs. 8-1 through 8-5). The H-series thermionic converter design is as illustrated in Fig. 8-1, and the representative TFEs for TRIGA test are pictured in Fig. 8-2.

8.3 ENGINEERING AND HARDWARE DESIGN

8.3.1 Test Article Design

Design work performed since the last report (GA-A20119) is described below.

TFE 3H1 and 3H5. A dummy cell design was completed to allow electrical testing of the TFE sheath insulators with an impressed voltage of 10 volts. The dummy cell is designed to allow incorporation of an additional ceramic-to-metal seal should its seal fail during assembly and processing. Miscellaneous tooling was designed to support the construction of the TFEs.

Initial planning for TFE 3H5 was to include 5 or 10 volume percent niobium-alumina cermet sheath insulators, and sapphire ceramic-to-metal seals

TABLE 8-3

TFE TEST MATRIX

	1H1	1H2	1H3	3H1	3H5	6H1	6H2	6H3
Emitter								
Outer surface material	W(C1)							
Body material	W(F)							
Emitter stem material	W(F)							
Length, in.	.43							
Thickness, in.	.020							
Emitter transition material	Ta							
Emitter cap material	Ta		Nb					
Flight fuel holddown	No, use spring				TBD			
Volatile fission product trap								
Location	Vac.		Cell					
Material	-		Al ₂ O ₃					
Optimized design	-		Mo			TBD		
Trilayer								
Collector	Nb							
Insulator	pcY ₂ O ₃	pcAl ₂ O ₃			TBD			
Square or shaped ends	Square				TBD			
Ceramic to metal seal								
Insulator	pcAl ₂ O ₃				TBD			
Configuration	Litton							
Emitter alignment								
Washer material	W/Re							
Insulator material	pcAl ₂ O ₃							
Configuration	3 pc		1 pc					
Cesium reservoir material	Liquid	POCO	Liquid	POCO				
		CZR-2		CZR-2				
		Graph		Graph				
Configuration	Developmental					Prototypical		
						Integral		
Fuel pedestal, material design	W/Re				W			
	2 pc		1 pc		2 pc			
Top of converter string								
Bus bar material	Nb				Nb/Mo			
Lead trilayer insulator	pcAl ₂ O ₃							
Stem seal insulator	pcAl ₂ O ₃							
Stem seal configuration	Litton					Proto		
Fission product port tube	Proto							
Vessel head penetration	Not applicable					Proto		
Dummy reflector block	Not applicable					Proto		
(and positioner)								
Bottom of converter string								
Dummy cell	Yes		No		Yes		No	
Dummy reflector block	Not applicable					Proto		
(and positioner)								
TFE alignment pin	Not applicable					Proto		
U-tube connector	Not applicable							
Operating design point								
Emitter temperature, K	1800							
Collector temperature, K	1070							
Average current density, A/cm ²	7							

pc = polycrystalline

TBD = to be determined

Figure 8-1. H-series thermionic converter (typical of 3H1)

Figure 8-2. TFEs for TRIGA test

in the design. Neither of these options became available to meet fabrication schedule requirements.

TFE 6H1. A drawing tree was constructed for TFE 6H1 and an assembly layout was prepared to guide detailed design efforts for all TFE components. Fuel pellet enrichment and configuration was defined so fuel fabrication could be initiated.

8.3.2 Test Vehicle Design

The TFE test articles must be instrumented and doubly encapsulated in stainless steel containment tubes for irradiation in the TRIGA reactor. Design features have been added to continuously measure the pressure in the fission gas collection chambers of containments for TFE 3H1 and future TRIGA test capsules. The test vehicle design has been described in Refs. 2 and 3. Efforts concerning the test vehicle design are described below.

Protocols for outgassing and calibrating the diagnostic vacuum instrumentation and its connecting lines for fission gas pressure monitoring were developed and procedures were written for the fission gas chamber vacuum gauge assembly preconditioning and calibration. The design shown in Ref. 3 was modified so as to position the gauging into an axisymmetric, cylindrical envelope fitting the current containment geometry of 1H TFEs on test. The change will allow more flexibility in locating the multicell TFEs near the center of the core, and more latitude in relocating them to new test positions in TRIGA. A Pirani gauge of the type to be used in the containment tube above the core was built into a test structure by TTC and subjected to a stability test at approximately 45°C for 10 days after degassing and back-filling to 6×10^{-2} torr of argon. It was initially intended that the gauge would be exposed to the capsule environment above TRIGA to assess stability of electronic components attached to the gauge tube assembly. Experience gained in fabricating the test assembly showed the electronic package could be removed from the tube and located away from radiation above the reactor core. The stability test was successful, and the fabrication exercise demonstrated the gauge tube assembly should be degassed at 300°C along with all connecting tubulation for stable operation during reactor testing.

Primary and secondary encapsulation drawings for TFEs 3H1 and 3H5 were revised to incorporate changes determined to be necessary by encapsulation experience with TFE 3H1.

8.4 TFE FABRICATION

TFE fabrication is based on an all welded TFE assembly to improve reliability and fabrication economy. Assembly of converters and TFEs in a clean room atmosphere is necessary to ensure that contamination of electrodes is minimized, and the effect of particulate contamination on subsequent fuel element degassing operations is eliminated. In order to provide for stable long term converter operation, bulk degassing is performed for machined components and subassemblies to remove sources of gas that could degrade TFE performance. Accurate rotary weld fixturing and electron beam welding techniques are specified for converter and TFE assembly operation to help control and minimize welding distortion from weld shrinkage. The electron beam welder chamber is installed as part of the clean room so that the benefits of clean room assembly extend to the assembly welding operations.

Final degassing and cesium loading of TFEs must be performed within an ultra high vacuum chamber utilizing all metal-to-metal seals and ion pumping to provide sensitive leak checking methods and vacuum safety should a power failure occur with the TFE at degassing temperature ($\sim 1250^{\circ}\text{C}$).

Impurities in test environments have contributed to rapid embrittlement and failure of TFE envelopes. An appropriate test environment for TFEs is within a static envelope filled with high purity inert gas. The test containment must be sealed by welding, and with ceramic-to-metal seals for power and instrumentation lead feedthroughs. It must be vacuum degassed to remove residual impurities before inert gas backfilling to provide the test environment.

Reproducible converter and TFE performance requires use of a consistent set of specifications and procedures for TFE material procurement, and component machining assembly and processing.

A system of manufacturing controls incorporating detailed machine shop and assembly processing travelers is used. Materials, component and assembly procurement and processing specifications, and detailed scheduling methods are necessary to guide the fabrication effort. These systems were designed to comply with the Quality Assurance program applied to the overall program activity.

8.4.1 Summary of Past Work

TFE fabrication and fabrication development facilities were set up and fabrication process parameters and assembly sequences were established for planned TFEs. Work on process improvement and weld parameter qualification has continued as needs became apparent. These activities are described in detail in Refs. 8-1, 8-2, 8-3, 8-4 and 8-5. Fabrication of an H-series mockup TFE was used to verify the selected processing methods.

Fabrication of H-series TFE components and subassemblies during earlier reporting periods included preparation of sintered, degassed and machined UO_2 fuel forms for TFE's 1H1, 1H2, 1H3 and 3H1. Isostatically processed graded trilayers, ceramic-to-metal seals, and tungsten tantalum emitter assemblies were prepared and finish machined for these TFEs. Ceramic-to-metal seal backups were completed for these TFEs. Assembly of TFE's 1H1, 1H2 and 1H3 was accomplished, and the TFEs were installed into the primary and secondary containments and testing was initiated. For 3H1, containment detail work was completed for a majority of components, the notable exception being details associated with collector heat rejection and fission gas pressure measurement.

Fabrication of TFE 3H1 proceeded to completion of the converters and the converter-lead subassembly ready for plasma spraying of the intercell and emitter electric lead regions.

8.4.3 Fabrication Process Development

Efforts this period were devoted to establishment of a new emitter alignment spring geometry, improvement in the UO_2 pellet pressing procedure, and resolution of an emitter cracking problem.

Emitter alignment spring. The improved emitter cap alignment insulator design adopted for TFE 3H1 and described in Ref. 8-2 consists of a trilayer of niobium, alumina and niobium. A spring alignment device for the cell above the emitter cap was designed as two conical tungsten-25% rhenium washers welded together at the outer edges of the cones. The inside diameter of the washers fit over projections on the electrically isolated portion of the emitter cap, and at the bottom of the emitter above. Fabrication of the alignment device was not found to be feasible because of weld shrinkage distortion of the alignment diameters when a weld of adequate cross section was achieved. Two new configurations were defined and fabrication experiments conducted to evaluate cost and ease of fabrication. In one configuration, two conical washers of tungsten-rhenium alloy were used in a non-welded configuration, with one washer nesting into a recess in the other at the large diameter. A second configuration consisted of a short tube fitting between the emitter cap and emitter projections with two slots cut 180° apart transverse to the tube axis so as to create a spring. Tests of the two configurations at 1250°C were performed in a molybdenum-niobium fixture constructed so as to apply the same compressive distortion to the alignment devices as the TFE operating conditions. Both configurations performed acceptably, however, machining of the tubular device was much easier than for the conical washer configuration and the tubular device was adopted for fabrication of TFEs.

UO₂ pellet fabrication. Holes in fuel pellets for TFEs (and for UFAC tests) were made using carbide drills, a process causing breakage of some pellets. The hole drilling process was also laborious. In order to avoid the majority of drilling costs, a new fuel pellet pressing die was designed, purchased and tested as a process improvement prior to fabricating fuel for TFE 6H1. Test pellets fabricated from depleted material showed the die sizes selected were suitable and that internal diameter machining of pellets would not be necessary.

Emitter microcracking. Flaws were detected on the closed ends of two of three finish machined emitters for TFE 3H5 in March. The flaws appeared to be grinding induced microcracks that occurred when the parts are prepared at

GA for diffusion bonding to tantalum transition pieces. Attempts to remove the flaws by lapping failed because the flaws had penetrated the fluoride substrates. The grinding operation was replaced by a lapping process (free abrasive machining) and an evaluation program was initiated to discover the source of the problem. In May, microcracking appeared on the outside diameter of several emitters, ruining the chloride coatings. Probable causes of the problem evaluated were coolant composition change (or contamination), grinding wheel bond hardness deviation from specification, procedural deviations by operators, and grinding machine bearing wear out. After sample tests, it was determined that the problem was caused by grinding wheel bond hardness deviation of a specific lot of grinding wheels. A change to an alternate vendor's wheels resolved the difficulty, however, use of free abrasive machining of the closed end of emitters was incorporated as a standard (lower risk) process.

8.4.3 H-Series Fabrication

Fabrication efforts concentrated on TFE's 3H1, 3H5 and 6H1 this reporting period. Component status is shown on Table 8-4.

TFE 3H1. Sheath tube bonding was accomplished for this TFE, prior to the final processing steps, by heating the TFE subassembly in vacuum at 1225°C for three hours. Post bonding radiographs and ultrasonic testing showed the structures of the TFE to be normal and the sheath tube-to-trilayer bonds to be excellent. The cesium loading apparatus was redesigned at GA, rebuilt at TTC, then assembled and loaded with 3 grams cesium on the TFE final processing system at GA. Once pumpout tubulation and cesium reservoir components were welded and/or brazed to the TFE, final degassing, leak testing, cesium loading and electrical testing was performed for the TFE (see Sect. 7.3.2, this report.

Primary and secondary components were fabricated at TTC, and the containment process for 3H1 was taken to completion of installation of the emitter electrical bus and all thermocouples to the TFE and primary penetration assembly. The collector bus includes a copper collector heat rejector, machined in a complex and accurate way to provide collector heat transfer and passage of sheath tube thermocouples and potential probes, and brazed to a

TABLE 8-4

CELL AND TFE FABRICATION STATUS SUMMARY THROUGH MARCH SEPTEMBER 30, 1990

	CELLS:	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
<u>Major Cell Components</u>																												
Fluoride deposited emitter		C	C	C	C	C	C	C	C	C	C	C	C	C	C	C												
Chloride deposited emitter		C	C	C	C	C	C	C	C	C	C	C	C	C	C	C												
Emitter transition		C	C	C	C	C	C	C	C	I	I	I	I	I	I	I												
Fuel		C	C	C	C	C	C	C	C	C	I	I	I	I	I	I												
Trilayer		C	C	C	C	C	C	C	C	C																		
Ceramic-to-metal seals		C	C	C	C	C	C	C	C	C	I	I	I	I														
<u>Subassemblies</u>																												
Fueled emitter		C	C	C	C	C	C																					
Cell assembly		C	C	C	C	C	C																					
	TFE:	1H1	1H2	1H3			3H1			3H5				6H1						6H2						6H3		
Emitter lead assembly		C	C	C			C			C																		
Cesium reservoir assembly		C	C	C			C			C																		
<u>TFE Assembly</u>																												
Cells welded		C	C	C			C																					
Sheath tube welded		C	C	C			C																					
<u>TFE Final Processing</u>																												
Instrumentation		C	C	C			C																					
Bonding complete		C	C	C			C																					
<u>Test Containment</u>																												
Primary penetration		C	C	C			C																					
Containment housings		C	C	C			C																					
Primary encapsulation complete		C	C	C			I																					
Secondary encapsulation complete		C	C	C																								
Begin Testing		9/88	3/90	8/89		1/91		9/91					2/92						TBD							TBD		

Legend: C - Complete
I - In Process

copper tube above the TFE. This structure was distorted in shipment from TTC to GA, apparently because of severe mishandling by the carrier, delaying work on the 3H1 containment process. Realignment of the lead was nearly completed at TTC, and a new rugged shipping container was constructed to allow use of more protective packaging material during shipment.

TFE 3H5. Fabrication of trilayers and ceramic-to-metal seals for this TFE were completed, however, problems of emitter microcracking delayed initiation of emitter fuel loading and cell assembly operations. The third emitter was finish machined at TTC. Components for the dummy cell that will allow electrical testing of trilayers in the reactor were completed and assembled. Cermet trilayers and polycrystalline YAG options for this TFE did not become available as planned.

TFE 6H1. Because of losses of emitters for 3H5, emitters planned for 6H1 were diverted for use in 3H5. Six emitters were carried through the chloride deposition process but were held up in machining until the emitter microcracking problem described in Section 8.4.2 was resolved. At the end of the reporting period, OD and closed end machining was initiated for these emitters, and mandrels to produce an additional group of backups were in progress. Next reporting period, fuel fabrication, emitter diffusion bonding and trilayer and ceramic-to-metal seal fabrication will be initiated.

8.5 TFE OPERATING EXPERIENCE

Irradiation testing of 1H1, 1H2 and 1H3 continued during this reporting period. Table 8-5 summarizes the events that occurred. TFEs 1H1 and 1H3 are identical in construction except for a fabricated passage connecting the interelectrode and fission product spaces for 1H3. TFE 1H2 is similar in construction to 1H1 except that it has a cesium/graphite reservoir rather than a liquid cesium reservoir. The operating characteristics of the three TFEs are summarized in Table 8-6. The last row of the table shows the converter electrode voltage calculated using TECMDL for the cell parameters listed earlier in the table. For 1H1 and 1H3, the operating point is sufficiently far from the knee in the I-V curve that TECMDL calculates a

TABLE 8-5
IRRADIATION TESTING EVENTS - MAY THROUGH SEPTEMBER 1990

5-9-90	MARK-F scrambled due to a defective fuse in 1H2 stem heater.
5-10-90	Reactor scram due to utility company power outage.
5-13-90	Reactor scram due to unexplained interruption in 1H1 bus bar coolant flow.
6-2-90	Reactor scram due to 1H2 Cs reservoir heater power supply failure.
7-16-90 to 8-9-90	Annual MARK-F shutdown for fuel inspection.

TABLE 8-6
IRRADIATION STATUS OF H-SERIES TFEs

	1H1	1H2	1H3
Irradiation time, hours	15070	3937	8323
Emitter temperature, K	1720	1800	1780
Collector temperature, K	1166	1065	1038
Current density, amps/cm ²	3.9	6.4	3.3
Cesium pressure, torr	3.2	3.8	4.1
Measured TFE voltage, volts	-0.94	0.20	0.42
	(see text)		
Corrected cell voltage for series of resistance of 2.11 milliohms	-.78	.47	.56
Cell voltage from TECMDL, volts	0.27	0.51	0.58

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voltage about 10% high. In addition, neither of the estimates in the last row of Table 8-6 account for the presence of resistive elements in the TFE, and for this reason the cell voltages in the last row should be compared with those in the row immediately above, and not with the uncorrected TFE voltage.

8.5.1 TFE-1H1

A gradual decrease in the output voltage of 1H1 was noted toward the end of the last reporting period, as indicated by the I-V curves of Figs. 8-3a and 8-3b. The decrease was more prominent during the present reporting period. Typically, at recent reactor startups, the I-V curve lies entirely in the first quadrant, as in Fig. 8-4a. This is followed by a rapid shift to the left in a period of days, followed by a much slower shift in later weeks; an example taken just before the shutdown for fuel inspection is shown in Fig. 8-4b. A large number of factors have been considered in the effort to explain this behavior. All of these possible factors fall into one of three broad categories: changes in the equivalent circuit of the TFE outside of the thermionic cell, changes in the thermionic behavior of the cell, and changes in the instrumentation. These various factors will be discussed separately.

TFE equivalent circuit. Figure 8-5 shows the equivalent circuit of the H-series TFEs. In this figure, R_{d1} is the resistance of the dummy cell lead, R_c is the resistance of the collector electrode, R_e is the resistance of the emitter electrode and transition piece together, R_{t1} is the resistance of the TFE lead and R_s is an inadvertent shunt resistance across one or more of the insulators. This circuit can be analyzed to give the following expressions for the voltage and current of the TFE, V_{tfe} and I_{tfe} ,

$$V_{tfe} = [R_a R_b / (R_s + R_a + R_b)] I_c - [R_a / R_s + 1] V_c \quad (1)$$

$$I_{tfe} = [1 / R_s] [R_b + R_s] I_c - V_c \quad (2)$$

$R_a = R_{d1} + R_{t1} = 0.00211$ ohm, $R_b = R_e + R_c = 0.00074$ ohm and $R_s = \infty$ (Ref. 8-6). V_c and I_c are the actual cell voltage and current, and in this analysis were taken from the I-V curves of converter #46.

Converter Data file: 08_52

Date: 12 Jul 1900

Time: 10:01:14

Converter Data file: 09_43

Date: 12 Jul 1900

Time: 10:08:13

Figures 8-3a and 8-3b. 1H1 current voltage curves

Converter Data file: 09_29

Date: 12 Jul 1900 Time: 10:14:20

Converter Data file: 07_38

Date: 16 Jul 1900 Time: 08:14:38

Figures 8-4a and 8-4b. 1H1 current voltage curves

Figure 8-5. Equivalent circuit of 1H1

Simulated I-V curves were generated for a wide range of values of R_a , R_b , and R_g , and while the starting I-V curves could be fit, i.e., Figs. 8-3a and 8-4a, it was not possible to fit the degraded I-V curves of Figs. 8-3b and 8-4b with satisfactory accuracy. However it was possible to fit the TFE I-V curves using the nominal resistor values if a constant voltage offset was applied to the curves and the emitter temperature is varied in the converter #46 data set. Figures 8-6 and 8-7 for the TFE I-V curves of Figs. 8-3a and 8-4b show this comparison. Examples of the sensitivity of the calculation to changes in R_b and R_g are given in Figs. 8-8 and 8-9. The overall conclusion from these studies is that a voltage shift is required in order to match the online TFE data, but that circuit changes and changes in thermionic behavior may be occurring at the same time.

Collector work function changes. An increase in collector work function, ϕ_c , will give rise to a voltage shift in the I-V curve. In order to account for the shift observed in 1H1, $\Delta\phi_c$ would have to be on the order of 1.0 to 1.5 eV. A shift in work function of this magnitude could result from the buildup of contamination on the collector. One potential candidate for this contaminant is uranium, according to the following scenario. In the UFAC series of fueled emitter tests, PIE indicated the occurrence of a chemical reaction and formation of a liquid phase in a region where the UO_2 fuel came into contact with the W-25% Re heat shields (Ref. 8-7). This liquid phase could provide a source of free U which could diffuse through the emitter, evaporate from its surface and deposit onto the collector. 1H1 also has W-10% Re heat shields above the fuel. Extensive neutron radiographs have been taken of all three TFEs and it has not been possible to confirm or rule out the possibility of a reaction at the heat shields in 1H1.

Earlier work at JPL with a UO_2 fueled converter that employed a rhenium emitter showed performance degradation over 2400 hours of operation (Ref. 8-8). Associated with the performance drop was an increase in ϕ_c of about 0.4 eV, which was attributed to uranium diffusion through the rhenium emitter, followed by evaporation onto the collector. No detailed mechanisms are suggested in this earlier work. There does not seem to be any thermodynamic data available on the U-Cs-W system to aid in estimating the work

Figure 8-6. 1H1 converter #46 comparison (1900 K)

Figure 8-7. 1H1 converter #46 comparison (1800 K)

($T_e=1800$, $R_s=10$, $R_a=.00211$, $V_o=1.6v$)

Figure 8-8. Variation of electrode resistance

Figure 8-9. Variation of shunt resistance

function of a uranium-contaminated niobium collector in a cesium vapor. A very approximate estimate can be made by employing an image charge model to calculate the heat of adsorption, the Frenkel equation to estimate the Cs coverage and the dipole layer contribution to estimate the change in work function. The relevant equations are shown in Ref. 8-9.

$$H = e^2/4R^+ + \phi_0 - E_{ion}$$

$$dN/dt = -Nf \exp(-H/kT), \text{ and}$$

$$\Delta\phi = 4\pi Ne^2 R^+.$$

The work function, ϕ_0 of pure uranium is 3.2 eV and that of niobium is 4.0 eV. The resulting cesium coverage of the collector in this approximation is down by a factor of 1000 when the niobium is covered by uranium. The value of $\Delta\phi$ for U then becomes negligible and the work function increases from about 1.8 eV for cesiated Nb to 3.2 eV for pure U, an increase of 1.4 eV, as would be suggested by the shift in the 1H1 I-V curves. Qualitatively similar results are obtained from analytical work of Rasor and Warner (Ref. 8-10), although the magnitude of the voltage shift amounts to only about 0.7 volts. More recent experimental measurements of the work function of Nb in Cs vapor increases the allowable voltage shift to slightly more than 1.0 volts. (Ref. 8-11).

A large increase in ϕ_c would also cause a dramatic decrease in back electron emission. In the case of 1H1 it is not possible to determine if this is true, since there is an ohmic component that dominates the I-V curve in the unignited mode, as seen in Figs. 8-1 and 8-2. Another effect that could be expected to accompany an increase in ϕ_c is a change in the ignition point. If the collector work function increases from 1.8 to 3.2 eV, with the collector at 1100 K, surface ionization of cesium at the collector will increase by a factor of 10^6 as predicted by the Saha-Langmuir equation. Some of these Cs⁺ ions will drift to the emitter and contribute directly to the diode current. Cesium⁺ will also reduce the space charge in the interelectrode space, giving rise to larger current at ignition. This feature is displayed in a MASTERPC calculation shown in Fig. 8-10. In this calculation, the current at ignition is constant as ϕ_c increases from 1.5 to 2.5 eV, but from 2.5 to 3.0 eV there is a significant increase.

Figure 8-10. MASTERPC calculation - I-V curves of 1H1 converter

If ϕ_c is 3.2 eV and the collector temperature is increased, the ion production will increase and the current at ignition will again increase, for the same reasons previously discussed. In 1H1, it was possible to increase the collector temperature from 1160 K to 1203 K using the auxiliary heater. When this was done, a 20% increase in the current at ignition was observed. Of course, the same qualitative trend would be expected if ϕ_c were 1.8 eV. However, in this latter case the overall ion emission is a million times smaller, as discussed above, and therefore the magnitude of the change would be unobservable.

Fission product gas. If there should be a leak between the fuel space and the cesium space of the TFE, fission product gases could enter the interelectrode space. The presence of these gases could cause some degradation of performance. Indeed it is just this scenario that is part of the 1H3 test. In 15,000 hours of operation, the production of Xe would be sufficient to raise the pressure in the interelectrode space by about 5 torr, if the ducting out to the fission product plenum chamber in the upper portion of the TFE is not plugged and there is a leak. If the ducting is plugged, the Xe pressure could rise to perhaps 150 torr. From Rufe and Kitrilakis (Ref. 8-12), the first case would give rise to a voltage decrease of about 0.01 V, while the second case (150 torr) would cause a voltage drop of about 0.2 V. For these estimates the cesium optimized current density was taken to be 10 amps/cm². It seems unlikely that fission product gas makes any appreciable contribution to the degradation of 1H1.

Emitter swelling. Swelling of the emitter and a consequent reduction of the interelectrode gap could cause degradation of performance (Ref. 8-13). The neutron radiographs that were taken at 11,000 hours and at 15,000 hours were carefully examined with a vernier driven cross hair inputting a micro-computer and the maximum emitter swelling measured was 0.0007". This is inadequate to cause any appreciable drop in performance.

Cesium pressure. There could be an error in determining the cesium pressure from the temperature indicated by the thermocouple on the reservoir. Either a faulty thermocouple or a cold spot in the converter could cause the error. From Table 8-6, the cesium pressure deduced from the thermocouple was

3.2 torr throughout much of the reporting period. Note also that in Figs. 8-3 and 8-4, the knee in the I-V curves, separating the obstructed and saturated modes, is off scale. From converter #46 data, the cesium pressure could fall to about 2.0 torr before the knee would be in the plot window. In this event, the cell voltage would have actually increased by about 0.3 V. If the cesium pressure fell further to 1.4 torr, the cell voltage would drop by about 0.45 V, but the knee in the I-V curve would be just below 50 amps. It is not likely that there is a significant error in cesium pressure contributing to the degradation of 1H1.

Instrumentation problems. Resistance measurements at zero reactor power, between the three voltage probes and two TFE current leads, dc voltage measurements at full power between these same leads and finally measurement of the transient response of the voltage between these leads when the TFE current is swept, were measured. In addition, the voltage measurement was calibrated with an NBS traceable standard at +0.5 and -0.5 volts. The only anomalous result was an indication that the resistance of both the emitter and collector bus bars had increased. This increase would have no effect on the I-V curves, since the voltage probes are located inside the bus bars, i.e., the voltage drop across these bars is not measured.

1H1 degradation summary. The behavior of 1H1 remains thermionic, but its continued testing is prejudiced by the uncertainty in emitter temperature that results from the possible ambiguities that are inherent in the accessible diagnostics. This uncertainty is currently being evaluated.

8.5.2 TFE-1H2 and TFE-1H3

Testing of TFE's 1H2 and 1H3 continued with stable performance and without significant events through the reporting period.

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