T10-25901

RECEIVED BY TIC FEB 7 1972

MASTER

T10--25901

TBC-1 POST INITIAL TEST

EVALUATION REPORT

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

MASTER

TBC-1 POST INITIAL TEST
EVALUATION REPORT

CONTRACT NO. AT(29-2)-2831
SUBCONTRACT NO. 026--AN2092

OCTOBER 1, 1971

PREPARED FOR

GENERAL ELECTRIC COMPANY
SPACE DIVISION
VALLEY FORGE SPACE TECHNOLOGY CENTER
P. O. BOX 7667
PHILADELPHIA, PENNSYLVANIA

PREPARED BY

THERMOELECTRIC PRODUCTS ENGINEERING
SPECIAL COMPONENTS OPERATIONS
ELECTRONIC COMPONENTS
RCA
HARRISON, NEW JERSEY

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Atomic Energy Commission, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

DISTRIBUTION OF THIS DOCUMENT

11-13

peg

TBC-1 POST INITIAL TEST EVALUATION REPORT

TABLE OF CONTENTS

	<u>PAGE</u>
I. SUMMARY AND CONCLUSION.....	1
II. TEST RESULTS.....	2
OPERATING SEQUENCE.....	2
ELECTRICAL AND THERMAL PERFORMANCE.....	2
LEAKAGE RESISTANCE AND SHORTS.....	2
VOLTAGE OUTPUT ANOMALIES.....	4
DISASSEMBLY.....	6
III. INVESTIGATION PROCEDURE.....	13
IV. RESULTS OF THE INVESTIGATION.....	14
CAUSE OF THE POWER LOSS.....	14
ANALYSES AND TESTS.....	16
OTHER POSSIBLE CAUSES.....	24
RECOMMENDED COURSE OF ACTION.....	28
EFFECT OF DISTRIBUTED LEAKAGE RESISTANCE.....	
ON POWER OUTPUT OF THERMOELECTRIC.....	
GENERATOR.....	APPENDIX A

I. SUMMARY AND CONCLUSION

Thermal vacuum testing of TBC-1 demonstrated good power performance at the 715°C and 935°C hot shoe temperature conditions, but provided 91% of predicted power at the 1035°C condition. During operation of TBC-1, a single point short was detected which by itself would not account for the power loss. Upon return to room temperature and removal of the shell, heavy black, electrically conductive deposits were observed to be randomly distributed on the cold side of the thermopile. This was significant because a distributed short in combination with the single point short could result in a converter power loss.

To determine the cause of the power loss, postulations of failure modes were made for the observed and other possible conditions. Tests and analyses in conjunction with detailed reviews of other data were performed to confirm or reject the postulated modes.

It was concluded that the loss of power was due to the combination of a single point short (cold side instrumentation in parallel rows 1-2) and a distributed short (carbonaceous and sodium deposits which bridged across most of the cold stack alumina ceramics). The origin of the carbonaceous material was shown to be the graphite compliance pad used in the electrical heat source; the sodium came from the Norton cement used in the heat source.

All attempted methods suitable for cleaning the ceramics in TBC-1 to increase the resistance to ground proved unsuccessful because the deposits penetrated the ceramics to depths of greater than 20 mils. Sodium is known to attack the glassy phase of alumina ceramics at the temperature of operation. Even if a suitable cleaning method could be achieved it would prove a fruitless labor because deposits are also present in the Astroquartz wrap around the unicouples and the Astroquartz spacers at the colder half of the thermopile and end cap foil insulation; these deposits may be expected to continue to vaporize and redeposit at the cold stacks during heat-up and operation of TBC-1. It is expected that about a 2% power loss would initially occur in the absence of a single point short upon resumption of TBC-1 testing. However, this may increase due to redeposition of the carbonaceous and sodium materials.

It was decided with G.E. to pursue the following course of action:

1. The cold side of the thermopile will be cleaned to the extent possible replacing parts wherever practicable.
2. A spool piece will be used to better accommodate the instrumentation leads bundle.
3. The amount of instrumentation will be reduced about 50% and all splices will be made using the crimp technique.
4. G.E. will use a graphite heating element in the heater and reused heater parts will be fired to remove residual contaminants.
5. The refurbished TBC-1 will be tested at the 1035°C operating condition to verify expected performance and then delivered to G.E.

It is RCA's position that all aspects of the materials and components to be used in converters to be tested at RCA be identified so that acceptability may be established.

II. TEST RESULTS

Operating Sequence

After mounting in the vacuum station and pump down to the 10^{-5} torr range, the Test Bed Converter #1 was brought to the design operating temperature of 1035°C . Temperatures were allowed to stabilize and complete sets of operating data were recorded at nominal hot shoe temperatures of 715°C and 935°C as well as at the 1035°C level. The rate of temperature increase was limited to a value which permitted keeping the vacuum as measured in the bell jar surrounding the converter in the 10^{-5} torr range. This required about 200 hours between the time power was first applied to the heater and when TBC-1 reached the 1035°C operating temperature. During the entire test the liquid nitrogen cold trap on the vacuum system was kept filled to reduce any backstreaming of diffusion pump oil. This was done to minimize the possibility of pump oil causing a leakage resistance path from the electrical circuit of the converter to the shell. After taking readings at 1035°C hot shoe temperature, the test plan called for maintaining a constant power input for 300 hours to determine the short term stability of the converter. However, within 100 hours, the heater operation became erratic. This became progressively worse, and on several occasions the heater current suddenly surged to a sufficiently high value to trip the power supply circuit breakers. Because of the problems with the heater, the converter was returned to room temperature after 150 hours operation at the 1035°C level.

Electrical and Thermal Performance

The measured and predicted values of power input and output, operating temperatures, converter voltage and current and efficiency are shown in Table 1.

At the 1035°C level, the power input can be seen to be about 5% lower than predicted for the hot shoe temperatures achieved, indicating that the thermal performance of the foil system was slightly better than expected. However, the power output is about 12% lower than predicted. The cold shoe temperature is higher, probably reflecting a difference from the assumed emissivities in the radiation path from shell to bell jar.

When the power output is adjusted for the difference in cold shoe temperature from the predicted value, a power output loss of 3.7% is observed. Such a large discrepancy could not be attributed to possible performance variations of the SiGe thermoelectrics between the measured temperatures, which lead to the investigation reported in this document.

Leakage Resistance and Shorts

Resistances from the converter electrical circuit to the shell and from the

TABLE 1

TBC-1 THERMAL AND ELECTRICAL PERFORMANCE

<u>Hot Shoe Temp. (°C)</u>			
Predicted	735	935	1035
Measured	715	936	1038
<u>Cold Shoe Temp. (°C)</u>			
Predicted	265	307	327
Measured	266	317	342
<u>Heat Input (Watts)</u>			
Predicted	1460	2050	2350
Measured	1325	1918	2236
<u>Output Current (Amps)</u>			
Predicted	3.42	4.57	5.19
Measured	3.68	4.74	5.10
<u>Output Voltage (Volts)</u>			
Predicted	17.4	24.2	27.6
Measured	14.9	22.3	24.6
<u>Output Power (Watts)</u>			
Predicted	59.5	113	143
Measured	54.9	106	126
Difference, adjusted	+0.6%	-2.8%	-8.7%
for ΔT			
<u>Efficiency (%)</u>			
Predicted	4.07	5.42	6.03
Measured	4.13	5.52	5.65
Difference, adjusted	+6.4%	+3.4%	-3.8%
for ΔT			

heater to the shell were monitored throughout the test. Initial room temperature readings of both resistances, with the converter mounted in the test station, were in excess of 20 megohms. As soon as power was applied to the heater and temperatures of the hot shoes increased, the resistance from shell to both heater and converter circuit decreased. By the time the hot shoes had reached 715°C, the resistance to the converter had fallen to 10,000 ohms and the resistance to the heater to 60,000 ohms. These leakage resistances continued to decrease with increasing temperature. At the higher temperatures accurate measurement could not be made of leakage resistances because of the comparatively higher internal impedance of the device used for bucking out the developed voltage of the generator. Calculations taking account of the internal impedance of the device indicates that the converter to shell resistance was within 0 to 10 ohms, while the converter was at 1035°C hot shoe temperature. A series of voltage measurements were also made from each voltage tap on the converter to the shell while the converter was at 1035°C. These indicated a null near one end of the converter electrical circuit, which gave evidence of a point short at that end.

When the converter was being returned to room temperature, the leakage resistance was measured at 1 ohm at the 50°C hot shoe temperature, but increased to 75 ohms at the next reading taken at 26°C hot shoe temperature. The most probable cause for this large change in resistance for a small change in temperature is that the 1 ohm represented a point short, and that slight mechanical movement caused the shorting path to open. The mechanical movement could have resulted either from vibration of the test station or thermal expansion changes. The probability of point shorts in the instrumentation is considered high because the method of making splices in the instrumentation leads could have allowed the ends of some of the welded splices to penetrate through the fiber glass if it were compressed. This was in fact experienced during emplacement of the bundle of instrumentation leads containing the splices into the small space inside the end dome. Moderate force was required to close the end dome which resulted in several visually observed shorts during final assembly. These were cleared by standing-off the end dome from the shell by using $1\frac{1}{4}$ " spacers. Although this corrected the shorts at that time, the probability of recurrence was high, especially when only slight movement would be required to reestablish a short. The volume of the instrumentation leads relative to the available space is illustrated in Figure 1. The probability of shorting under this situation would be enhanced by thermal expansion causing relative movement of the wires during the heatup cycle and operation of the converter.

Voltage Output Anomalies

Deviations were observed from expected voltage distribution of the 12 paired rows of the converter. Rows 23-24 showed a low open circuit voltage of 3.622 volts relative to the others which ranged from 3.899 to 3.645

VIEW OF TBC-1 INTERNAL INSTRUMENTATION LEADS
ATTACHED TO END DOME CONNECTORS. NOTE LIMITED
SPACE AVAILABLE FOR LEADS WHICH INCREASES
POSSIBILITY OF SHORTS.

FIGURE 1

volts at the 1035°C operating hot shoe temperature. It was postulated that this might be caused by a reversed couple, since the magnitude of the voltage difference was what would be expected under such circumstances. A shorted couple was ruled out because the resistance of the low voltage pair was normal. Upon disassembly, a reversed couple was found at position 24-12 which has been corrected. The loss in power output from the reversed couple was only 0.5 watts, which would not account for the lower power output of the converter. Examination revealed that the uncouple was correctly fabricated with respect to polarity of parts, but the stencil marking on the hot shoe to designate "N" side was inadvertently placed on the "P" side which accounts for the error in placement. This could have been prevented under a formal quality control program which was not in effect during TBC-1 fabrication. Such a program was not funded but has been authorized starting in the FY'72 period. To assure that this will not occur in the future, it is planned to use an in-gradient couple tester as part of a quality control check prior to insertion of the couples into the generator. The observed polarity will be checked against the hot shoe marking.

The second anomaly observed in the pattern of output voltages is that after correcting for the output of the reversed couple, the voltages of the paired rows decrease in sequence from rows 23-24 to rows 1-2. It may be assumed that if there were equal temperatures and thermoelectric material properties throughout the converter, such a pattern would be indicative of a distributed leakage to the shell plus a point short at one end. The reason for this can be seen in Figure 2 which is a schematic of a simplified converter. The current through that converter is highest through R12, which is the internal impedance of the section of the converter nearest the short at point 1. The converter current becomes progressively lower through internal resistance R23, R34, etc., since current is being diverted to each of the leakage paths. Since the output of each converter section will be the developed voltage (deflected by a battery) less the voltage drop from current flow in the internal impedance, it can be seen that the voltage across each section of the converter will increase with increasing distance from the point short. It is to be noted that a uniformly distributed short in the absence of a point short would result in a different voltage pattern where the lowest voltage would occur in the center of the converter with higher voltage output in the paired rows at each end.

Disassembly

The converter was disassembled to the point where the heater assembly was removed and taken to G.E. for analysis, and the thermopile was removed from the shell. Four SiGe couples were removed from the thermopile for tests and inspection.

Black and gray deposits were found on various parts of the converter and heater assembly. The heavier deposits were on the cold side of the thermopile, particularly where there was a path through the insulation, such as

FIGURE 2 - SIMPLIFIED SCHEMATIC OF TBC-1
SHOWING LEAKAGE PATHS

$$I_{12} = I_{LOAD} + I_{LEAK 1} + I_{LEAK 2} + I_{LEAK 3}$$

$$I_{34} = I_{LOAD} + I_{LEAK 3}$$

THEREFORE THE VOLTAGE DROP ACROSS THE
INTERNAL RESISTANCE R_{12} WILL BE GREATER
THAN THAT ACROSS R_{34} .

penetrations for instrumentation leads. Each of the 288 SiGe couple penetrations also provided a path, and the deposits were particularly heavy near some couples principally due to eccentricity of couples in the holes. From this pattern it was apparent that the deposited material came from the hot side of the thermopile. Photographs illustrating these deposits on several parts of the converter are shown in Figures 3 and 4.

No deposits were observed on the hot side of the thermopile except on the alumina insulation sleeves used for the hot shoe temperature measuring thermocouples, Figure 5. These insulating sleeves had heavy black deposits, but ~~these were not~~ electrically conductive (> 20 megohms) at room temperature. The deposits on the cold side were electrically conductive. Of particular interest, the ceramics on the cold stacks of the SiGe couples were conductive. A chart showing the room temperature leakage resistance across each ceramic is shown in Table 2. The parallel combination of these resistances equal 390 ohms, which shows excellent agreement with the 335-395 ohm measured values of converter to shell resistance before the shell was removed.

Before disassembly of the converter, the leakage resistance of converter to shell was observed to increase slowly from 75 to 390 ohms during the initial 36 hours of converter exposure to air. This change may be expected for a carbonaceous type deposit which would oxidize to form a resulting surface condition with a higher electrical resistivity.

TBC-1 THERMOPILE AFTER OPERATION SHOWING
BLACK DEPOSITS ON ASTROQUARTZ CLOTH (LEFT)
AND INSTRUMENTATION LEADS (RIGHT)

FIGURE 3

GENERAL VIEW OF FOIL END CAP OF TBC-1 AFTER TEST AND CLOSE UP OF INSTRUMENTATION LEADS EMERGING FROM FOIL. AREA OF CLOSE UP IS IN SEGMENT OF SPIDER IN TOP PICTURE CLOSEST TO VIEWER. NOTE HEAVY DARK DEPOSITS ON INSULATION.

FIGURE 4

THERMOPILE OF TBC-1 AFTER OPERATION.
NOTE GENERALLY CLEAN APPEARANCE OF
ASTROQUARTZ.

FIGURE 5

TABLE 2 - ROOM TEMPERATURE LEAKAGE RESISTANCES ACROSS TBC-1 CERAMICS II MEGOITS

Row Location	1	2	3	4	5	6	7	8	9	10	11	12
1	35	35	100	55	.16	14	.023	5	20	50	13	8.5
2	0.2	15	90	55	6	35	9	.046	.023	3	.26	11
3	35	50	60	55	15	23	.066	.17	.135	.023	5	8.0
4	50	35	50	55	50	30	20	16	5.5	.015	1.7	90
5	100	100	90	95	35	.055	20	.16	.0036		.100	30
6	100	100	100	100	35	60	.085	100	10		15	18
7	100	100	150	100	150	150	100	40	16		.15	55
8	100	100	150	140	150	150	50	50	.0026		.030	8
9	100	150	200	140	150	150	150	100	.023		150	.0115
10	150	150	200	140	200	200	150	100	150		.14	.036
11	150	150	200	150	200	200	200	150	150		90	150
12	150	150	200	150	200	200	200	170	150		150	150

Row Location	13	14	15	16	17	18	19	20	21	22	23	24
1	20	18	25	11	13	3	0.2	.139	19	.150	1.9	15
2	20	15	25	30	.140	3.5	1.5	20	.000	2.0	.055	0.6
3	7	25	35	.065	3	7.0	5	.0030	.030	.036	2.2	.042
4	3	100	.32	9.5	7	14	.080	.075	.125	.011	0.2	.400
5	40	20	.020	20	1.2	1.6	.021	.030	5.5	0.5	6.0	0.13
6	80	.070	50	10	.110	0.85	13	10	0.37	.012	30.0	15
7	50	45	.55	50	.115	0.017	.014	25	20	.024	9.0	6.5
8	95	100	.012	30	2-	50	16	14	.035	4.8	7.5	4.5
9	50	100	140	.018	0.7	30	.065	.033	.50	.070	7.0	0.8
10	100	140	.75	.027	.014	45	30	.095	11	30	2.2	8
11	150	160	.014	.022	50	.070	50	11	25	22	30	1.5
12	170	200	.050	150	70	30	80	30	0.8	33	30	0.1

III. INVESTIGATION PROCEDURE

To enable proper assessment of the causes for the power loss, the following possible failure modes were postulated:

1. Leakage resistance across the cold stack ceramics or the Astroquartz wrap in combination with a single point instrumentation short.
2. Leakage resistance solely across cold stack ceramics or through the Astroquartz wrap.
3. Multiple instrumentation shorts.
4. Diode effects.
5. TBC-1 thermoelectric materials not following the standard property curves or incorrect performance predictions.
6. Non-uniform heat pattern due to defective heater.
7. Shunt resistance across ceramic between N and P legs of each couple.

Various test and analyses were conducted to support or reject the above postulations. These included use of data from the tests of TBC-1, C-7, C-8, 4-A, and the 6.3.1 and 6.3.4 modules series. Tests were conducted to determine vaporization products of suspected contaminated materials and their effects on resistance to ground. Another series of tests using instrumented couples and Panel 4A were run to obtain additional leakage resistance data through Astroquartz yarn under temperature conditions. The supplementary tests involved both sealed ampule and dynamically pumped conditions.

IV. RESULTS OF THE INVESTIGATION

Cause of the Power Loss

The most probable cause for the observed loss of power during the initial TBC-1 test has been determined to be a single point short at one end of the converter in combination with a distributed short. Appendix A, attached hereto, is a mathematical analysis to show what magnitude the leakage resistances (Case 1) must be in order to effect the TBC-1 power loss. It is indicated that to lose on the order of 9% of predicted power at the 1035°C hot shoe operating temperature would necessitate a leakage resistance of 19 ohms across the distributed short when it is assumed that a single point short of zero ohms exists at one end of the converter. The occurrence of each short condition is supported in the following discussions.

(1) Single Point Short

During TBC-1 test there was strong evidence giving indication of the presence of a single point short. Measurements of voltage taken from each voltage tap to the converter shell showed the existence of a null point in the rows 1-2 string. A leakage resistance of between zero and 10 ohms was recorded throughout the test. A leakage resistance value of this magnitude is typical of an instrumentation short as was actually encountered more than once during the final assembly of TBC-1.

More than one point short is ruled out because under those circumstances the voltage outputs in the affected converter strings would have been substantially reduced from expected outputs. This was not in evidence in TBC-1. The observed anomaly of uneven distribution in the TBC-1 voltage outputs can only be explained by the presence of a single point short in Rows 1-2 and a distributed short return path.

See Section II for greater detail on the findings and conclusions regarding the single point short.

(2) Distributed Short

To have a distributed short between the converter circuit and ground would necessitate a leakage path through the Astroquartz wrap around each uncouple to the thermopile foil or across the cold stack ceramics.

Published data on electrical resistivity properties versus temperature for silica suggested the possibility that the leakage path could be attributed to the Astroquartz wrap. An added consideration was the deposition of sublimates in the Astroquartz yarn during TBC-1 operation which might tend to

further reduce its electrical resistance. Two special tests were conducted to investigate the yarn as a leakage path. In one test a unicumple removed from TBC-1 with its Astroquartz yarn intact was wrapped with molybdenum foil around its legs and instrumented to measure resistance change across the Astroquartz yarn with changing temperature. This test was run isothermally in a pumped ampule in the 10^{-5} torr range. The second test involved Panel 4A which is a 4-couple module having the same type unicouples and foil insulation materials of construction as TBC-1. In that test, the foils were instrumented to measure the resistance values between module circuit and foil across the Astroquartz yarn with varying temperature.

Table 3 summarizes the data from these tests.

TABLE 3

RESULTS OF TESTS TO DETERMINE RESISTANCE CHANGE OF UNICUPLE ASTROQUARTZ WRAP WITH VARYING TEMPERATURE

<u>Resistance - Couple or Module to Foil (megohms)</u>		
	<u>Test 1</u>	<u>Test 2</u>
Maximum Temp. ($^{\circ}$ C) (Hot Shoe)	(Single Couple, (Isothermal)	(Panel 4A, (4-Couple Module, (In-Gradient)
700	31.0	3.50
800	6.0	0.90
900	1.3	0.23
990	0.9	0.08
1035	0.56	0.076

As may be observed, the lowest resistance value per unicumple at a 1035° C hot shoe operating temperature is not sufficiently low to account for the distributed short. The calculated distributed leakage of 1055 ohms (76,000 ohms divided by 288/4 unicouples) is greater than one order of magnitude than the 19 ohms leakage resistance shown analytically to be required to account for the TBC-1 distributed short. It is also to be noted that in subsequent disassembly of TBC-1, the resistance from thermopile circuit to foil was approximately 10,000 ohms. On the basis of the foregoing tests and observations, leakage across the Astroquartz wrap was ruled out as a factor in the TBC-1 power loss.

Initial visual examinations both before and after the converter shell was removed indicated the cold stack ceramics as the most likely leakage path for the distributed short; see Figures 3 and 6. As discussed in Section II of this report, it was observed that the equivalent distributed resistance of the values measured across each ceramic when the shell was removed equalled the measured resistance to ground before the shell was removed. Black to gray deposits, carbonaceous in appearance, were observed on most of the ceramics, but the deposits were not always prevalent where relatively low resistance values were measured which suggested the possibility of other contaminant(s) beside carbonaceous material causing the leakage condition.

Analyses and Tests

Numerous analyses and tests of deposits and materials selected from TBC-1 were conducted to identify their constituents and to determine their origin. Because the black deposits were carbonaceous in appearance, initial emphasis was placed on carbon analyses.

The ceramic washers surrounding the heater leads (Figure 4) were observed to be coated with heavy black deposits. One of the washers was submitted to a 450°-500°C in-firing which caused disappearance of the black coating. Since few metals or metal oxides will behave this way, the deposit was preliminarily concluded to be carbon which reacted with oxygen to form carbon dioxide.

An optical emission spectrographic method was used to confirm the presence of carbon in the deposit on the other ceramic washers. The method is sufficiently sensitive to positively detect any form of elemental or combined carbon in very thin films; the limit of detection is approximately four micrograms. Deposits can be analyzed regardless of the substrate and is completely non-destructive if the film can be removed by rubbing with a moistened glass fiber cloth.

For this method the sample is transferred to a copper electrode cup. This electrode serves as an anode and is opposed by a tellurium-copper cathode. The carbon in the sample is vaporized, dissociated and recombined with nitrogen to form cyanogen (CN). The CN formed at the high temperature of the DC arc is a metastable diatomic species which emits a series of band spectra. The ultraviolet-CN band system, which is the most intense, has a 3.2 excitation potential. The most sensitive band head of this system at 3883 Angstroms is used for the detection of carbon in this spectrographic method. A Jarrell-Ash 3.4 meter Ebert mounting grating spectrograph is used to disperse the spectrum which is recorded in the first order on Kodak Spectrum Analysis Number 1 plates.

Using this extremely sensitive method to detect carbon, the following additional areas of TBC-1 were analyzed using controls whenever practicable.

TBC-1 UNICOUPLERS 936 AND 623, REMOVED FROM
CONVERTER AFTER OPERATION. NOTE DARK
DEPOSITS IN COLD STACK AREA.

FIGURE 6

1. Cold stack deposits from selected locations around thermopile
2. SiGe leg deposits from Unicouple #275
3. Astroquartz yarn removed from Unicouple #275
4. TBC-1 fiberglass insulating sleeve

As found in the deposit on the heater lead ceramic washer, the major constituent of the black deposits on specimens 1 and 4 above was carbon. Also, the deposits of samples 2 and 3 contained carbon in quantities higher than there should be for the materials involved.

It is known that none of the materials used in the TBC-1 thermopile including the foil insulation could be the source of the carbonaceous deposits. Carbon is only present in trace quantities at most in any of these materials which if it all could be released would be insufficient to cause the observed deposit. This is further supported by the many module tests being conducted in the sublimation and compatibility, 6.3.1 and 6.3.4, series and Panel 4A. The tests were cycled down purposely to observe and determine the presence of similar deposits with correspondingly low resistances to ground. None showed any black deposits on the cold side and the resistances to ground were found to be acceptable.

Review of the materials used by G.E. in the electrical heater and discussions held with G.E. revealed that one of the graphite materials used as compliance pads in the heater was not vacuum fired before its use in TBC-1. This material consists of carbon fibers bonded with a carbonaceous material, usually resins, tars or pitches. Operation of the electrical heater in TBC-1 resulted in vaporization of these species (cracking, resulting in breaking down to simpler hydrocarbons or to elemental carbon) and condensation. These condensates or cracked products are usually electrically conductive.

To confirm the compliance pad material as the source of the carbonaceous deposit, samples of the material were obtained from G.E. for testing. The most significant finding involved a dynamically pumped ampule test in which a sample of the graphite material was heated at about 1100°C and an instrumented TBC-1 design cold stack assembly was maintained at about 300°C; see Figure 7. At the conclusion of the test, the quartz ampule was observed to be coated with a black deposit; Figure 8. Analysis of the deposit showed the major constituent to be carbon and resistance measurements revealed the deposit to be highly conductive. It was observed, however, that the resistance across the instrumented cold stack did not reduce appreciably during the test, nor did the color of the cold stack ceramic change significantly from its original color. This is attributed to the graphite material's vaporization products depositing preferentially at the colder quartz ampule walls rather than the hotter ceramic located away from the ampule walls; see Figure 8.

PUMPED AMPULE TEST BEFORE OPERATION. NOTE CARBON COMPLIANCE PAD MATERIAL AT LEFT AND COLD STACK ASSEMBLY NEAR CENTER OF AMPULE.

FIGURE 7

PUMPED AMPULE TEST AFTER OPERATION. DARK DEPOSIT WAS IDENTIFIED AS CARBON.

FIGURE 8

A parallel investigation was conducted to determine means of removing the deposit on the TBC-1 ceramics in-place in the thermopile without causing detrimental effects. Two unicouples, #623 and #936, Figure 6, removed from the converter were instrumented and placed in an ampule set-up similar to that previously described. Before being placed in the ampule, the ceramic in uncouple #623 was sandblasted; the ceramic on #936 was brushed. It was noticed that the resistance of the ceramic, #936, increased slightly after brushing whereas the #623 ceramic resistance decreased after sandblasting. Of greater significance was the virtual gouging of the ceramic material around the edges which resulted from the sandblasting operation. This was never before encountered on new or aged ceramics. Application of heat to the above uncouples in the pumped ampule revealed no significant change in resistance across the ceramics. Also, the deposits on the ceramics showed opposite resistivity changes with respect to varying temperature, one increasing and the other decreasing with increasing temperature.

As a result of the gouging experienced on uncouple #623, uncouple #380 as removed from TBC-1 was subjected to metallographic examination; see Figure 9. It can be seen in Figures 9A and 9C that the outer edges of the ceramic were attacked and penetrated. Figure 9B shows a central portion of the ceramic which is representative of the quality and porosity level typical for both new and aged material.

Semi-quantitative spectrographic analyses which were conducted to supplement the foregoing analyses did indicate the presence of sodium in larger quantities than control which would cause the ceramic erosion and would contribute to low resistance to ground and account for the variable results obtained in the previously discussed tests. The carbonaceous material by itself could not have accounted for the observed behavior and effects.

To further confirm the presence of sodium, the uncouple #380 ceramic was submitted for electron-probe microanalysis. Qualitative analysis was made for all elements having atomic number ≥ 11 (Na) at three places on the section of the ceramic disk in the section of cold stack MHW202-380N (Figure 9):

- (1) A black area at the rim
- (2) A black area ~ 0.020 inch inward from the rim
- (3) Near the center of the section of the ceramic (Figure 9B)

The elements detected, together with approximate net x-ray spectral-line intensities read directly from the ratemeter-recorder charts, are listed in Table 4. The table also indicates the spectral line used for each detected element.

FIGURE 9

PHOTOMICROGRAPHS OF UNICOUPLE #380 COLD STACK CERAMIC

FIGURE A: End (1) of the
ceramic appears eroded.
MHW202-380N 145X

FIGURE B: Central portion
of ceramic is representative
of normal product used.
MHW202-380N 145X

FIGURE C: End (2) of the
ceramic appears eroded.
MHW202-380N 145X

TABLE 4

ELECTRON-PROBE MICROANALYZER STUDY OF CONTAMINATION
OF THE CERAMIC DISK IN THERMOELECTRIC COLD STACK MHW202-380N

Summary of Detected Elements

<u>Element</u>	<u>X-ray Spectral Line</u>	<u>Approximate Net Intensity (counts/s)</u>		
		<u>Black Area at rim</u>	<u>Black Area ~0.020" inward from rim</u>	<u>Uncontaminated Area near center</u>
Al	<u>Kα</u>	900	>>1000	>>1000
Mn	<u>Kβ</u>	90	31	42
Si	<u>Kα</u>	54	12	42
Na	<u>Kα</u>	220	100	N.D. *
Ca	<u>Kα</u>	48	36	30
Ni	<u>Kα</u>	N.D. *	27	N.D. *
Cu	<u>Kα</u>	24	27	33
Mo	<u>Lα_1</u>	36	24	N.D. *
W	<u>Lα_1</u>	36	24	N.D. *

* N.D. - Not Detected

In considering the data in the table, intensities of the same element at the rim, near the rim, and at the center of the ceramic may be compared as a measure of relative concentrations of that element at those points. But intensities of different elements at the same location may not be compared as a measure of relative concentrations. It is seen that the NaK^α intensities at and near the rim are 220 and 100 counts/s, respectively, and Na is not detected (N.D.) at the center. From this, it is concluded that the Na concentration is highest on the rim, decreases within the visibly contaminated dark region near the rim, and is substantially zero in the clean, uncontaminated portion of the ceramic at the center.

~~All elements identified in Table 4 except sodium are related to the ceramic body or adjacent materials of construction in the cold stack.~~ It is known that sodium attacks the glassy phase of alumina ceramics at the temperature of operation which would account for the ease of material removal during sandblasting. The presence of sodium accounts for the other contaminant besides carbon contributing to the low resistance to ground measured in TBC-1.

Investigation for potential sources of the sodium revealed that the cement G.E. used in the electrical heater contained approximately 0.5 percent by weight of sodium oxide which under the operating conditions of TBC-1 would be released from the heater and redeposit at the colder portions of the converter. This percentage although relatively small becomes significant because of the large quantity of cement used in the heater.

To assure that the effect of the sodium attack on the alumina ceramics to depths of about .060 inches would not prove detrimental to a re-test of TBC-1, three of the removed couples were subjected to tensile or beam deflection tests. All fractures occurred at acceptable strength levels in the SiGe which is indicative of normal product. However, it must be noted that although TBC-1 would appear suitable for a retest on steady state conditions, the presence of altered cold stack ceramics makes the unit unsuitable for dynamic evaluation including repeated thermal cycling.

Other Possible Causes

As indicated in Section III, various modes of failure were postulated to account for the TBC-1 power loss. Those not previously discussed in this section of the report are presented briefly below.

A. Diode Effects

Diode effects is the possibility that with hot surfaces in a vacuum, with a voltage potential between them, the negative surface could have been emitting electrons which would be attracted to the positive surface, thus resulting in a current flow. This possibility was checked out by measuring the current flow in Module 4-A, both between module and foil and between

module and base plate, as a function of applied DC voltage. Both positive and negative voltages were applied, ranging from zero up to 30 volts, which is the nominal output voltage of TBC-1. Some minor non-linearity was observed, but no current flow of the magnitude needed to cause the power loss observed in TBC-1.

B. TBC-1 Thermoelectric Materials Not Following the Standard Property Curves, or Incorrect Performance Predictions

These two related possibilities were checked by comparing the measured performance of TBC-1 and the measured performance of Module 4-A with predicted values. Since Module 4-A uses TBC-1 couples and insulation, either problem should be evident in 4-A as well as TBC-1. The results of this comparison are shown in Figures 10 and 11. Figure 10 is a comparison of open circuit voltages for 4-A and TBC-1 versus TBC-1 prediction. Figure 11 compares the circuit resistance of 4-A to TBC-1. In each figure the values of 4-A represent actual measured data adjusted to account for the larger number of unicouples in TBC-1. Clearly the performance of 4-A is much closer to the predicted values than is TBC-1. In particular, the difference in the resistances of 4-A and TBC-1 are what would be expected if there were a leakage path of some kind across the output of TBC-1. Neither non-standard material performance or incorrect performance predictions appear to have accounted for the lower than predicted power output from TBC-1.

C. Non-Uniform Heat Pattern Due to Defective Heater

Investigation of the electrical heater by G.E. revealed six tungsten heating elements had failed on one side of the heater. The pattern of failure of the heater, in which all of the open heater legs were on one side of the heater, might have been expected to result in some of the SiGe legs of the converter operating at lower temperature and thus producing low power output. However, this does not appear to be the case, since the voltage output pattern of the 12 converter legs does not line up with the location of the failed heater legs, and also because the low power output was evident as soon as the converter reached 1035°C, while the heater failures did not appear to occur until several days later. Since it was possible to nearly duplicate during cool-down the 935 degree power output that was achieved during heat-up, the evidence indicates that in fact very good temperature equalization in the heater was being obtained in the outer graphite shell. Non-uniformity of heating was not considered significant in the loss of power output.

Shunt Resistance Between N and P Legs of Individual Couples

Shunt resistance resulting from deposits on the alumina ceramics between the "N" and "P" legs of individual couples would reduce the power output of the converter. However, since these deposits would be across the low

FIGURE 10

VISIGRAPH
MADE IN U.S.A.

NO. 15, 20 GRAPH PAPER
20 X 20 PER INCH

FIGURE 11

NO 15 20 GRAPH PAPER
20 X 20 PER NCH
VISIGRAPH
MADE IN U S A

resistance of a single couple, rather than across the much higher resistance of the complete converter, the required resistance of the deposits across the alumina ceramic between the "N" and "P" legs would have to be much lower. This form of shunt would not lead to the pattern of voltages observed from converter to shell or across the 12 legs of the converter. This form of leakage could only be measured directly by breaking the hot shoes off couples to eliminate the parallel path. Measurement of this resistance path in one of the fractured uncouples revealed a value of greater than 200 megohms which is at least seven magnitudes higher than the value required to effect any TBC-1 power loss.

Recommended Course of Action

Because there are no suitable methods for cleaning the cold stack ceramics in-place without further violation of the integrity of TBC-1, the presence of the conductive deposits on the ceramics will continue to provide a distributed leakage path resulting in some loss of converter power upon resumption of test. In the absence of instrumentation shorts and a further supply of the deposit materials from the converter, TBC-1 would be expected to provide about 98% of predicted power. However, it is known that both the carbon and sodium contaminants from the heater are present in the thermopile. These materials are expected to continue to vaporize during reheat of TBC-1 and redeposit at the colder portions of the thermopile which may cause further power loss during operation.

To assure that instrumentation shorts will be prevented during a retest of TBC-1, pursuant to RCA's earlier recommendations, a spool piece should be used at the instrumentation end dome side of the converter to allow more space between the end dome and the thermopile to accommodate the large volume of instrumentation leads, Figure 1, and crimp connectors should be used to make the instrumentation splices so that no wire ends may protrude through the fiberglass insulation sleeving. Further assurance of preventing instrumentation short recurrence would be realized if the amount of instrumentation would be substantially reduced. A repeat of many of the measurements recorded in the initial test of TBC-1 is not required during its retest.

With respect to the electrical heater, pursuant to RCA's earlier recommendations, a heater employing a graphite heating element should be used for resumption of steady-state testing of TBC-1 in lieu of the tungsten filament heater used in the original test. RCA experience with heaters for various applications involving SiGe devices has indicated the graphite element heaters to be more reliable. Recrystallization of tungsten at the operating temperatures and reaction which occurs with silicon vapors causes degradation of the tungsten filament heater making it unsuitable for steady-state or dynamic use.

As regards the selection of materials for use in the converter, it must be a foregone conclusion that such selection be supported by acceptable compatibility and cleanliness with the MHW system as verified or demonstrated

in inspections, tests or analyses. This should be satisfied even with respect to the resumption of TBC-1 testing. Those parts of the converter including the heater which are intended to be used for the resumption of TBC-1 testing should be cleaned or replaced wherever possible to remove the existing contaminants.

Based on discussions held with G.E., the following course of action will be pursued:

1. The deposits on the cold side of the TBC-1 thermopile will be cleaned to the extent possible by brushing the cold stacks and electrical connectors and by replacement of instrumentation sleeving. Unicouples removed from TBC-1 for analyses will be replaced with new unicouples.
2. A spool piece will be used to provide additional space for instrumentation leads, and instrumentation splices will be done using the crimp technique. Approximately 50 percent of the instrumentation will be removed for the re-test.
3. G.E. will replace the heating element of the heater with a graphite element design. Before use in TBC-1, the original heater parts to be reused will be baked out at temperatures above the operating temperature, and tested to ensure that no undesired materials are vaporizing from the heater. Replacement parts will be contaminant-free.
4. TBC-1 will be operated at RCA to verify improvement in the power output at the 1035°C operating temperature and the unit will be delivered to G.E.

Finally, RCA's position must be made clear with respect to the selection of converter materials and components. No component or material is acceptable for use in a converter to be tested at RCA unless RCA is completely apprised of the details of the items including design data, constituents and prior processing or handling, so that it may be determined that such items are suitable for converter use.

APPENDY A

EFFECT OF DISTRIBUTED LEAKAGE RESISTANCE ON POWER OUTPUT OF THERMOELECTRIC GENERATOR

This analysis shows the amount of power lost in a uniformly distributed leakage resistance from active elements of a converter to the frame. Such a leakage path might be across the ceramic insulators, or from the legs or hot shoes thru the wrap to the foil. Two cases are considered

Case 1: Distributed Leakage Plus Zero Resistance Short at One end.

For this case it is shown that

$$P_L = \frac{1}{3} \frac{E_{cc}^2}{R_S}$$

Case 2: Distributed Short Only

For this case it is shown that

$$P_L = \frac{1}{12} \frac{E_{cc}^2}{R_S}$$

where:

P_L = Power dissipated in leakage resistance

E_{cc} = Converter closed circuit voltage

R_S = Leakage resistance

Application to TBC-1

Applying these results to TBC-1 results in the following conclusions:

1. The approximately 9% lower than expected power output of TBC-1 could have resulted from a 4.8 ohm distributed short, or a 19 ohm distributed short plus a zero resistance short at one end.
2. If, as seems probable, there was a short at one end to the frame thru the instrumentation leads during operation, removal of this short could reduce the power loss to only 2% in the distributed leakage path, even if this distributed leakage could not be eliminated or reduced. This would bring the output of TBC-1 very close to predicted performance.

Case 1:

Let X = distance from shorted end of converter as fraction of total length of converter

E_{cc} = converter closed circuit voltage

R_s = total shunt leakage resistance

P_L = Power dissipated in R_s

$X E_{cc}$ = voltage at X

then Power in small increment of length dx :

$$dP_x = \frac{E^2}{R} = \frac{(X E_{cc})^2}{R_s/dx}$$

$$P_L = \int dP_x = \int_0^1 \frac{(X E_{cc})^2}{R_s dx} = \frac{E_{cc}^2}{R_s} \int_0^1 x^2 dx$$

$$P_L = \frac{E_{cc}^2}{R_s} \left[\frac{x^3}{3} \right]_0^1 = \frac{E_{cc}^2}{R_s} \cdot \frac{1}{3}$$

$$P_L = \frac{1}{3} \frac{E_{cc}^2}{R_s}$$

Case 2:

By symmetry it can be seen that if the leakage resistance is uniformly distributed the voltage at the base plate will be equal to the voltage at the midpoint of the converter. Thus the base plate and converter could be shorted at this point with no effect, since there is no voltage difference. Thus the equation of Case 1 can be applied to each half of the converter of

Case 2. But the voltage for half the converter is $E_{cc}/2$, and the leakage resistance is $2R_s$. Thus for the total converter of Case 2:

$$P_L = 2 \cdot \frac{1}{3} \cdot \frac{(E_{cc}/2)^2}{2R_s} = \frac{1}{3} \cdot \frac{E_{cc}^2/4}{R_s}$$

$$P_L = \frac{1}{12} \cdot \frac{E_{cc}^2}{R_s}$$

Calculation of Leakage Resistance Required for Various Power Losses in TBC-1

At nominal 1035°C hot shoe temp:

$$E_{cc} = 25 \text{ V}$$

$$P = 126 \text{ Watts to Load}$$

$$9\% P = 11 \text{ Watts}$$

for 11 watts in Leakage Resistance:

Case 1 short at one end:

$$R_s = \frac{1}{3} \cdot \frac{E^2}{11W} = \frac{25^2}{3 \times 11} = 19 \text{ ohms}$$

Case 2 no point short:

$$R_s = \frac{1}{12} \cdot \frac{E^2}{11W} = \frac{25^2}{12 \times 11} = 4.8 \text{ ohms}$$