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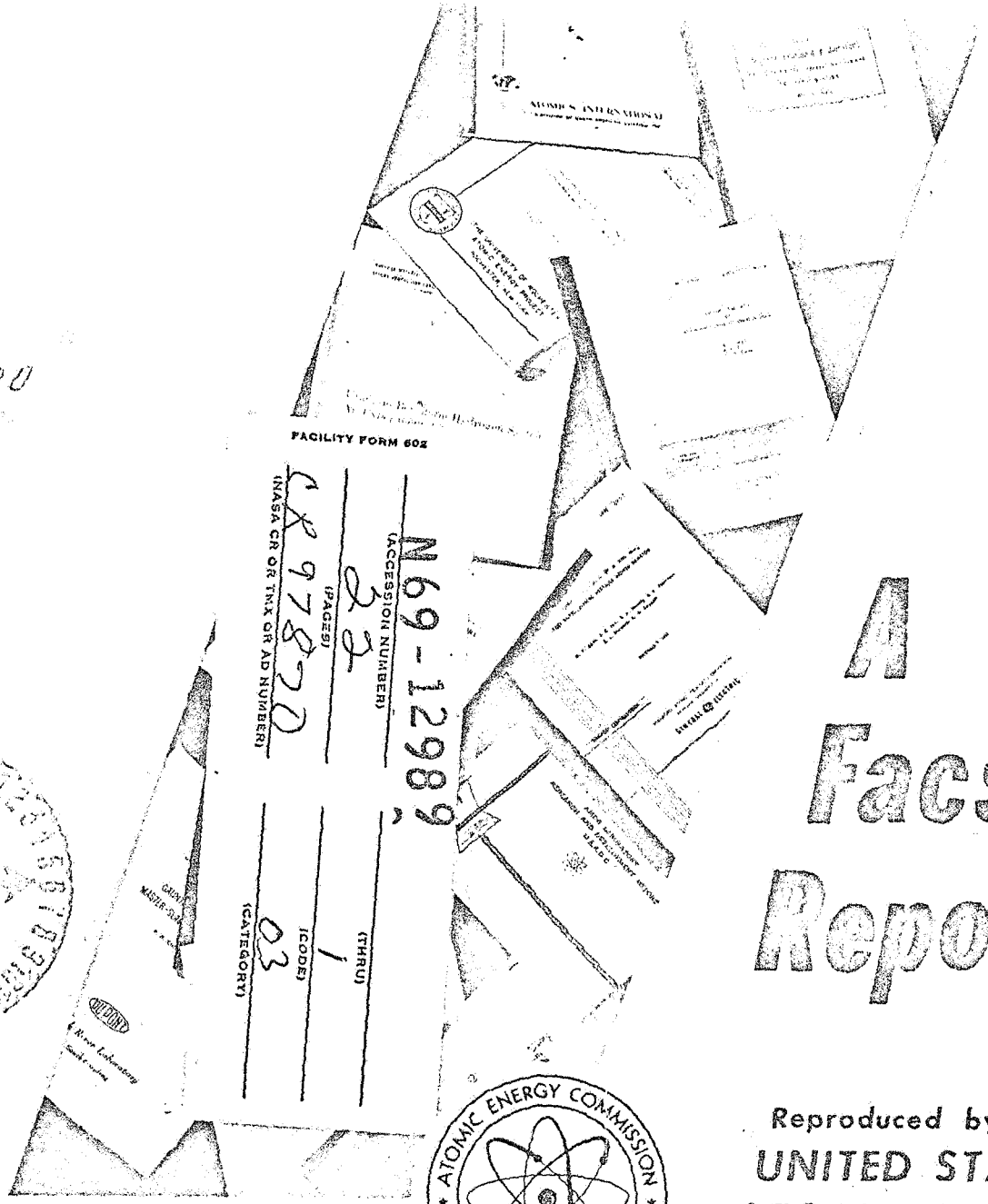

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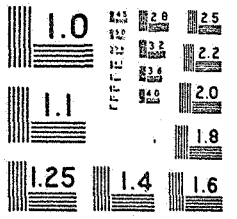

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LONG TERM OPERATIONS OF IN-PILE AND OUT-OF-PILE THERMIONIC CONVERTERS

by

J. W. Holland, M. K. Yates, D. E. Schwarzer and J. Kay

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ABSTRACT

Ten cylindrical geometry converters with series designation Mark VI have been life tested in-pile for a total of 20,034 hours, an average life of 2003 hours, and an average electrode power density of 7.2 W/cm^2. The longest test to date ran for 5369 hours at an average electrode power density of 10 W/cm^2. That test designated as IC-15 was fueled with UO_2 and achieved a burnup of 2×10^{20} fission/cm^3.

Out-of-pile models of the Mark VI converters were life tested for a total of 51,542 hours, an average life of 6443 hours and an average power density of 7.9 W/cm^2. The longest test to date ran 10,406 hours at an average electrode power density of 8.6 W/cm^2. Both unfueled and fueled versions were tested.

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PART 1

LIFE TESTS OF FISSION HEATED THERMIONIC CONVERTERS

INTRODUCTION

Development of fission heated cylindrical geometry thermionic converters, designated as the Mark VI series, has been in progress at Gulf General Atomic Incorporated since 1962. The first converters tested served to eliminate gross defects from the converter design and test apparatus. The first long term test was conducted in 1964 when 1006 hours were achieved on a 90UC-10ZrC fueled converter, designated as Mark VI IC-6. Including that test, a total of ten Mark VI IC-series converters have been life tested to date for a total operating time of 20034 hours. Nine of the ten converters were fueled with 90UC-10ZrC; one converter was fueled with UO_2. Because significant differences were observed between converters using the two types of fuel the test results will be presented according to fuel type.

CONVERTER DESIGN AND PARAMETERS

The configuration of the Mark VI in-pile converter is shown in Fig. 1. Significant design and material features are:

Fuel--UO_2 or 90UC-10ZrC, 93% U^{235}	Collector material--wrought molybdenum
Emitter material--CVD (WF6) tungsten	Interelectrode spacing--0.020 cm hot
Emitter area--13 cm^2	Insulator seal--Litton design, Lucalox-Nb
Emitter diameter--1.64 cm	Cesium reservoir--2 grams liquid
Fuel clad thickness--0.1 cm	Fission product retention volume--20 cm^3

These converters were tested either in the Gulf General Atomic TRIGA or the General Electric Test Reactor. Waste heat from the conversion process was dissipated by way of gas gaps to reactor cooling water. Temperatures of the cesium reservoir and collector were adjustable by means of electrical heaters. Instrumentation included: chromel/alumel thermocouples for measuring cesium reservoir, collector and converter body temperature profiles; W/Re thermocouples located between the emitter wall and the fuel to measure

changes in the emitter temperature; voltage probes for measuring converter and electrode potentials; and a shunt for measuring the cell current.

Several parameters were calculated from the measured data. Changes in emitter temperature and values of relative power, P_r, and efficiency, η_r, were computed by means of a correlation that related changes in cell voltage to differences in plasma losses arising from cesium pressure changes required to maintain maximum cell voltage.[1] The relative power is defined as the fraction of the output that can still be produced at the initial operating conditions except for the cesium reservoir temperature which was optimized. The relative efficiency is defined similarly. Methods for calculating these parameters are described in Ref. 1. The initial emitter temperature was estimated by performance comparison with similar converters in which the emitter temperatures were accurately determined. Changes in emitter temperature were computed using the same correlation. The thermocouples in the fuel cavity were used only as a rough guide to the emitter temperature since they read as much as 200° C higher than the emitter temperature.

Deviations in the relative power from unity are interpreted to be caused by work function changes, alterations in the interelectrode gap or in the scattering of electrons by a foreign gas. Deviations in the relative efficiency from unity arise from the combined effects of changes in the relative power and changes in thermal transport such as would result from an electrode emittance change or from a change in electron waste heat. For these converters the external environment was an inert gas, either helium or argon, so that inleakage of these gases would also contribute to the thermal transport if such were to occur. Inleakage of fission gas from the fuel chamber into the converter is another possibility.

IN-PILE TEST SUMMARIES

A summary of the in-pile tests is presented in Table 1. Listed are the test designation, fuel and electrode materials, test durations, average electrode power density and emitter temperature, final relative power and efficiency, test termination date, burnup, and failure mode. Several

generalizations on this table are apparent. First, the highest average performance of 10 W/cm^2, and longest operation, 5369 hours, were obtained from the UO_2 fueled IC-15 converter. Also, the final power and efficiency relative to initial values were somewhat greater than unity. For the carbide fueled converters the average output powers were generally lower, ranging between 4 to 7 W/cm^2. The final relative power and efficiency were sometimes substantially below unity, and ranged down to as low as 0.45 in one case.

In all but three cells, IC-11, IC-12, and IC-15, the failure mode was related to envelope leaks which allowed inleakage of gas into the converter interior. Test IC-11 was terminated by contractual commitment and IC-12 and IC-15 by interelectrode shorting. The location of leaks in the envelope were not found in hot cell examinations, but from examination of similar out-of-pile converters the most probable locations were in the seal or in joints between dissimilar converter components. The IC-15 interelectrode short was found to have been caused by breakage of a getter ring during movement of the cell. The short found in IC-12 was related to a change in the emitter geometry due to a fuel interaction.

PERFORMANCE TREND IN UO_2 FUELED CONVERTER

The trends in relative power and efficiency of the UO_2 fueled Mark VI converter test IC-15 are shown in Fig. 2. The relative power factor varied between 1.00 and 1.10 over the 5369 hours of operation. The relative efficiency factor varied between 0.9 and 1.10. An upward trend in both the factors indicates the cell performance was improving. The reason for the improvement is attributed to the diffusion of oxygen through the fuel cladding. Experimentation has demonstrated that the bare emitter work function increases at emitter temperatures below 1800° C when oxide fuels are in contact with the inside wall of the emitter. The upward trend in the IC-15 performance was accompanied by a slight decrease in emitter temperature which is thought to have been responsible for the increase in performance.

PERFORMANCE TRENDS IN 90UC-10ZrC FUELED CONVERTERS

Relative power and relative efficiency factors are shown in Fig. 3 for IC-6 through IC-14, all fueled with 90UC-10ZrC. In examining these trends, several conclusions are reached. First, in the longest tests the relative powers were typically on the order of 80% by 2500 hours; and, second, there were additional thermal losses amounting to 10 to 25% as evidenced by the differences between the P_r and η_r factors. In the two cases of IC-10 and IC-13, P_r dropped below 80%, but these decreases were expected since they were accompanied by decreases in emitter temperature. This effect is discussed below.

A decrease in P_r by 15% was indicated in the carbide fueled emitter out-of-pile tests (Part II) so that there appears to be little added effect by the nuclear environment on the relative power.

The observed changes in relative power are interpreted to be the result of work function changes due to the diffusion of uranium to the emitter surface. Experiments investigating the effects of uranium (from non-stoichiometric UC-ZrC fueled emitters) on work function and thermionic performance have been conducted which showed that accumulation of uranium on the emitter surface lowered the emitter work function from 4.6 eV at 1800° C to as low as 3.5 eV at 1500° C. Decreases in emitter work functions yield significant decreases in performance. A decrease in emitter work function by 0.1 eV was found to have resulted in a 10% loss of output power. The cause for uranium diffusion to the emitter surface was attributed to the substoichiometric carbon content of the fuel.

The decrease in the relative efficiency appears to be significantly higher in-pile than out-of-pile. The cause for the higher thermal losses is not certain, but some insight is obtained in comparing the 2500 hour IC-11 test to the 3300 hour IC-12 test. In doing so, one observes an almost identical correspondence between the two results--that the relative efficiencies stabilized at the same values at about 2500 hours. This seems to rule out erratic phenomena such as inleakage of the helium containment gas into the

converters as the cause for the rather large decrease in efficiency. About half the effect could be explained if the emissivity of the collector changed from 0.15 to 0.8. Such an emissivity change could have been related to tarnishing of the collector surface by active gases or from the accumulation on the collector of fuel material or fission products. It is unlikely that enough fuel material could have collected on the emitter at its operating temperature to affect its emissivity. Surface roughening of the emitter could be a minor factor. Inleakage of fission gases from the fuel chamber on the other hand cannot in theory be eliminated as a causative factor since there is enough xenon buildup in the fuel chamber to give the observed results. Part of the added thermal loss may have been due to increased electron waste heat caused by an increase in effective collector work function or by an increase in kinetic energy of electrons entering the collector surface. It is estimated that such effects would have probably constituted less than 5% change in η_I.

CONCLUSIONS

The primary conclusion from these tests is that the oxide fueled converter presently represents the highest state of development as exhibited by its superior performance, stability and life. We speculate that the carbide fueled tests all suffered from a common difficulty of having employed a fuel substoichiometric in carbon. Future tests of carbide fueled converters with increased carbon content will determine the usefulness of the carbide fuel in its upgraded form.

As shown in Fig. 4, progress is being made in increasing the longevity of the tests. The increased longevity has been due to the combined efforts of improving the technology of fabricating converters, and the test environment. Our present goal of 10,000 hours of reproducible operation seems to be within reach in the next few years.

PART II

LIFE TESTS OF ELECTRICALLY HEATED THERMIONIC CONVERTERS

INTRODUCTION

As a companion effort to the in-pile program, development of an out-of-pile electrically heated Mark VI converter was undertaken for the purposes of determining: 1) the life and failure modes of the cells under high vacuum and outside of the nuclear environment, 2) the effects of fuel diffusion on the thermionic performance without the complications of fission products, 3) performance reproducibility, and, 4) effects of electrode material selection. To study the effects of fuel diffusion, slabs of fuel materials were imbedded within the emitter walls. Emitter thermocouples were also employed in the emitter walls to obtain accurate measurements of emitter temperature and hence direct determinations of the relative power. Since the input power was easily determinable, the relative efficiency was also directly derivable. Effect of electrode material selection on converter performance was studied in several converters by varying the crystal orientation of the tungsten emitter and by replacing the previously used molybdenum collectors with niobium.

To date eight of these life converters (LC-series) have been tested for a total time of 51,542 hours, an average life of 6443 hours, and an average power density of 7.9 W/cm^2. One converter is presently under test with 9353 hours of stable performance accumulated.

This part of the paper is organized according to the following subjects: Converter Design and Parameters; Test Summaries; Performance Reproducibility; Effect of Electrode Materials on Performance; Performance Trends; and Conclusions.

CONVERTER DESIGN AND PARAMETERS

The configuration of the Mark VI LC-series converter is shown in Fig. 5. It may be noted that the working part of the electrode configuration is essentially identical to the in-pile Mark VI. The main differences in

instrumentation were the inclusion of W/Re thermocouples in the emitter wall for a direct measurement of emitter temperature and the ability to directly measure the input power. When fuel slabs were contained within the emitter wall, they covered 53% of the surface area and were located at 0.1 cm from the emitter surface, the same clad thickness as used for the in-pile cells.

The converters were operated in ion pumped bell jars. Power to the emitter was supplied by means of electron bombardment. Collector and cesium reservoir heat sinks were fit onto the outside diameter of the collector structure and cesium reservoir and were either water or air cooled. Electrical heaters were used for automatic control of the collector and cesium reservoir. Both the cell and electrode potentials were measured as well as the cell current. For some of the converters, emitter and collector work functions were routinely measured to correlate work function alterations to changes in performance.

TEST SUMMARIES

A summary of the out-of-pile tests is presented in Table 2. Listed are the test designations, electrode and fuel materials, test durations, average electrode power density and emitter temperature, final relative converters contained W-60 v/o UO_2 cermets; three converters contained UC-ZrC in various molar percentages of 30-70, 50-50 and 90-10; one converter was unfueled. These converters all employed emitters fabricated by means of hydrogen reduction of WF_6 and used molybdenum collectors. The unfueled converters, LC-7 and LC-9 used different combinations of electrode materials.

With respect to performance the converters, with one exception, produced average output powers between 6.8 and 8.8 W/cm^2. That one exception was LC-6 which will be discussed in greater detail below. Conclusions regarding the final relative power and efficiency are made when the performance trends are discussed below.

The distribution of failure modes among the seven converters failed to date has been one short circuit and seven envelope leaks. One converter, LC-3, actually failed by envelope leak plus an interelectrode short caused by a

broken getter ring. The envelope leaks were generally located at the junction of two dissimilar converter components. Usually, the leaks were either in the final braze or the insulator seal.

PERFORMANCE REPRODUCIBILITY

Among the cells, six have used tungsten emitters, made by the hydrogen reduction of WF_6, and polycrystalline molybdenum collectors spaced at .008 in. from the emitter. The initial maximum power densities of these six cells are compared with each other to examine the degree of performance reproducibility achieved in these cells. For a comparator an earlier cell designated as OC-5[2] is used because it was performance mapped over a wide range of operating conditions and corresponds well with the performance of cells with similar materials and spacing produced in other laboratories.

The initial performances mentioned above are compared in the table below where the comparative factor is the initial maximum output power of the cell divided by the output of OC-5 at the same current density, emitter temperature, and collector temperature as used for the compared cell but at optimum cesium pressures. In examining the results there is found close

Out-of-Pile Converter Designation	Fuel	$\frac{Po}{Po\ (OC\text{-}5)\ T_E,\ T_C,\ J,\ T_{Ropt}}$
LC-1	30UC-70ZrC	0.77
LC-2	W-60 v/o UO_2 Cermet	0.97
LC-3	W-60 v/o UO_2 Cermet	0.97
LC-4	None	0.84
LC-5	90UC-10ZrC	0.98
LC-6	50UC-50ZrC	0.66

comparisons between OC-5 and LC-2, LC-3, LC-5, certainly within experimental errors. Converters LC-1 and LC-6 both contained UC-ZrC fuel material. Their low relative initial outputs of 0.77 and 0.66, respectively, were attributed to fuel diffusion to the emitter surface during processing which lowered the emitter substrate work function. The low relative output of the unfueled cell LC-4 of 0.84 was attributed to gaseous contamination of the electrodes.

Except for the effects of gaseous and fuel contamination in the cells, the out-of-pile cells have demonstrated reproducible performance. The effect of electrode materials on converter performance is discussed in the next section.

EFFECT OF ELECTRODE MATERIALS ON PERFORMANCE

One of the purposes of testing different combinations of electrode materials and crystal orientations was to determine performance advantages that might be gained through selection of electrode materials. The converters selected for comparison of electrode materials are:

Converter Designation	Emitter/ Preferred Orientation	Collector
LC-7	W/{100}	Nb
LC-9	W/{110}	Nb
OC-5	W/{100}	Mo

The LC-9 emitter surface was made by the hydrogen reduction of WCl_6. The orientation was determined to be a partial {110}; its vacuum work function was 4.78 eV. By comparison, latest reported values[3] for the {110} orientation range around 5.0 to 5.4 eV. The performance advantage to using emitters with work functions greater than obtained for LC-9 is discussed in Ref. 4. Electrode work function measurements on LC-7 and LC-9 are also presented in Ref. 4.

By comparing the performances of LC-7 and LC-9, both with niobium collectors, the advantage was determined for a converter using a 4.78 eV work function tungsten emitter over a 4.55 eV work function tungsten emitter. By comparing OC-5 and LC-7, the performance advantage was found for a polycrystalline molybdenum collector over the use of a polycrystalline niobium collector.

Maximum electrode power densities of LC-7, LC-9 and OC-5 are compared in Fig. 6 as a function of current density at an 1800°C emitter temperature. The cesium reservoir and collector temperatures were optimized at every

point on these curves. The results show that the improved emitter work function by 0.23 eV in LC-9 yielded a significant performance increase over the LC-7 performance. At 12 A/cm^2 LC-9 produced 21% more power than LC-7. The advantage diminished at low currents, but at higher currents the advantage grew larger. The optimum current density is shown to be higher for the higher performance converter. Comparing the output of LC-7 to the extrapolated output of LC-9 at optimum current densities, the maximum performance advantage of LC-9 is estimated to be 25%.

The increase in output resulting from use of molybdenum over niobium for the collector is found by comparing the OC-5 and LC-7 curves. The comparison is a little lopsided in favor of the molybdenum collector because the OC-5 hot spacing was .008 in., or .001 in. smaller than the LC-7 hot gap. Using correlation data[5] to correct for the difference in spacing, OC-5 at a .009 in. spacing would have produced about 8% less power to make the real performance advantage of OC-5 29% at 12 A/cm^2. Again the advantage diminishes at low currents and becomes larger at higher currents. At optimum current densities the difference is about 40%.

PERFORMANCE TRENDS IN OUT-OF-PILE LIFE TEST CONVERTERS

Trends for the power and efficiency of eight out-of-pile life test converters relative to their initial values are shown in Fig. 7. In all of these tests the relative power exhibited fair stability and remained within ±15% of the initial value over their test durations with two exceptions: 1) the unfueled LC-4 showed a temporary 40% increase in power during the first 600 hours that was interpreted as being due to oxygen contamination remaining from the fabrication process; and, 2) the 50UC-50ZrC fueled LC-6 showed a very low initial performance due to a uranium contaminated emitter.

In all of the tests with the exception of LC-1 the relative efficiency closely tracked the relative power which indicates there were no significant added thermal losses. In LC-1 the relative efficiency was found to be about 10% less on the average than the relative power except near the end of the test. In the postoperational examination of LC-1 a defect in the emitter structure was found that had allowed a direct introduction of the carbide

fuel into the gap. From the operating data the defect was determined to have occurred 242 hours after the start of the test. The large decrease in η_r between 5000 and 7174 hours was attributed to leakage of atmospheric contaminants into the converter through an envelope leak which occurred at the time of a shutdown for thermocouple calibration.

The scatter in the LC-2 and LC-3 values is attributed to changing of oxygen contamination on the emitter resulting from fluctuations in the emitter temperatures. The fluctuations were due to varying input powers, changing operating parameters and shutdowns. In a separate experiment the source of contamination was attributed to the oxide fuel. Part of the scatter in the LC-2 and LC-3 values was the result of uncertainties in the determinations of P_r and η_r due to varying operating conditions employed in the test.

In the LC-5 test the relative power gradually decreased to about 0.85 over the first 3000 hours and then remained constant thereafter. The cause of the decrease was related to an accumulation of uranium on the emitter surface to lower its work function and decrease output power. The relative efficiency appeared to track the relative power within 5% which is within experimental uncertainties and thus no significant added thermal losses are indicated.

The very large changes in the power and efficiency of LC-6 were related to uranium diffusion to the emitter surface from the 50UC-50ZrC fuel. The main reason LC-6 showed such large changes was that the emitter temperature was operated at about 1650° C. At that temperature the emitter work function is lowered to about 4 eV by uranium accumulation. The cell output was about the level expected from an emitter with a 4 eV work function. In vacuum work function measurements on the emitter after it had been removed from the converter, it was found that if the emitter had been operated at 1800° C, the output would have been closer to the output of OC-5.

The relative power and efficiency factors for unfueled LC-7 and LC-9 tests showed no change throughout their operation, indicating completely stable performances.

In Fig. 8 relative powers of LC-1, -2, -3, -4, and -5 are normalized to the OC-5 performance, for the purpose of comparing LC-1 through LC-5 on an equal basis. In this way, the fact that LC-1 and LC-4 began at lower power densities than the rest of the cells can be factored into the comparison. Test data on LC-1, LC-4, and LC-5 are presented as curves while the LC-3 data are presented as a band ±16% wide, because of fluctuations in the relative power due to varying operating conditions employed during its test. The LC-2 test data are omitted since they fall within the LC-3 band. Converter LC-5 began 2% below OC-5 and was operating at an output power of 16% below OC-5 at 5500 hours at the time of the cesium leak. Converters LC-1 and LC-4 began 23% and 16% below OC-5, respectively, and ended (prior to cesium leakage) at 25% and 23% below OC-5, respectively.

The most significant observation is that in all cases the upper limit of loss in power density in these LC-series converters appears to be 25% as long as the emitter temperature is maintained in the region of 1800° C. A similar result was shown for the in-pile tests where the upper limit on power loss was about 20%. The explanation of this power loss limit is that once the collector became contaminated, additional accumulation caused little effect, and the emitter operated at a high enough temperature that gross accumulation of fuel or contaminants did not occur. The fact that LC-1 electrodes were heavily contaminated with fuel tends to support the theory of a 25% limit on loss of P_r for the operating conditions used in these tests.

CONCLUSIONS

The main conclusions reached from these tests were:

1) High work function emitters yielded a significant performance advantage.
2) Converters with niobium collectors exhibited completed stable performance but inferior performance to the molybdenum collector.
3) Carbide fuels in LC-1, LC-5, and LC-6 were most likely substoichiometric in carbon.
4) Operation of uranium rich carbide fueled emitters at temperatures below 1800° C leads to significant performance losses.
5) The added thermal loss mechanism observed in the carbide fueled in-pile converters was not found in the carbide fueled out-of-pile converters.

TABLE 1

IN-PILE TEST SUMMARY

Test	Emitter/ Collector	Fuel	Hours	Average Electrode Power Density (W/cm^2)	Average Emitter Temperature (°C)	Final Relative Power	Final Relative Efficiency	Test Termination Date	Burnup (f/cc)	Failure Mode
IC-6	W/Mo	90UC-10ZrC	1006	7.3	1760	0.80	0.65	4/19/64	$3x10^{19}$	Envelope leak-not found
IC-7	W/Mo	90UC-10ZrC	520	6.4	1720	0.90	0.80	6/28/64	NC	Envelope leak-no post-operational
IC-8	W/Mo	90UC-10ZrC	1552	6.3	1650	0.80	0.60	12/4/64	$5x10^{19}$	Envelope leak-not found
IC-9	W/Mo	90UC-10ZrC	1105	6.8	1660	0.90	0.80	6/28/65	$3x10^{19}$	Envelope leak-not found
IC-10	W/Mo	90UC-10ZrC	1552	6.9	1650	0.60	0.45	12/7/64	$5x10^{19}$	Envelope leak-not found
IC-11	W/Mo	90UC-10ZrC	2506	6.9	1690	0.80	0.60	8/26/65	$8x10^{19}$	None-contractual committment
IC-12	W/Mo	90UC-10ZrC	3300	6.2	1670	0.80	0.50	6/3/66 ⊙	$1.6x10^{20}$	Short due to growth on emitter
IC-13	W/Mo	90UC-10ZrC	1796	4.5	1490	0.70	0.50	6/30/66	$7x10^{19}$	Envelope leak-not found
IC-14	W/Mo	90UC-10ZrC	1328	4.0	1620	0.95	0.85	6/30/66	NC	Envelope leak-no post-operational
IC-15	W/Mo	UO_2	5369	10.0	1730	1.10	1.01	10/13/67 ⊙	$2x10^{20}$	Short due to getter ring

⊙ Test interrupted for reactor shutdown of several months.

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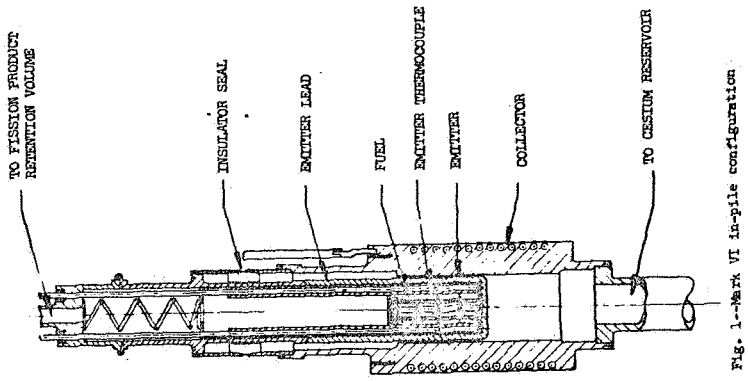

Fig. 1--Mark VI in-pile configuration

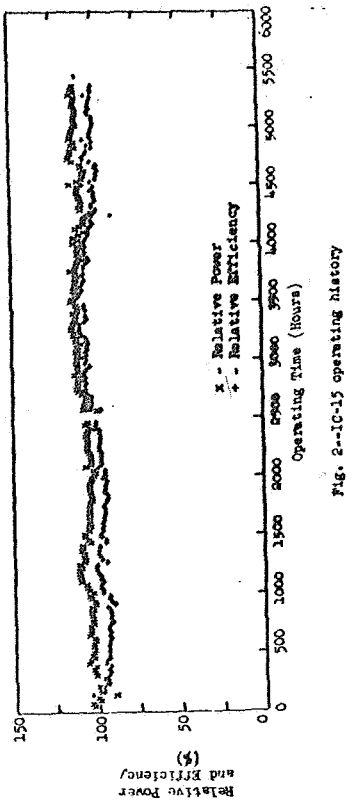

Fig. 2--LC-15 operating history

TABLE 2

OUT-OF-PILE TEST SUMMARY

Test	Emitter/ Collector	Fuel	Total Test Hours	Average Electrode Power Density (W/cm^2)	Average Emitter Temperature (°C)	Final Relative Power	Final Relative Efficiency	Test Termination Date	Failure Mode
LC-1	W/Mo	30UC-70ZrC	7174	6.8	1750	0.90	0.40	4/27/65	Envelope leak - cesium attack on insulator metallizing
LC-2	W/Mo	W-UO_2 cermet	3235	7.8	1650	1.10	1.10	12/29/64	Envelope leak - crack in emitter stem at transition joint
LC-3	W/Mo	W-UO_2 cermet	10406	8.6	1750	1.10	1.10	11/31/66	Envelope leak + short; leak not found; getter ring broken and shorted
LC-4	W/Mo	--	7345	8.7	1750	1.00	1.00	11/11/65	Envelope leak - final closure braze
LC-5	W/Mo	90UC-10ZrC	7558	8.8	1750	0.85	0.85	12/18/65	Envelope leak - cesium tube-collector braze
LC-6	W/Mo	50UC-50ZrC	2800	4.8	1650	1.18	1.13	8/10/66	Envelope leak - final closure braze
LC-7	W/Nb	--	3671	6.7	1800	0.99	0.99	7/13/67	Envelope leak - Cu-Nb weld in cesium reservoir
LC-9	*W/Nb	--	9353	7.9	1700	1.01	1.00		

+ Still operating as of 3/12/68

* Emitter from WC16

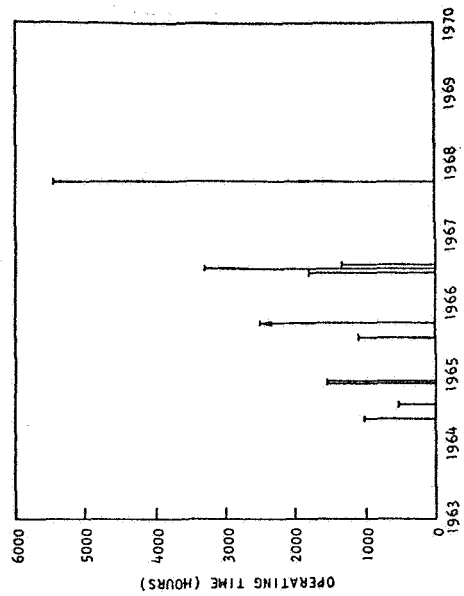

Fig. 4--In-Pile Mark VI converter tests

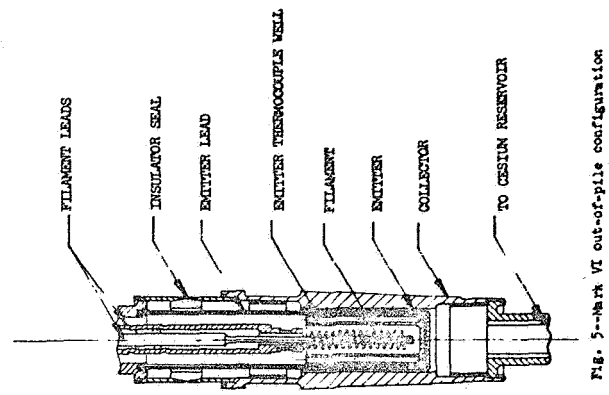

Fig. 5--Mark VI out-of-pile configuration

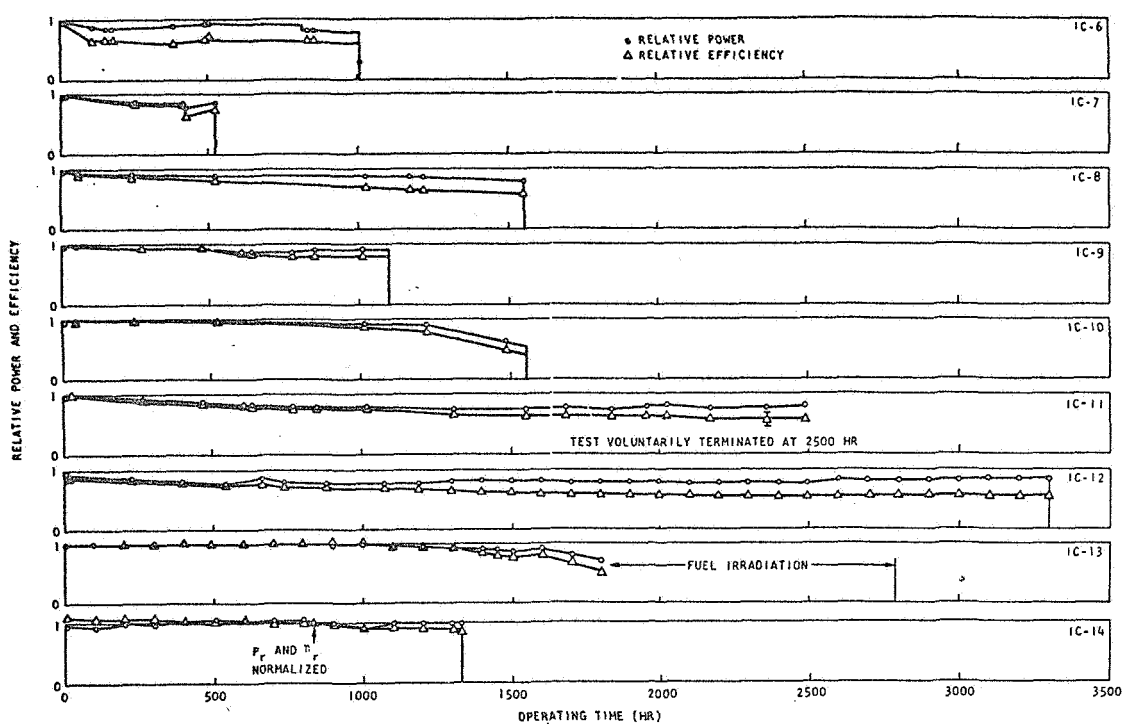

Fig. 3--Relative power and efficiency of carbide fueled in-pile converters

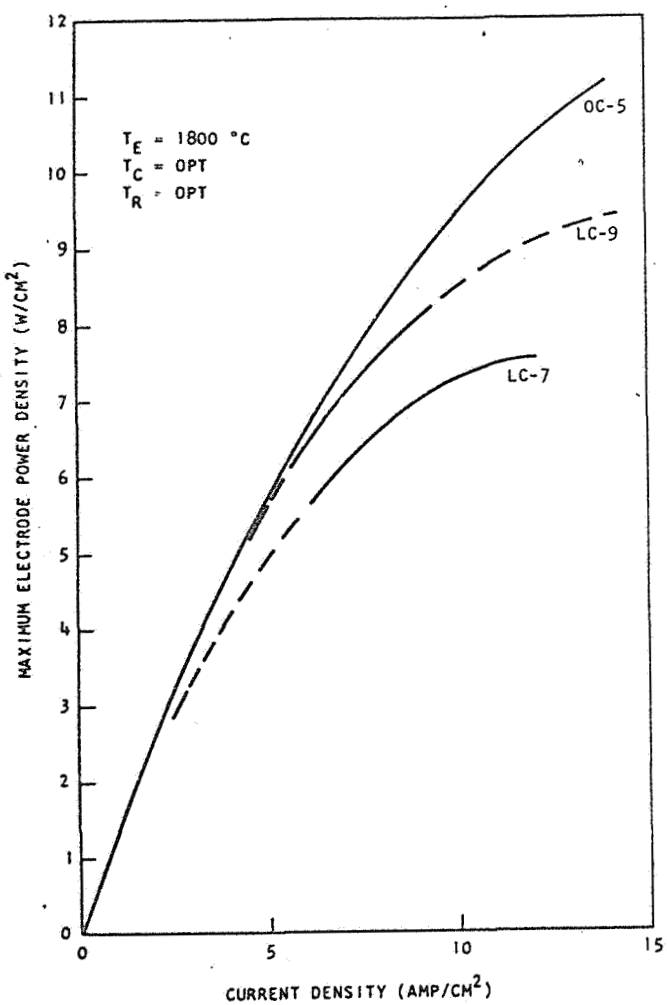

Fig. 6--OC-5, LC-9, and LC-7 performance comparison

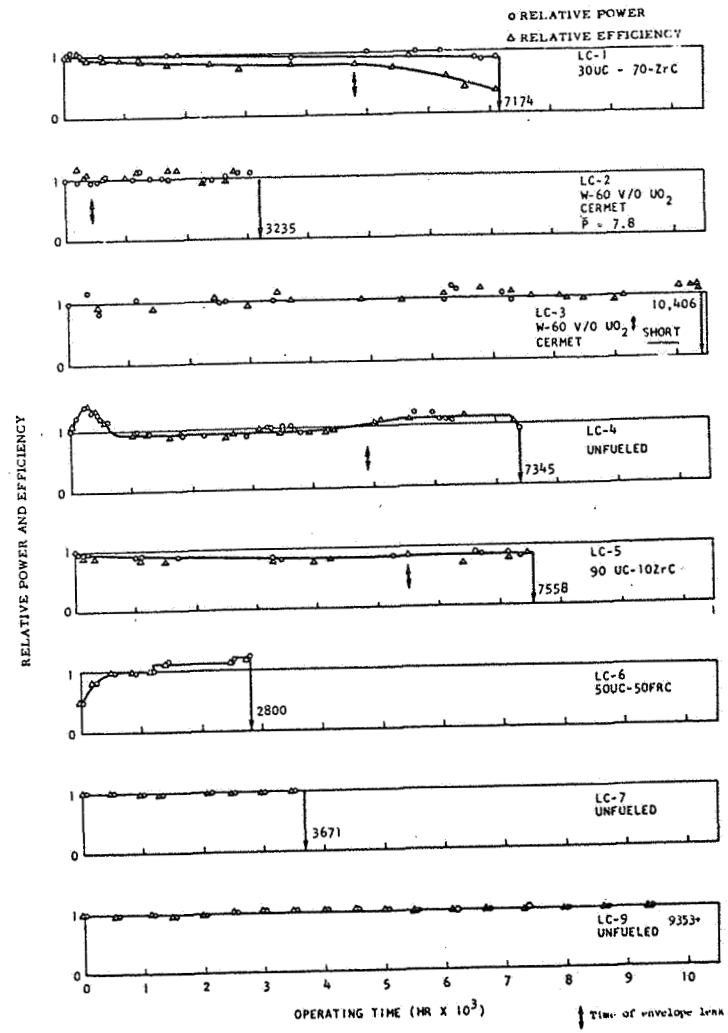

Fig. 7--Relative power and efficiency of out-of-pile converters

Fig. 8--Comparison of out-of-pile relative power data prior to cesium leakage