27
6/15/77
2508-NTIS
MLM-2417

MLM-2417

**A Study of the Unusual Failure
of Milliwatt Generator
Strength Members**

Ronald E. Zielinski, Edsol Stacy

and Clyde E. Burgan

May 16, 1977

Monsanto

MOUND LABORATORY

Miamisburg, Ohio
operated by

MONSANTO RESEARCH CORPORATION

a subsidiary of Monsanto Company

for the

**UNITED STATES ENERGY RESEARCH
AND DEVELOPMENT ADMINISTRATION**

U. S. Government Contract No. EY-76-C-04-0053

MASTER

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, 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.

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.

A Study of the Unusual Failure of Milliwatt Generator Strength Members

Ronald E. Zielinski, Edsol Stacy and Clyde E. Burgan

Issued: May 16, 1977

PRINTED IN THE UNITED STATES OF AMERICA

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22161
Price Printed Copy \$3 50, Microfiche \$3 00

NOTICE
This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, 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.

MONSANTO RESEARCH CORPORATION

A Subsidiary of Monsanto Company

MOUND LABORATORY

Miamisburg, Ohio 45342
operated for

**UNITED STATES ENERGY RESEARCH
AND DEVELOPMENT ADMINISTRATION**

U. S. Government Contract No. EY-76-C-04-0053

ENTER

Abstract

In order to qualify Milliwatt Generator heat sources for an extended design life, multi-axial mechanical tests were performed on the strength member components. The results of these tests indicated that failure occurred predominantly in the middle of the weld ramp-down (down-slope) zone.

Examination of the failure zone by standard metallographic techniques failed to indicate the cause of failure. A modified technique utilizing chemical etching, scanning electron microscopy, and energy dispersive x-ray analysis was employed and dramatically indicated the true cause of failure, viz., inclusions in the parent material which were precipitated along the welds.

As a result of the initial investigation, weld parameters for the heat sources were altered and preliminary tests on sample welds suggested that pulse-arc welding can eliminate this type of failure.

Introduction

THE FUELED HEAT SOURCE

The milliwatt generator (MWG) is a radio-isotopic thermal generator designed as a long-term, reliable source of low-wattage power. Thermal energy generated by the alpha (α) decay of a radioisotopic fuel is converted to electrical energy by thermoelectric conversion. Containment of the radioisotopic fuel, $^{238}\text{PuO}_2$, is the major safety factor associated with the use of the MWG. This containment is achieved by encapsulating the fuel in an assembly consisting of three separately welded components. The final product is called a fueled heat source. A cutaway view of the fueled heat source is shown in Figure 1. Figure 2 illustrates the components of the fueled heat source, while Figure 3 shows the actual heat source hardware. The liner and strength member components are fabricated from T-111 (Ta-8W-2Hf) and the clad components are fabricated from Hastelloy C (Ni-16Cr-16Mo-5Fe-4W).

The strength member is the main structural component of the fueled heat source and all safety analyses performed to qualify the heat source system call for the strength member to remain intact. Throughout the design life, helium is being generated by the α decay of the $^{238}\text{PuO}_2$ fuel. The helium gas remains in the closed volume of the strength member, since it is assumed that the inner liner may be compromised sometime during the lifetime of the heat source. The following incident is postulated for the end of the design life of the heat source: the heat source could be exposed to an elevated temperature (1273 K) for one hour, during which time, the pressure within the strength member could increase to 37.92 MPa. The strength member would have to remain integral during this period.

MULTI-AXIAL MECHANICAL TESTING

To demonstrate this integrity, a multi-axial mechanical test is performed on typical strength members. The test specimen (Figure 4) is filled with a known volume of helium through the high pressure tantalum tubing. After the capsule is filled with helium, the fill tube is crimped and welded closed. The crimp fixtures on the tubing not only aid in

making the closure weld, but they also prevent closure weld failure during the test.

After the fill tube is sealed, the test specimen is heated in the vacuum furnace following a heat-up curve that raises the sample temperature from 573 to 1273 K in 270 sec. This produces internal pressure in the test capsule in excess of 41.37 MPa. The furnace pressure is maintained at $1-2 \times 10^{-6}$ torr and the strength member remains on test until failure. Once the strength member is at test temperature, the helium atmosphere inside the vacuum furnace is monitored by means of a helium leak detector. During the test, the helium leak rate is normally 2×10^{-8} scc/sec, scc being a standard cubic centimeter (cc of volume at 1 atm pressure). When this leak rate is in excess of 2×10^{-6} scc/sec, the test specimen is considered a failure and an alarm circuit is activated which stops a test clock and turns off the furnace power.

Although most of the test specimens failed above what would be considered design minimum, the failure zone was rather peculiar. Rather than fail by a random creep failure at the interface of the weld and body heat-affected zone (HAZ), a typical failure for this design, most capsules failed by means of a "blow hole" occurring in the ramp-down (down-slope) zone of the weld bead. The ramp-down zone is the weld area where penetration decreases as the power is reduced. Because of this unusual failure, a study was initiated to try to pinpoint the cause of the "blow hole" failure.

Post-Test Examination

METALLOGRAPHY

Upon completion of the multi-axial mechanical test, the failure zone was located. In all strength members which did not fail in the fill tube region or by separation of cap and body, the failure was primarily a "blow hole" which occurred in the weld ramp-down area. Once the failure zone was identified, the strength member cap was sectioned so that the interface between weld and body heat-affected zone (HAZ) was preserved. Visual examination of the interior surface of the failed specimens indicated that a circumferential crack was present at the weld and HAZ interface on the body side of the strength member. The crack was present in all specimens that had been heated to test temperature and it was demonstrated that this crack occurs during the heat-up to test temperature.

Once the strength members were sectioned and visually examined, they were mounted for metallographic examination. Some of the samples were mounted perpendicular to the weld bead and others, parallel. The mounted specimens were ground toward the point of failure. At various times during this procedure, the samples were examined in both the as-polished and the etched conditions. While this study showed the extent of the circumferential crack (Figure 5) and crack paths through the weld (Figure 6), it did not provide any data which would explain why the failure occurred in approximately the same zone in each tested specimen.

SCANNING ELECTRON MICROSCOPY

As the next step in the evaluation process, the scanning electron microscope (SEM) was employed. Using this instrument, it was possible to confirm the "blow hole" fracture zone (Figure 7) as well as identify the cause of the peculiar type of failure. Examination of the as-tested specimens using the SEM was helpful in pinpointing the exact point of failure. In addition, through use of the energy dispersive X-ray (EDX) system which is ancillary to the SEM, high concentrations of iron were detected in the "blow hole" regions.

In an attempt to identify the source of the iron signal, it was decided to chemically etch the as-tested specimens and examine them after various lengths of time in the etchant bath. This identification technique had been successfully applied to inclusions in the as-received T-111 sheet metal. The etchant consisted of 70% HNO₃ and 30% HF by volume. Using this solution, material was removed at the rate of 0.15 to 0.20 mm per min. The first specimen placed in the solution underwent a violent localized etching in the failure zone and at several isolated areas in the body HAZ.

SEM examination of this specimen after the initial etch showed that a foreign material was concentrated in the ramp-down zone of the weld (Figures 8, 9, and 10). This material was also present in isolated locations in the body HAZ (Figure 11). In fact, in every area that had etched violently, a concentration of foreign material was found beneath the surface. Since it was spherical in shape, this material had evidently been molten, presumably during the weld operation. The only location of the impurity in the weld was the ramp-down zone, where it extended through the cross section as is shown in Figure 12. EDX analysis indicated that

the material consisted of iron, silicon, tantalum, and some minor constituents.

Examination of other strength members that failed in the same manner indicated similar results. An impurity concentration was observed in the ramp-down zone of each strength member examined. The shape of the inclusions varied somewhat from capsule to capsule (Figures 13, 14, 15, and 16), but the elemental composition remained essentially the same with iron and silicon as the major constituents, while trace amounts of molybdenum, copper, and zinc were also detected.

Discussion

Localized concentrations of impurities cannot be detected using standard ultrasonic inspection techniques on the T-111 sheet material. As previously stated, however, it was possible to prove the existence of these concentrations as inclusions by chemically etching random samples of the sheet material and examining these samples at various steps during the etching process.

This type of analysis indicated that there were three basic types of inclusions present in the sheet material (Figures 17, 18, and 19). The inclusions of the type observed in Figure 17 were primarily iron and silicon; those observed in Figures 18 and 19 consisted of silicon, iron, molybdenum, copper, zinc, and potassium. The difference between the inclusions observed in Figures 18 and 19 was their orientation with respect to the rolling direction. The inclusion in Figure 18 was parallel to the rolling direction, while the one in Figure 19 was perpendicular. The inclusion observed in Figure 19 extended approximately 0.25 mm into the sheet material.

The distribution of these inclusions was quite random with only the iron-silicon type (shown in Figure 17) found in clusters. The adverse effects of their presence both on the hardware forming operation and on the mechanical integrity of the strength member bodies have been established. Figures 20, 21, and 22 show areas of strength member bodies that ruptured during forming and in each rupture the presence of an inclusion just below the surface was noted. In strength member bodies that failed in the body sidewall during testing (Figure 23), the presence of included material was also observed (Figure 24).

Knowing that the inclusions were randomly dispersed throughout the starting

sheet material and knowing the composition of the inclusions found in the welded capsule, it was possible to postulate the following as the mechanism by which included material became concentrated in the ramp-down area of the strength member assemblies: A continuous radial gas-tungsten arc weld had been used to attach the end cap to the strength member body. During the weld cycle, the molten "weld puddle" had picked up all the inclusions in its path. These impurities were transported radially around the weld bead. In the ramp-down zone, the impurities precipitated out as a concentrated mass. From capsule to capsule, this mass varied in size, physical appearance, and composition. These variables depended upon the number and type of inclusions which were originally present in the weld zone of each capsule. However, the effect on the mechanical integrity of the strength member was the same.

After the initial circumferential crack was formed at the interface of the weld and body HAZ at the outset of the test, several crack paths were initiated and as soon as one reached the included zone, it progressed rapidly through the zone and resulted in a linear crack path through the weld. This path terminated in "blow hole" failure on the outside of the weld bead.

Since a similar type of "blow hole" failure had been observed earlier in 16-year design capsules, several of these were examined in the same manner. The 16-year capsule design had a thinner strength member cap, and presumably a different type of failure mechanism. The examination of these capsules, however, showed that included material was also concentrated in the ramp-down zone (Figures 25 and 26). Thus, these capsules probably failed by the same mechanism.

Pulse-Arc Welding

To prevent "blow hole" failures from occurring in the future and, as a result, possibly increase the life of the strength member, the effectiveness of a pulse-arc welding technique for the closure weld is being studied. The technique pulses the weld arc through a programmed current range at the rate of two pulses every second. The pulsing should prevent the accumulation of included material in the weld ramp-down zone and should minimize the heat-affected zone.

While no pulse-arc welded strength member specimens have, as yet, been tested, several sample welds have been made and

examined. SEM examination of the weld zones showed that the included material was randomly dispersed throughout the weld bead and not concentrated in the ramp-down area. The interior surface of a typical pulse-arc weld bead can be seen in Figure 27. Included material was frozen to the bead. Approximately 0.18 mm into the weld bead, inclusions were randomly dispersed (Figure 28) as they were in the starting material. In fact, several of the inclusions seemed to have suffered very little effect from the welding process (Figures 29 and 30). Thus, from the standpoint of preventing a buildup of impurity material in the weld ramp-down zone, the pulse-arc weld seems to be successful. Also, it provides a more uniform weld bead on the interior of the capsule and a smaller, less pronounced heat-affected zone. This should result in a strength member that is structurally stronger than those previously tested.

Along with the good features, however, some possibly detrimental effects have been observed. In the pulse-arc welded capsules, the initiation of the weld ramp-down zone is physically more apparent (Figure 31). Another adverse consequence might be porosity, since the pulse-arc welded material appears to have more isolated gas bubbles in the weld zone. The third effect, which is rather isolated having been observed only twice in the same weld, is a dendritic structure (Figure 32 and 33) found at the center of the weld structure. This zone is exposed to the highest temperature during welding. It is quite possible that some unusual inclusions were present in the two areas and the resulting heat input caused the formation of the dendritic structure. This effect was quite isolated in that it was found in only one sample, and in only two widely separated areas of that sample.

It is impossible to assess the effects of these unusual features at the present time. However, the first series of pulse-arc welded strength member samples will be thoroughly evaluated after testing to assess whether these features, or any other peculiar to the welding process, adversely affect the mechanical integrity of the strength member bodies.

Conclusions

This study has shown that inclusions present in the parent material were carried along in the weld puddle during normal gas-tungsten arc welding and precipitated out during weld ramp-down. This concentration of impurities provided

an easy path for crack growth that resulted in "blow-hole" failures of strength member capsules being tested under multi-axial test conditions.

In an attempt to eliminate the concentration of impurities in the ramp-down zone, a study involving the use of pulse-arc welding has been initiated. An examination of the weld development capsules indicates that the impurity concentration has been eliminated, the interior weld bead is more uniform, and the heat-affected zone is smaller and less dis-

tinct. These features should be beneficial to maintaining the integrity of the strength member.

Some unusual features which appear to be characteristic of the material and the new welding technique have also been observed. Whether these features will have any deleterious effect on the integrity of the strength member cannot be determined until multi-axial mechanical tests are performed on pulse-arc welded strength member capsules.

FIGURE 1 - This cutaway view shows the fueled heat source.

FIGURE 2 - The heat source consists of three individually welded components. The strength member is the structural component.

FIGURE 3 - The actual heat source hardware is simple in design and small in size.

FIGURE 4 - A fill tube is welded to the strength member cap; crimp fixtures prevent failure during test.

FIGURE 5 - A circumferential crack occurred in the body heat-affected zone when the capsule was heated to test temperature.

FIGURE 6 - After the initial circumferential crack was formed, radial cracks propagated through the weld and body heat-affected zone.

FIGURE 7 - Helium lost through these "blow holes" in the center of the weld ramp-down zone caused failure.

FIGURE 8 - Concentration of inclusions in the weld ramp-down zone provided path for a linear crack.

FIGURE 9 - Included material present in the weld ramp-down zone was molten during welding, spherical upon solidifying.

FIGURE 10 - The primary constituents of these inclusions were determined to be iron and silicon.

FIGURE 11 - This included material, found in the body heat-affected zone, had also been molten at one time.

FIGURE 12 - Inclusions, found just beneath the surface of the weld bead, extended through the cross section of the ramp-down zone.

FIGURE 13 - Included material, slightly different in composition from Figure 8, assumed a different shape also in the weld ramp-down zone.

FIGURE 14 - Material of a third composition assumed a shape completely different from those in Figures 8 and 13.

FIGURE 15 - Included material from another weld ramp-down zone appeared similar to that in Figure 13 and had the same composition.

FIGURE 16 - Included material from another weld ramp-down zone had a different appearance and composition.

FIGURE 17 - Included material consisting of only iron and silicon was found in clusters in the starting sheet material.

FIGURE 18 - Elongated inclusions lying parallel to the rolling direction were found in the starting sheet material.

FIGURE 19 - Inclusions located perpendicular to the rolling direction extended ~0.25 mm into the starting sheet material.

FIGURE 20 - Cracks occurred in the side-walls of some strength member bodies and contained included material just beneath the surface.

FIGURE 21 - Cracks in the as-fabricated parts took on various shapes, dependent upon the inclusions associated with them.

FIGURE 22 - The direction of the inclusions in the parent material also affected the nature of the subsequent crack.

FIGURE 23 - The sidewall failure in this capsule was a linear crack located longitudinally on the interior side of the body.

FIGURE 24 - Upon closer examination, the crack shown in Figure 23 was found to contain included material.

Figure 25A

Figure 25B

FIGURE 25 - The 16-year design capsules which failed by a "blow hole" were also examined using the SEM. Included material (see A at left) was also found in the weld ramp-down zone of these capsules. The nature of the included material is more accurately shown by the photomicrograph in the γ' mode (see B at right).

FIGURE 26 - As in the 25-year design capsules, the inclusions in the weld ramp-down zone varied in composition and shape.

FIGURE 27 - Pulse-arc welding of the strength members resulted in freezing some of the included material on the weld bead surface.

FIGURE 28 - Approximately 0.18 mm into the pulse-arc bead, the included material is still randomly dispersed.

FIGURE 29 - Included material in the interior of the pulse-arc weld bead retained an elongated shape as in the starting material.

FIGURE 30 - Original inclusions underwent minor alterations, including break-up, as a result of the welding operation.

Figure 31A

Figure 31B

FIGURE 31 - In the pulse-arc weld, the area where the beam loses its full penetration is very apparent (see A at left). This area appears physically different from the rest of the weld bead (see B at right).

FIGURE 32 - Midway into one weld bead, a dendritic structure was found. Some of the isolated porosity is also visible.

FIGURE 33 - This dendritic structure is well defined. A similar structure was found $\sim 70^\circ$ away. No others were found in example welds.

DISTRIBUTION

EXTERNAL

Technical Report Library, Monsanto, St. Louis
TIC, Oak Ridge (27)
J. A. Chacon, DAO
R. K. Flitcraft, MRC
G. R. Gartrell, DAO

SLA

W. R. Abel
R. T. Jankowski
G. J. Jones
M. K. Parsons
P. Syroid
T. J. Young

GEND/Pinellas

J. F. Mevers

INTERNAL

W. R. Amos
C. O. Brewer
C. E. Burgan
W. T. Cave
C. W. Huntington
E. W. Johnson
L. V. Jones
D. P. Kelly
J. R. McClain
E. Stacy
R. E. Zielinski

Document Control
Library (15)
Publications (15)