FSC-ESD-217/86/380
July 30, 1986

To: J.J. Lombardo, DOE

From: E.A. Skrabek, FI

Subject: Status Report on Multicouple Anomaly Investigation

This memo summarizes the work on the multicouple problem since the July 11 report:

1) The GE test stations failed on a loss of vacuum signal on July 12. No operating personnel were available to check it until July 15. At that time it was concluded that it failed due to high internal building temperatures not allowing the finned heat exchanges to operate properly.

The test has not been restarted while arguements over the next step have dragged on. We could have had well over three hundred more hours of test if it had been restarted while waiting for a decision to be reached.

2) The work on the destructive analysis of MC#116 is proceeding very slowly. The results of the work are very good and very useful, but because of writing plans and preparing briefings, Larry has not been able to spend sufficient time with the hardware.

The samples were back at GE from ORNL on June 26. Now, a month later, the major shorts in neither the "18 " slice nor the "800 " slice have been reached. The information obtained thus far has proven critical to our understanding of the problem, but the pace is much too slow.

3) The Fairchild module test was shut down on July 20 as a result of a severe thunderstorm that cut off power for over 13 hours. The back-up diesel generator system was apparently damaged by lightning strikes. The generator motor came on as expected, but no output voltage was obtained from the system. The UPS held everything for an hour and five minutes as the system cooled down to about 500°C hot junction temperatures. The negative bias was also maintained on the system until then.
The decision was made not to restart the test, but to make these multicouples available for destructive analysis at GE, and possibly Battelle and Ames.

4) Schock and I visited GE on July 22 to examine the x-ray pictures from ORNL and to look at the latest results of Larry's work. Indications are that all of the large pores are in the third glass layer between five couple slices and only the tiny (<0.3 mil diameter) pores are ever found in the other twolayers. The evidence so far also suggests that the large pores investigated to date have been coated with Ge, while most of the small pores show no evidence of Ge. This may mean that excess Ge from the incompletely reacted bond may be instrumental in causing the formation of the large pores during the manufacturing process.

We had asked GE to obtain a typical as-fabricated multicouple and section it to see if the large pore observations match those on #116.

Perimeter glass is extremely porous, worse than swiss cheese. The best description is "frothy". However, evidence to date does not indicated that the perimeter glass is involved in the shorting.

5) We pressed hard for an agreement to get the testing restarted as soon as possible, especially for MC#143. This multicouple, with the completely covered cold end and the Cu-free glass, has not shown the deep toggles after 1700 hours of testing. However, some small output voltage variations were observed for several hours about a week before the test shutdown. If I were running the test, I would have gotten the test back up to temperature the day after the system was checked out. MC#143 could have over 2,000 hours on it by now and we could possible have had an answer as to whether the earlier instabilities meant that toggling was about to start or not.

Since GE said they could get a new cold-glass multicouple ready in about two weeks, and since another multicouple will be available this week from the Fairchild tested module, we agreed that it is now best to wait for them before restarting the system. This means the system should be running again the week of August 4 and we should be able to pick up about 500 hours of new data before the first of the new fixes are ready to be tested. I don't think I am going to hold my breath, though.

6) At the end of the day we all got together for a review discussion and we agreed on a series of actions.

a) GE would pick-up the test module from FI on July 23.

b) MC#119 (FI-1), #115 (FI-2), #132 (FI-3), and #124 (FI-8) would be bisected and probed for resistance at the hot and cold ends.

c) MC#121 (FI-4) would replace #114 in the GE test fixture.

d) New cold end Cu-free glassed MC will replace TP-1 in the GE test fixture.

e) The fin on MC#120 will be modified to allow the heat collector to run 50 to 75^{o}C hotter.

f) The GE test will be restarted with the above changes.

g) MC#TP-1 will be sectioned and the hot and cold ends will be probed for resistance.

h) A typical as-fabricated MC will be selected by GE and sectioned at the hot end like MC#116. The mount will be sent to ORNL for x-ray studies to see if large pores can be detected in the as-fabricated condition.

i) Decisions as to who does what further destructive testing of the above samples will be made after we talk to Battelle, Ames and DOE.

7) Much of the last week was taken up with preparing the briefing to Wilcox.

8) We have asked Bob McClung to look at the possibility of using ultrasonics to probe for large pores at 30-40 mils from the hot-end in as-fabricated thermopiles prior to hot end glassing and installation of the heat receiver.

<u>Summary</u>

The results of the latest ORNL x-ray studies and the GE sequential lapping and ion microscopy work have greatly altered our perception of the shorting problem. It now appears that the primary shorting path is associated with large pores in the glass layer between five couple slices. Cracks, the perimeter glass, and bulk diffusion through the glass do not appear to be contributors.

It is possible that these large pores are formed during manufacturing. If so, they might be eliminated by process changes.

The work being done on the problem is of high quality, but it is still moving at a snail's pace. There is significantly more time and energy being spent on planning and scheduling than on solving the problem.

FSC-ESD-217/86/380 August 21, 1986

TO: Lombardo/Bennett, Wahlquist/Sholtis, Lanes/Murdoch

FROM: A. Schock

SUBJECT: Multicouple Anomaly Interpretation

Introduction and Summary

Following Joe Sholtis's suggestion that I discuss the above subject with Gerry Stapfer, because - as Joe put it - "you two speak the same language", we had an extended discussion on various aspects of the subject on July 31. We found that we do indeed speak the same language, in the sense that each of us can readily understand the other's arguments, but that does not mean that we necessarily agree with all of those arguments.

In fact, there appear to be some fundamental disagreements between the DOE project and JPL on the proper interpretation of the multicouple anomaly test results. We think that JPL's conclusions are not proven by the experimental observations, and are in fact contradicted by some of the test results. The principal purpose of this memo is to define these conflicting interpretations and to explain the basis for our position.

JPL's basic conclusions are that the anomalous shorts in the multicouples are caused primarily by whiskers at the thermopile's cold ends, at or near the output leads; that these whiskers are caused by the voltage bias between the multicouples and the converter housing (ground); and that it is not surprising that this whisker growth is polarity-dependent and occurs only in negatively biased multicouples and not in positively biased ones. JPL further concludes that the observed hot-end shorts are - at most - of secondary importance, and are insufficient to account for the observed drop in the multicouples' output voltage. At most, they will concede that the hot-end shorts are a second and independent failure mechanism, whose effect is small compared to that of the cold-end shorts.

By contrast, the project's conclusions (DOE's, GE's, FI's) are that the anomaly in multicouple #116, the only one examined in detail thus far, was caused primarily by internal hot-end shorts, through large germanium-coated bubbles in the 0.002"-thick glass separating the couples within the multicouple. It is believed that these large glass bubbles were formed during fabrication, that they became coated by hot-end germanium migration during the first few hundred hours of the test, and that this germanium migration was triggered through a still undefined mechanism by the negative voltage bias at the cold end. The cold end may be an important contributing factor, but was not in the direct shorting path. There is no evidence of cold-end whiskers, and the locations and resistances of the identified hot-end shorts are sufficient to account for the observed drops in output voltage. The basis for these conclusions is explained in detail in the discussion section of this memo.

Discussion

Before presenting the detailed reasons for our position, a brief review of the Mod-RTG program and of the multicouple anomaly observations is in order.

The modular RTG design was first proposed in 1981 [Ref. 1]. The original version of the design is shown in Figure 1. Except for its end sections, the RTG consists of identical modular slices. In addition to its modularity, the RTG design promises a substantially higher power-to-weight ratio and conversion efficiency than the RTGs recently built for the Galileo and Ulysses missions.

As shown in Figure 2, each modular slice consists of one General-Purpose Heat Source (GPHS) module surrounded by eight multicouples. Each slice is designed to produce approximately 20 watts at the full RTG output voltage of 28 volts.

Figure 1:
MODULAR RADIOISOTOPE THERMOELECTRIC GENERATOR
Illustrative 14-Slice Design

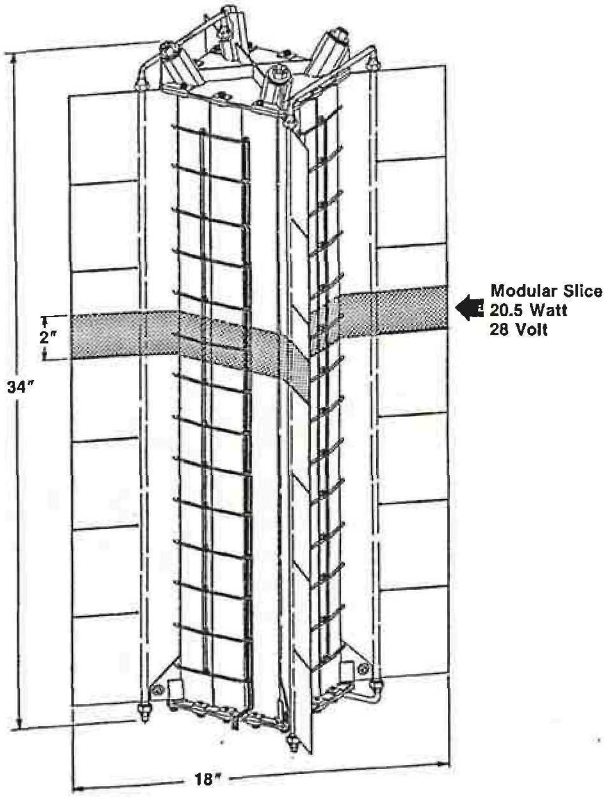
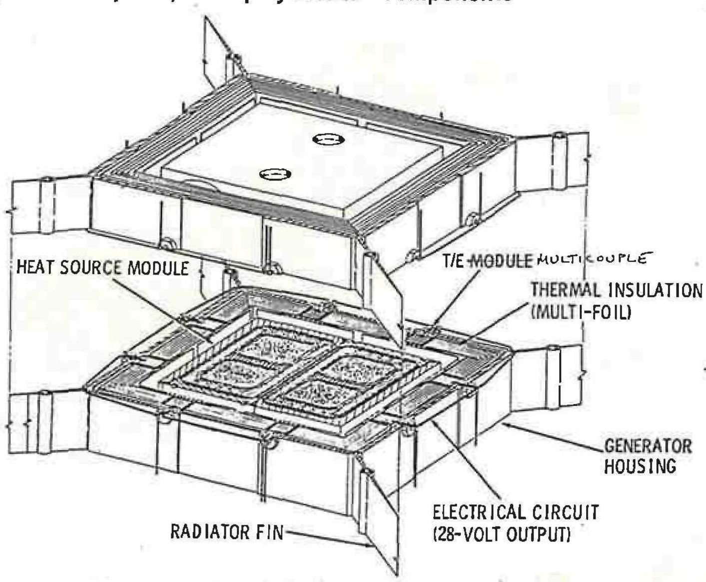


Figure 2:
TYPICAL GENERATOR SLICE (~20 watts at 28 volts)
Split at mid-plane, to display internal components



EXPLODED VIEW OF MULTICOUPLE (2.6 Watt, 3.5 Volt)

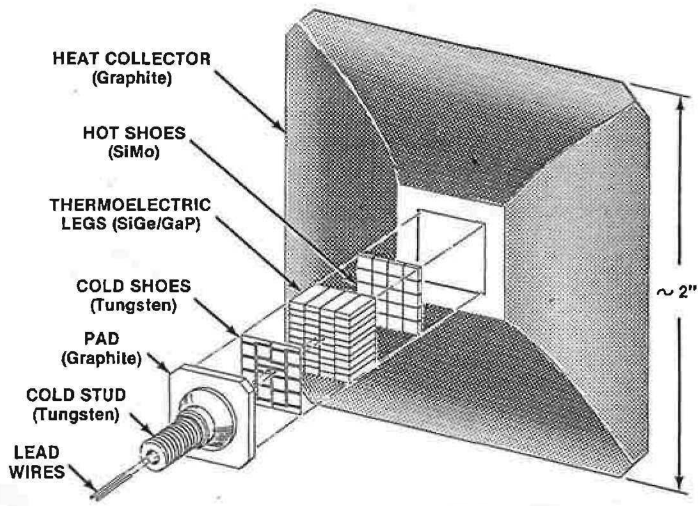


Figure 3 presents an exploded view of a typical multicouple, and Figure 4 depicts the fabrication sequence of the multicouple's thermopile assembly [2].

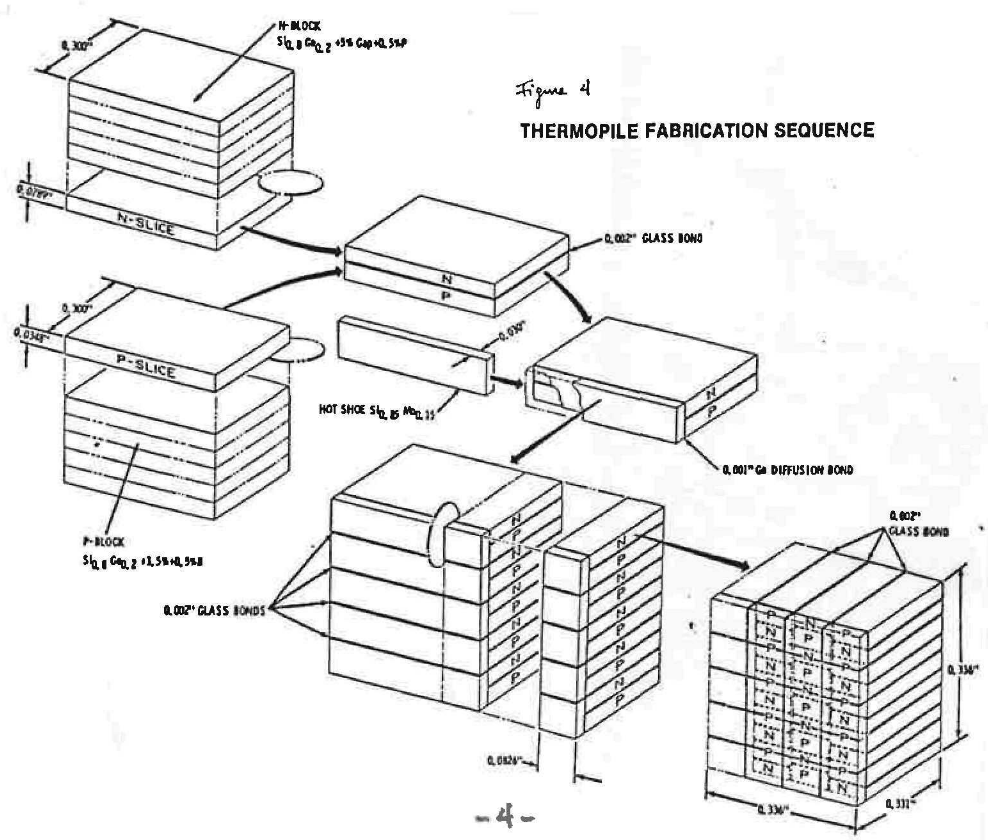


Figure 4

THERMOPILE FABRICATION SEQUENCE

Each multicouple contains 40 thermoelectric legs (20 n-legs and 20 p-legs), which are connected in series as shown by the number sequence in Figure 5. Note that the multicouple's terminals are at the center of the unit, and that the lead wires pass out through the center of its cold stud.

Figure 5:

THERMOPILE DESIGN
(Glass Coatings Omitted for Clarity)

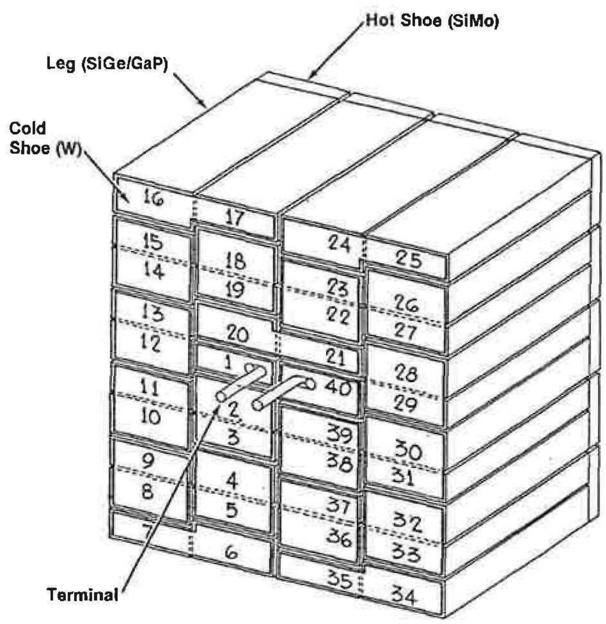
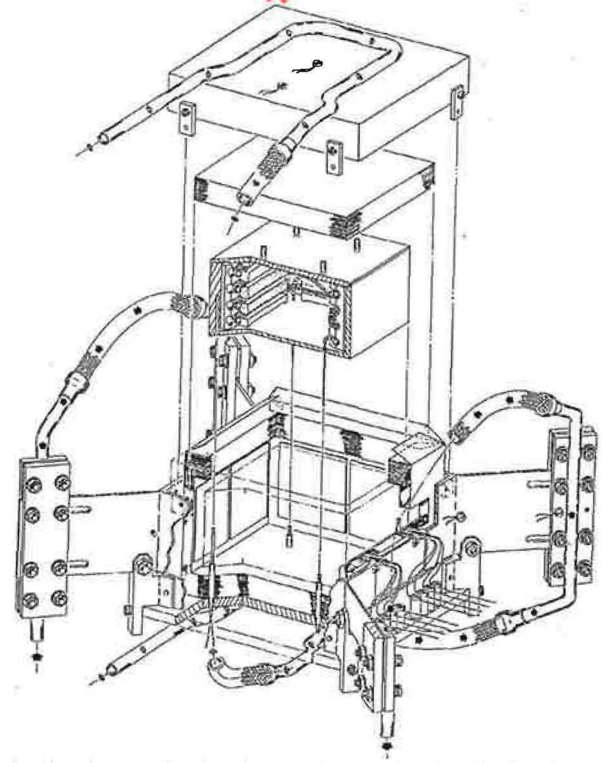


Figure 6:

EXPLODED VIEW OF MITG TEST ASSEMBLY



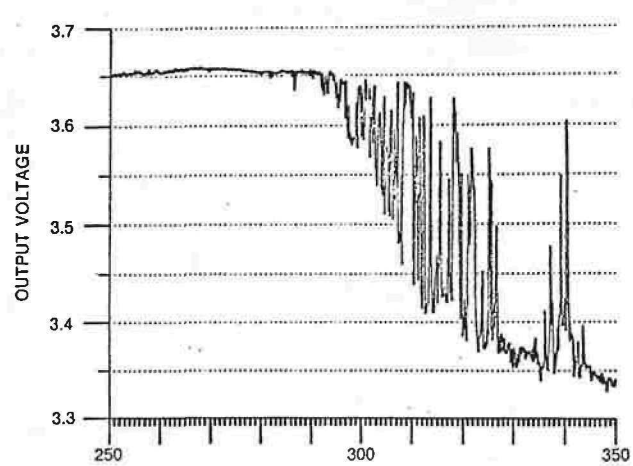
The latest RTG flight system design differs from the design depicted in Figures 1 and 2 in only minor respects (e.g., circular instead of square housing[3]). Figure 6 shows an exploded view of the modules tested at Fairchild(4). As can be seen, the test module contains eight multicouples, and closely simulates the geometry and dimensions of the modular RTG slice shown in Figure 2. The major difference is that the graphite heater block, which is identical in outer dimensions to the GPHS aeroshell, is heated by electrical heater coils instead of radioisotope fuel capsules.

The latest eight-multicouple test module was delivered by GE for performance and life tests at Fairchild in January 1986. Fairchild had performed similar tests on previous GE modules, and also on earlier Syncal and TECO modules [5]. The latest GE module used hybrid multicouples containing SiGe/GaP n-legs and SiGe p-legs. Its principal purpose was to demonstrate that earlier multicouple bond problems had been overcome, and the test did indeed show that to be the case. None of the module's multicouples exhibited any evidence of bond failures during Fairchild's 4300-hour test, although some bond failures at the heat collector occurred during the post-test disassembly.

However, a new type of anomalous behavior was observed during this test, in which the eight multicouples were initially connected in series and the series string was connected to a constant-voltage load. The anomaly fist manifested itself in multicouple #1, the most negative unit in the series string. As shown in Figure 7, its voltage output was stable during the first three hundred hours of operation, exhibiting only the expected very low rate of degradation attributable to normal dopant precipitation. After 300 hours, the multicouple went into a bistable operating mode, oscillating between normal and anomalously degraded performance, with extremely rapid transitions between the up-cycles and down-cycles.

Figure 7

INITIAL MANIFESTATION OF PERFORMANCE ANOMALY (MC #1)

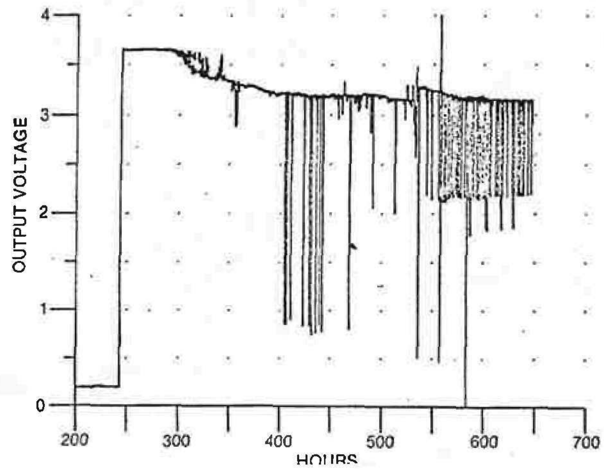


- Stable operation during first 300 hours
- Cycling between bi-stable modes during next 50 hours

The bistable behavior continued for about 50 hours, during which the down-cycles grew to be increasingly dominant until they became permanent. This is illustrated in Figure 8, which also shows that after 400 hours of operation new and much deeper down-cycles started to occur in multicouple #1. The most significant observation about these new down-cycles is that they do not appear to be random in magnitude. Instead, there was repeated cycling to a limited number of discrete voltage levels.

Figure 8

SUBSEQUENT BEHAVIOR OF MULTICOUPLE #1

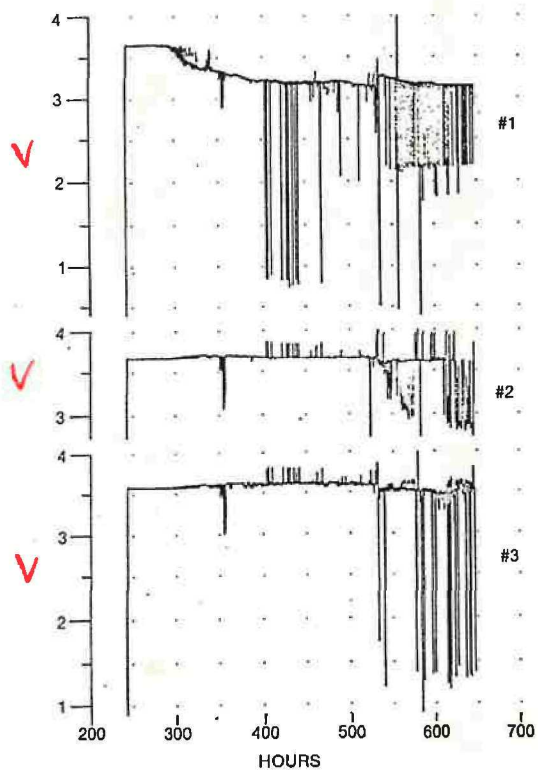


This is an important point, because it is one of the reasons for our disagreement with JPL's interpretation. In our July 31 discussion, Stapfer expressed the opinion that the multicouple's anomalous behavior was due to shorts through cold-end whiskers at or near the voltage leads, and that the observed variation in voltage output was due to random variation in whisker resistance.

It is Fairchild's view that the voltage levels displayed in Figure 8 are not random but discrete, and that these discrete levels are due to discrete locations of low-resistance shorts between adjacent legs or hot shoes within the multicouple. In other words, shorts occur at different times at different locations, and more than one short can co-exist within the same multicouple. This is corroborated by our repeated observation of abrupt transitions from one depressed voltage level to a different (higher or lower) depressed voltage level.

Initially, the anomalous behavior was only observed in multicouple #1, but after 500 hours of operation it also appeared in multicouple's 2 and 3. This is illustrated in Figure 9. At the same time, multicouples # 4 through 8 were still performing normally.

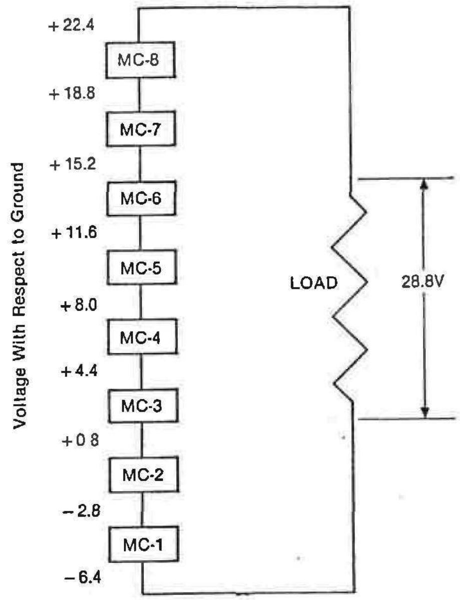
Figure 9:
PROGRESSIVE APPEARANCE OF ANOMALY IN MULTICOUPLES 1,2,3



Fairchild investigators concluded that the appearance of the anomaly in this precise sequence was unlikely to be a random coincidence, and started to look for a systematic cause. The only identifiable difference between the multicouples in the string was their voltage level. The series string had not been connected to the grounded converter housing, but was floating with respect to ground. Under these circumstances, the string seeks its own voltage level, with one end below ground and the other end above ground. The exact levels at which the string equilibrates are determined by a balance of very low leakage currents between the multicouples and ground. In the case of the subjecttest assembly, the eight multicouples initially equilibrated at the voltages displayed in Figure 10.

Figure 10

MEASURED VOLTAGES IN UNGROUNDED MULTICOUPLE CIRCUIT



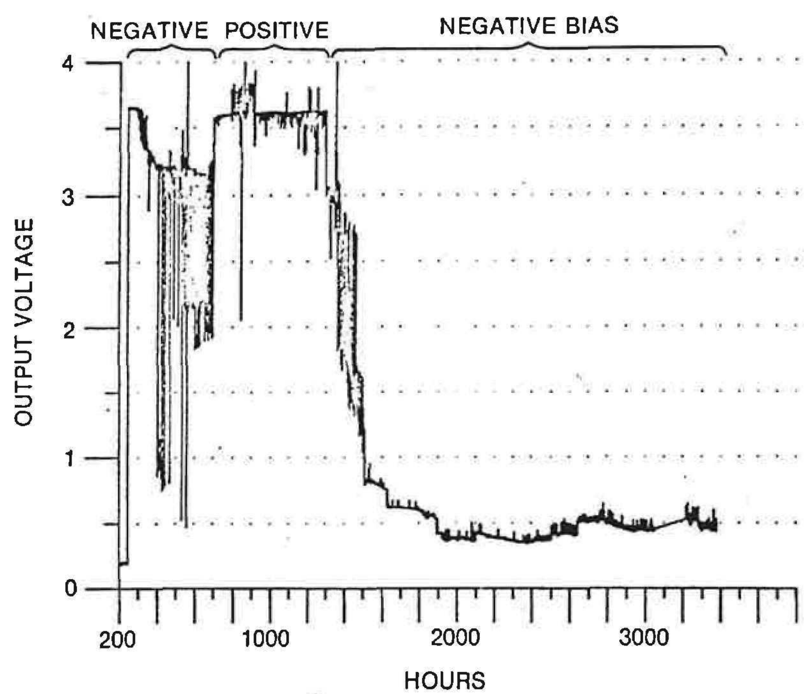
As can be seen, multicouple #1 was the most negative, and MCs 2 and 3 were also negative but less so. Fairchild investigators therefore hypothesized that the anomalous multicouple behavior was somehow caused by a negative potential with respect to ground. To check that hypothesis, a previously normal multicouple (#6) was disconnected form the series string. It was connected to its own constant-resistance load, and a negative bias of 14 volts with respect to ground was applied to it. Within a short time, it began to exhibit the same anomalous behavior previously observed in the multicouples at the negative end of the string. Thus, the anomalous behavior is not the result of interactions between the multicouples in the string, but is merely a function of the negative voltage bias. The results shown in Figure 9 also suggest that the greater the negative bias, the earlier the onset of the anomaly.

To extend the hypothesis, Fairchild took a previously failed multicouple (#2), and changed its bias from negative to positive by interchanging its circuit position with #7 in the series string. It was found that this resulted in the previously "sick" multicouple regaining its normal output within a period of a few minutes.

The deleterious effect of negative bias voltages and the curative effect of a positive bias was later reconfirmed by numerous other multicouple tests, both at Fairchild and at GE. These effects are illustrated by the test results on multicouple #1 presented in Figure 11. The figure shows the anomalous behavior with the initial negative bias, the performance recovery when the bias was changed to positive, and the reappearance of the anomaly when the bias was changed back to negative. It also shows that after extended operation with a negative bias, the cycling stops and the multicouple output settles to a steady "down" level.

Figure 11

EFFECT OF VOLTAGE BIAS ON PERFORMANCE OF MULTICOUPLE 1

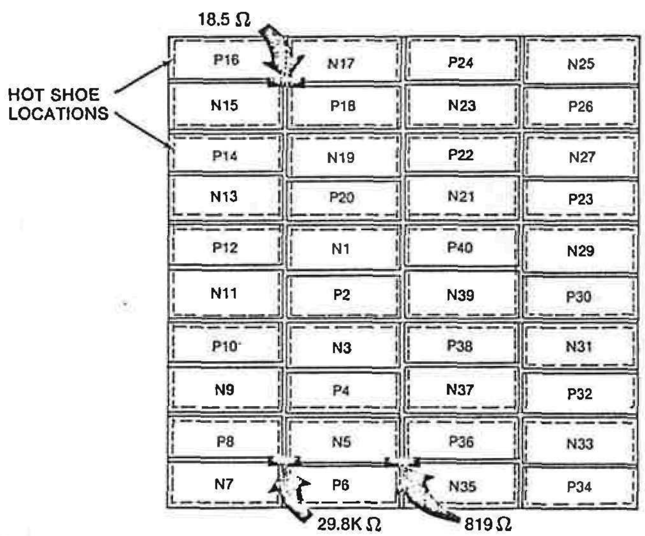


In studying the problem, GE personnel first conducted extensive tests at Fairchild to satisfy themselves that the observed problem was real and was not an artifact of Fairchild's test procedure. After they had done this, they were able to reproduce the same anomaly in tests at GE, using individual multicouples to which a negative voltage bias had been applied between the cold stud and the negative lead.

One of these multicouples (#116) was later taken off test for destructive diagnostics. It was first bisected midway between its hot and cold ends, and each half was probed to determine the room-temperature resistances between all adjacent legs. Contrary to the author's expectation, there were no significant shorts in the multicouple's cold half, but there were three low-resistance shorts in its hot end. The magnitude and location of those shorts is shown in Figure 12.

Figure 12

INITIAL BISECTION AND PROBING OF MULTICOUPLE 116 REVEALED THREE LOW-RESISTANCE SHORTS AT HOT END



Note: Resistances of shorts were measured at room temperature.
At operating temperatures, resistance drops to ~1 ohm.

The resistances shown are much too high to account for the observed drops in output voltage. However, these are room-temperature values. A separate hot test showed that the 819-ohm resistance dropped to about 1 ohm at operating temperature. This is low enough to account for the observed effects.

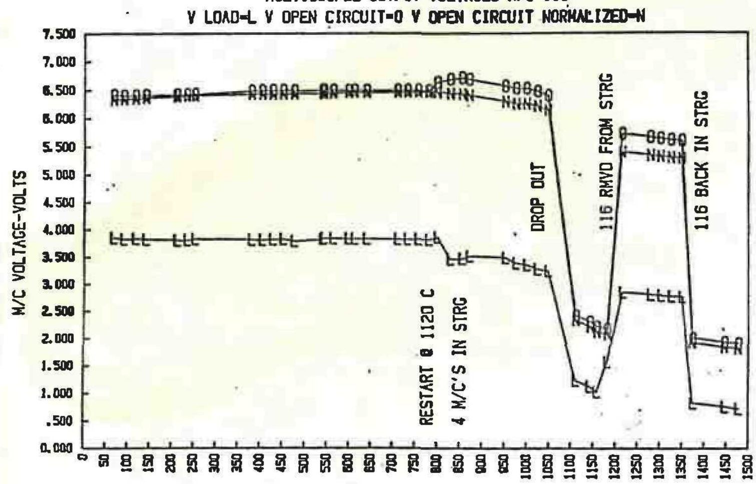
The latter conclusion was disputed by Stapfer in our talk on July 31. He stated that the identified short locations could not account for the lowest output voltages observed in the tests. To address this question, we must examine the detailed test data for the bisected multicouple (#116).

Stapfer also complained that GE had presented diagnostic results on one multicouple and test results from other multicouples, and that JPL was handicapped in not having access to all the relevant test information. He is correct that in applying diagnostic data to the interpretation of test results, one should deal with the same test unit. But the relevant test data are presented in GE's monthly reports on the "Modular RTG Program." Specifically, the performance data for multicouple #116 were presented in their Thirty-Second Technical Progress Report for May 1986, distributed on July 7, 1986. JPL is on the distribution list for those reports, with one copy to R. Campbell and one to R. Draper.

The salient test results for MC 116 are reproduced in Figure 13. MC 116 was part of a four-multicouple series string that was connected to a constant-resistance load and operated at a negative bias voltage with respect to ground. As can be seen, the anomalous behavior first appeared after 1050 hours of operation. After 1200 hours, its performance largely recovered when it was removed from the string and placed on positive bias. The anomaly reappeared after 1350 hours when it was again placed in the string with a negative bias.

Figure 13

MULTICOUPLE OUTPUT VOLTAGES M/C 116
V LOAD=L V OPEN CIRCUIT=O V OPEN CIRCUIT NORMALIZED=N

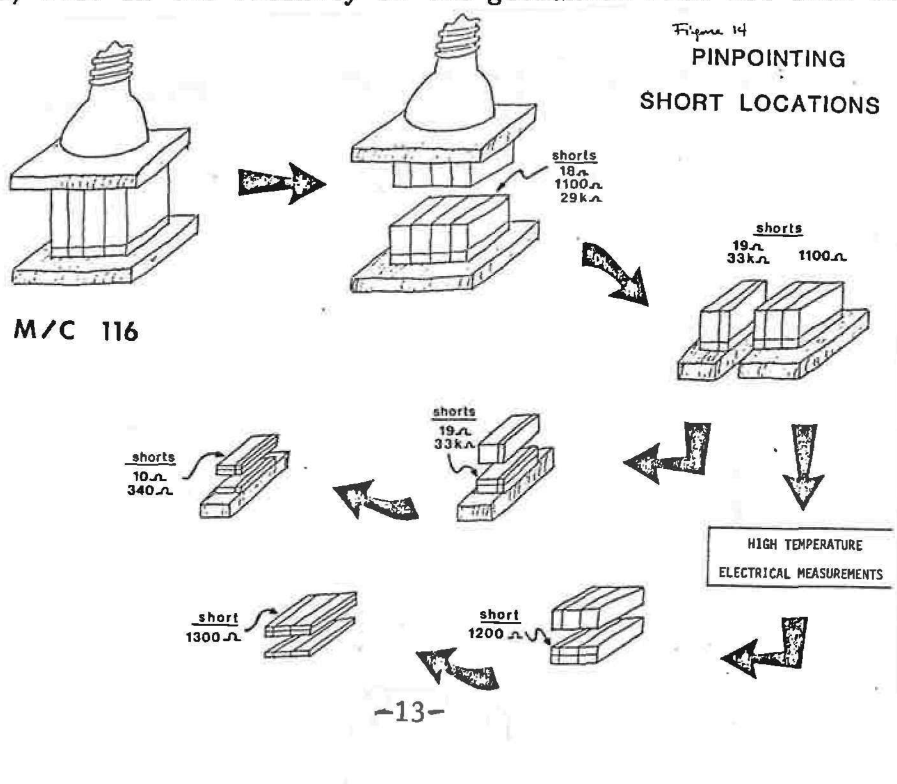


Quantitative interpretation of the load voltage curve (L) is somewhat complicated because there are three other multicouples undergoing their own fluctuations in series with MC 116. It is much easier to interpret the open-circuit voltage curves, since those are independent of what is happening in the other multicouples in the string. The open-circuit curve is marked O, and the normalized open-circuit curve is marked N. The latter curve is the most meaningful, because it includes corrections for departures of the hot and cold-junction temperatures from their normal values.

As shown, the normalized open-circuit voltage of MC 116 dropped from an initial value of 6.5 volts to an end-of-test value of 1.8 volts, a drop of 72%. As can be seen from Figure 12, the short between legs 5/6 and legs 35/36 effectively by-passes the output of thirty of the forty legs (i.e., legs 6 through 35). This should drop the open-circuit voltage by 75%. Thus, the identified short at that location is quite consistent with the observed loss in open-circuit voltage, and these test results do not support JPL's hypothesis about another (dominant) short at the cold end due to whisker growth.

After the general short location shown in Figure 12 had been identified, those locations were used by GE as a guide in carefully sectioning the hot-end half ot MC 116 to determine and isolate the exact short locations. The sectioning sequence used is depicted in Figure 14. Successive disections revealed that all three shorts were located at the hot end of the multicouple, at or near the interface between the legs and the hot shoes, i.e. in the vicinity of the germanium-rich hot shoe bond.

Figure 14



After enough of the unshorted regions were cut away, a .038"-thick shorted slice was left. ORNL succeeded in developing a technique for preparing radiographs of that slice which made it possible to identify the exact locations of pores in the glass layers between adjacent legs or hot shoes. In fact, the radiographic technique was sensitive enough to distinguish empty pores from pores containing a more opaque material.

Figure 15 shows the radiograph of the multicouple hot-end slice, with the three arrows indicating the locations of three opaque glass pores. Comparison with Figure 12 shows that these three locations are consistent with the three locations where shorts had previously been identified by electrical measurements. Enlarged radiographs of the three opaque pores are shown in Figure 16. The opaque pore between legs 5/6 and legs 35/36 clearly extends over the full thickness of the glass insulator, forming a bridge between those legs or their corresponding hot shoes.

Figure 15

RADIOGRAPH OF 1-mm SLICE OF MC-116 NEAR HOT END SHOWING LOCATIONS OF THREE SHORTS THROUGH GLASS

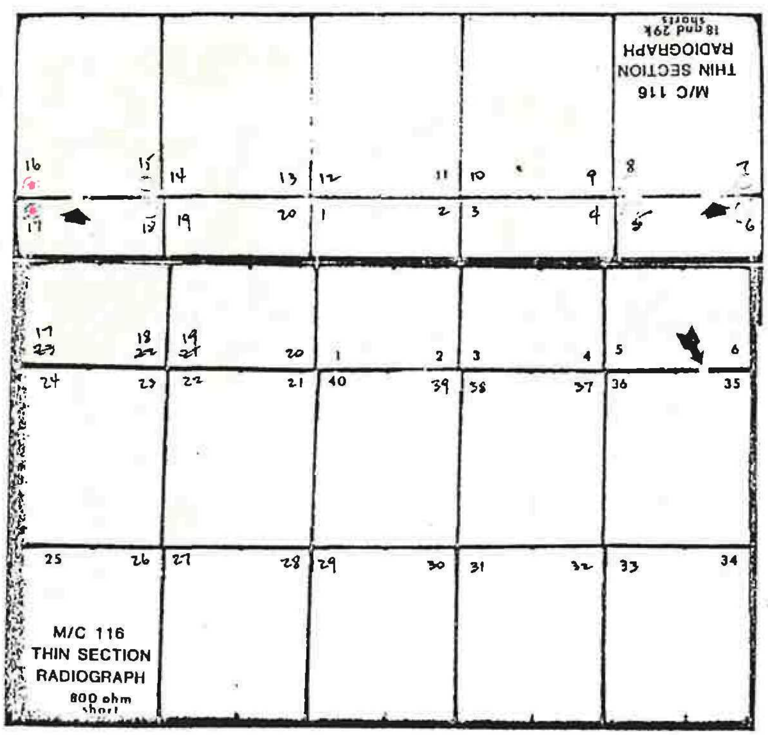


Figure 16

RADIOGRAPHIC CLOSE-UP OF THE THREE SHORTS IN MULTICOUPLE 116

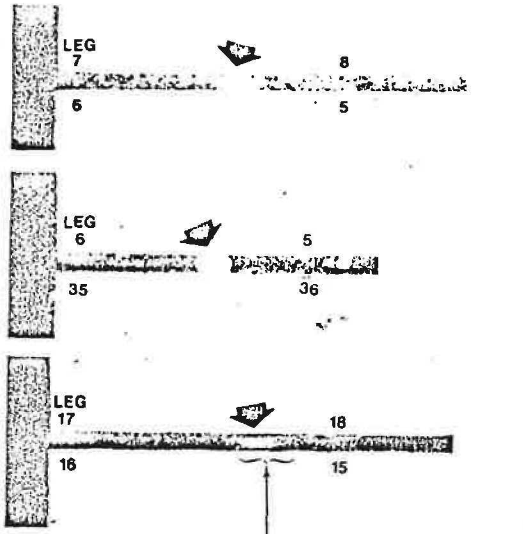
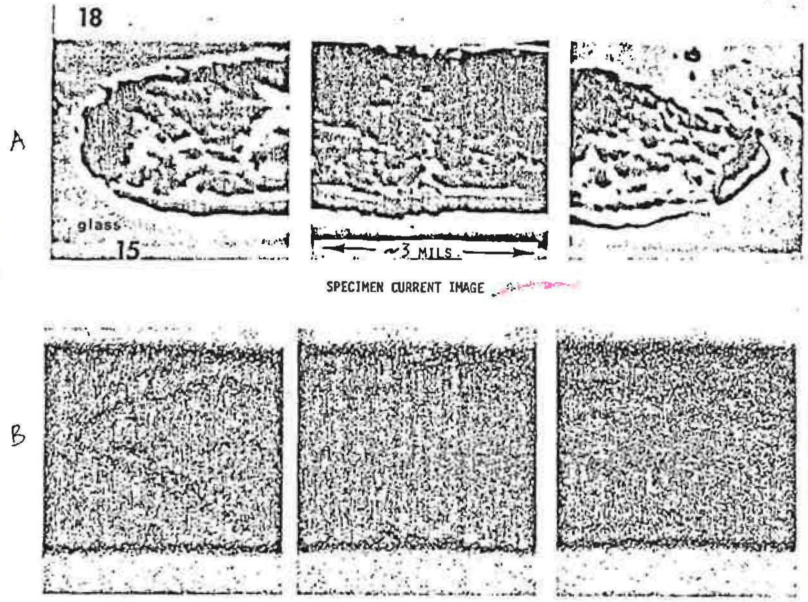


Figure 17: CLOSE-UP OF GLASS PORE BETWEEN LEGS 15 AND 18 OF MULTICOUPLE 116
PORE EXTENDS OVER FULL 2-MIL THICKNESS OF GLASS. ITS WALL IS COATED WITH GERMANIUM



Finally, Figure 17A shows an enlarged view of a cross-section cut through the pore between legs 15 and 18, and Figure 17B shows a germanium map of the same pore. The pore is about 8 mils long. As seen, at the depth of this cut it touches leg 18 and extends almost across the full 2-mil glass thickness. At a different depth it touched legs 15. Thus, the pore forms a bridge between the two legs.

Figure 17B shows that the center of the pore is empty, but its walls are coated with germanium. If this is metallic germanium, a pore of that size is more than sufficient to account for the observed low resistance (1 ohm) short. This was disputed by Stapfer during our July 31 discussion. He expressed the opinion that even if the pore were completely filled with solid germanium, its resistance would be more than 1 ohm. A subsequent check by us showed that a germanium conductor which is 2 mils long and 8 mils by 2 mils in cross-sectional area would have a resistance of only 0.07 ohm. In fact, a germanium thickness of only 0.1 mil on the walls of the pore would be sufficient to produce a 1-ohm short at operating temperature.

Thus, the hypothesis that the anomalous shorts are formed by germanium-coated pores extending over the full glass thickness is consistent with the diagnostic observations. Moreover, this hypothesis is also consistent with the delay of several hundred hours at temperature before the anomaly makes its appearance. Radiography of a separate as-fabricated thermopile (#159) showed the presence of numerous large pores at various locations in the glass, both in the hot-end and cold-end regions. This indicates that the glass pores are formed during fabrication, not during subsequent life testing. But these pores appear to be initially empty. It is surmised that several hundred hours at operating temperature are required for enough germanium to migrate into the hot-end pores to form a continuous path between adjacent legs or hot shoes.

Once a shorting path is formed, it carries current, which results in ohmic heating that raises its temperature until enough germanium has evaporated to break the shorting path. After some time, additional germanium migration starts the cycle all over again. The shorts are repeatedly made and broken, causing the cyclic behavior displayed in Figure 7. Theses cycles can occur independently at different locations in the multicouple, wherever large glass pores are present. This accounts for the repeated cycling to different specific voltage levels, as illustrated in Figure 8.

Finally, after prolonged operation, enough germanium has migrated into the pore so that evaporation due to ohmic heating can no longer break the short. After that, the affected multicouple operates in a steady "down" mode, as illustrated in Figure 11.

To confirm the above hypotheses, 1-mm thick slices are being cut from a number of additional multicouples for radiographic examination. First, a previously failed (negatively biased) multicouple (#1) was disected and probed, to determine whether its results duplicate those of MC116. It exhibited a large number (11) of low-resistance shorts at the hot end of the multicouple, and no shorts at the cold end. These results are completely consistent with those of MC116.

Next, it is planned to examine a multicouple that had always been operated with a positive bias and which had never failed, to check for the presence of germanium in its glass pores.

Finally, it is planned to examine a multicouple that had exhibited anomalous behavior for a long period while operating with a negative bias, which was subsequently "cured" by switching to a positive bias. This will be sectioned, radiographed, and checked for germanium in the glass pores.

When all these diagnostic tests are completed, the results should provide a much firmer understanding of the pore formation and germanium migration processes. However, even now enough information has been learned to define a logical program of corrective actions. The program, which is now under way, consists of several parallel approaches which are designed to reinforce each other.

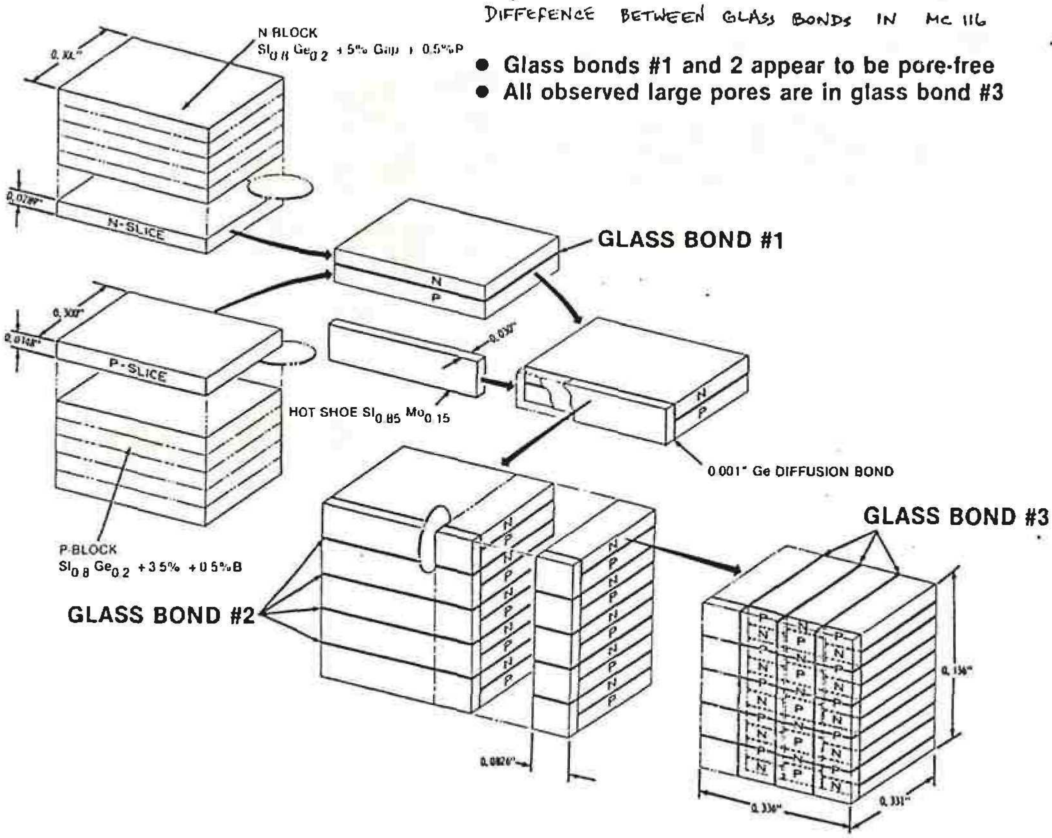
The first approach is to reduce the amount of free germanium in the multicouple, by modifying the method of bonding the SiMo hot shoes to the SiGe or SiGe/GaP legs. Previous multicouples had been bonded by means of a germanium braze, with the germanium applied in the form of an ink. This process resulted in excessive amounts of free germanium. To avoid this, alternative methods (e.g., sputtering) are under investigation. Leg-to-hot-shoe bonds with very much smaller amounts of free germanium have been made by GE.

The second corrective approach is to improve the glassing process to avoid the formation of large pores. This may be achievable through changes in the glass composition or frit size, through changes in the method of applying the glass coating to the surfaces to be bonded, through changes in the outgassing and oxidation of the surfaces to be bonded, or through changes in the process for melting and densifying the glass during fabrication (e.g., by applying higher pressures).

In this connection, a potentially important observation was made in examining multicouple #116. As shown in Figure 18, fabrication of the thermopile requires three successive glass bonds. The first glass bond joins the n- and p-leg of each couple. The second glass bond joins adjacent n-p sandwiches to form a five-couple assembly. After these five-couple assemblies are cross-cut, four cross-cut segments are joined together by the third glass bond. Examination of MC 116 showed that all three shorts had occurred in the third glass bonds. No shorts or pores were observed in any of the first or second glass bonds. Similar observations were made during disection and radiography of the as-fabricated thermopile (# 159). If this is confirmed on other multicouples, it may be an important hint on how to eliminate the large pores.

Figure 18:
DIFFERENCE BETWEEN GLASS BONDS IN MC 116

- Glass bonds #1 and 2 appear to be pore-free
- All observed large pores are in glass bond #3



The third corrective approach is to retard the migration of germanium into the glass pores by vapor depositing a thin ceramic coating onto the leg and hot shoe surfaces before they are glass bonded. Three coatings are under consideration: silicon nitride, silicon carbide, and silicon dioxide. The coatings will be applied by chemical vapor deposition. CVD silicon nitride coatings have been used in previous RTGs to retard silicon and germanium sublimation.

The fourth corrective approach is to eliminate or minimize the effect of the negative bias voltage. It appears that the negative bias promotes germanium migration into the glass pores, and that a positive bias reverses that process. Those effects on germanium migration are probably due to small leakage currents, although the exact mechanisms for this are not yet understood. Nevertheless, it appears desirable to try to eliminate leakage currents between the thermopile and the multicouple's cold stud. One approach for doing this is to improve the cold-end glass insulation.

The cold-end glass has a different composition (including copper oxide) and a lower melting point than the rest of the glass bonds. Moreover, in the multicouples discussed thus far, the cold end of the thermopile was only partially coated with glass. The tungsten cold shoes in the central region of the thermopile, near the terminal leads, were not coated with glass. To eliminate these potential defects, GE fabricated an additional multicouple (# 143) in which the entire cold end was covered with copper-free glass, and placed it on test with a negative voltage bias. The test was interrupted after 1700 hours of operation. At that time, the multicouple had not yet exhibited anomalous shorting. The test will be resumed shortly, to determine the continued effectiveness of these improvements.

Clearly, any one of the four corrective approaches discussed above may solve the multicouple anomaly problem by itself. Even if none of the four does so alone, there is an excellent chance that a combination of those approaches will solve the problem, or at least retard its onset sufficiently to meet the seven-year operational requirement.

Finally, I should mention one other reason why Fairchild disagrees with JPL's conclusion that the anomalous shorts are caused by whiskers that grow in response to a negative bias voltage between the thermopile's cold end (at or near the leads) and the multicouple's grounded cold stud. If that were true, then the short should be between the thermopile and ground. But no such short has ever been observed during any of the anomaly observations. The anomalous shorts were always within the thermopile, never between the thermopile and the grounded cold stud. Even during the anomalous cycling, whether the multicouple's voltage output was up or down (i.e. shorted), the isolation resistance between the thermopile and ground was never less that 50 kilo-ohms. This is many orders of magnitude higher than the short needed to produce the observed anomaly. Thus, the thermopile's continuous isolation from ground appears to contradict JPL's "whiskers" hypothesis.

Recapitulation

In our view, the test results on about a dozen multicouples, combined with the diagostic examination results on MC116 and the preliminary results on #1 and #159, indicate that:

- As-fabricated multicouples recently built by GE had many pores in the glass barriers between adjacent thermoelectric legs or hot shoes.

- Some of those pores are large enough to provide an open path between adjacent legs or hot shoes.

- After several hundred hours at operating temperatures, germanium from the hot shoe bonds or the thermoelectric legs migrates into the pores near the multicouple's hot end.

- For reasons not yet understood, the germanium migration only occurs when the thermopile has a negative bias with respect to the multicouple's cold stud, and is reversible by a positive bias.

- After sufficient germanium has deposited on the walls of a large hot-end pore, it forms a shorting path between the thermoelectric legs or hot shoes which it contacts.

- Such internal shorts effectively by-pass a number (sometimes all) of the 40 series-connected legs within the multicouple, reducing its open-circuit voltage and load voltage.

- Initially, such shorts are easily burned out by the shorting current, and are then re-formed by continuing germanium migration.

- The continual shorting and unshorting results in cyclic variation of the multicouple's voltage and power output.

- Shorts at two or more different locations can co-exist within the same multicouple.

- Since shorts can come and go at several locations, the multicouple's output cycles to different but discrete voltage levels.

- After extended operation, so much germanium has migrated into the pores that the shorting current can no longer burn out the shorts. After that, the multicouple operates in a steady down-mode.

- The locations and magnitudes of the identified shorts are sufficient to account for the observed open-circuit voltage loss.

- After extended operation in a degraded mode, multicouples 116 and 1 showed no evidence of cold-end whiskers.

- Whisker growth induced by a voltage bias between the thermopile and the cold stud would be expected to result in shorts between those components. No such shorts were observed in any of the tested multicouples.

- There is a high probability that the anomaly can be avoided by a combination of:

  - minimizing the formation of large glass pores, by improvements in materials, surface preparation, and/or bonding conditions,

  - reducing the amount of free germanium at the hot-shoe bond,

  - applying a ceramic diffusion barrier to the thermoelectric leg and hot-shoe surfaces to be glass bonded, and

  - improving the electric insulation of the cold end of the thermopile.

In conclusion, it may be of some interest to note that before the destructive tests were carried out, I -- like JPL -- had also been convinced that the problem was at the cold end, and even submitted a memo detailing my reasons for that conviction. But subsequent test results demonstrated rather convincingly that the shorts are at the hot end. One cannot stick one's head in the sand and reject test data because they do not conform to preconceived conclusions. After all, If it looks like a duck, walks like a duck, quacks like a duck, and is frequently seen in the company of other ducks, it very probably is a duck.

A. Schock

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