LA--11220-PR

DE88 011261

Milliwatt Generator Project

April 1983-March 1984

G. H. Rinehart

T. W. Latimer

Contributors

C. E. Frantz

C. C. Land

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.

MASTER

EB

ABBREVIATIONS

ALO	Albuquerque Operations Office
LANL	Los Alamos National Laboratory
MF	Mound Facility
MST	Materials Science and Technology
MWG	Milliwatt Generator
QA	Quality Assurance
RTG	Radioisotopic Thermoelectric Generator
SNLA	Sandia National Laboratories, Albuquerque
SRP	Savannah River Plant
VHN	Vickers Hardness Number

CONTENTS

ABSTRACT.	1
I. INTRODUCTION	1
II. FUEL PROCESSING AND CHARACTERIZATION.	1
A. Processing.	1
B. Characterization	2
1. Neutron Emission Data	2
2. Spectrochemical Data	2
3. Isotopic Data	3
III. PRODUCTION OF HEAT SOURCES.	3
IV. PRESSURE-BURST TEST UNITS.	5
V. COMPATIBILITY STUDIES	6
VI. IMPACT TESTING.	10
VII. SURVEILLANCE UNITS	13
A. Impact Tests	13
B. Metallography.	16
C. Oxygen Analyses and Microhardness Measurements of Liners	19
D. Fines Analysis	22
VIII. INCONEL WELD DEVELOPMENT.	23
IX. QUALITY ASSURANCE	24
REFERENCES	24

MILLIWATT GENERATOR PROJECT

April 1983-March 1984

by

G. H. Rinehart and T. W. Latimer

Contributors

C. E. Frantz and C. C. Land

ABSTRACT

This report covers progress on the Milliwatt Generator Project during April 1983-March 1984. Activities included fuel processing and characterization, production of heat sources, fabrication of pressure-burst test units, compatibility studies, impact testing, examination of surveillance units, Inconel weld development, and quality assurance.

I. INTRODUCTION

The major task of the Los Alamos Milliwatt Generator Project is to fabricate MC2893A heat sources (4.0 W) for MC2730A radioisotopic thermoelectric generators and MC3599 heat sources (4.5 W) for MC3500 RTGs. The MWG Project interfaces with the following contractors: Sandia National Laboratories, Albuquerque (designer); E. I. duPont de Nemours and Company, Savannah River Plant (fuel); Monsanto Research Corporation, Mound Facility (metal hardware); and General Electric Company, Neutron Devices Department (RTG). In addition to MWG fabrication activities, Los Alamos is involved in (1) fabrication of pressure-burst test units, (2) compatibility testing and evaluation, (3) examination of surveillance units, and (4) impact testing and examination of compatibility and surveillance units.

II. FUEL PROCESSING AND CHARACTERIZATION

A. Processing

During the past year, 28 lots (6.455 kg) of SRP feed powder were processed through the MWG fuel fabrication line to obtain 5.790 kg of fuel granules.

B. Characterization

1. **Neutron Emission Data.** Data on neutron emission rates for the feed lots are presented in Table I. The as-received SRP feed powder had an average neutron emission rate of $18\,200 \pm 700$ n/s · g ^{238}Pu . After ^{16}O exchange and other processing, the average neutron emission rate of fueled heat sources fabricated from these feed lots was $4\,510 \pm 330$ n/s · g ^{238}Pu .

2. **Spectrochemical Data.** Table II compares the average impurity levels determined by spectrochemical analyses for the as-received SRP feed lots with the impurity levels in the fuel after processing at Los Alamos. The data indicate that fuel processing reduces the calcium

TABLE I. Neutron-Emission Rate Data for Feed Lots

Lot Numbers			Neutron Emission Rate (n/s · g ^{238}Pu)		
LANL Lot	SRP Lot	Run	As Received	Processed	Loaded*
101	506	103254	17 400	5 340	5 350
102	583	212592	17 700	4 590	4 680
103	583	212593	17 600	4 530	4 560
104	589	301617	17 600	3 960	4 440
105	591	302624	16 700	4 450	4 710
106	591	302627	17 100	5 240	4 850
107	591	302628	18 400	4 610	4 740
108	592	302631	18 200	4 780	5 040
109	594	303643	18 100	5 990	4 850
110	596	303653	17 700	4 370	4 430
111	598	303661	18 100	4 390	4 350
112	603	304678	17 800	4 440	4 500
113	602	304673	17 800	4 360	4 490
114	604	305681	17 900	4 170	4 180
115	603	304679	17 900	4 930	4 920
116	613	307720	17 900	4 400	4 480
117	613	308731	19 300	3 800	3 900
118	613	308732	17 700	3 980	4 040
119	617	308737	18 500	3 930	3 920
120	617	308738	17 900	---	4 130
122	624	311766	19 300	4 320	4 360
123	625	311770	19 800	4 350	4 420
124	624	311767	18 500	4 160	4 240
125	626	312779	18 600	4 430	4 450
126	624	311768	18 700	4 420	4 560
127	625	312773	18 600	4 180	4 270
128	625	312775	19 400	4 620	4 610
129	625	312774	19 300	4 670	4 730
Average			18 200 ± 700	4 500 ± 470	4 510 ± 330

*Based on measurements of fueled heat sources.

TABLE II. Average Impurity Levels Determined by Spectrochemical Analyses for Feed Lots

Element	Specification (ppm)	Sensitivity Limit (ppm)	As Received (ppm)	As Processed (ppm)
Ag	25	1	1	2
Al	175	5	44	46
B	10	5	"	"
Ba	25	2	"	"
Bi	25	1	"	"
Ca	315	3	374	109
Cd	25	10	"	"
Co	50	3	"	"
Cr	150	5	53	59
Cu	50	1	1	"
Fe	500	5	168	142
Mg	50	1	10	6
Mn	50	1	5	5
Ni	100	5	34	"
Pb	50	5	10	"
Si	250	5	43	68
Sn	50	5	6	"
Zn	100	5	"	"

*Less than sensitivity limit.

impurity level by about 260 ppm but increases the silicon impurity level by about 25 ppm above the as-received feed. By comparison, fuel processed from April 1982 to March 1983¹ had silicon impurity levels about 40 ppm higher than the as-received feed. During the year, SNLA approved changes in the impurity-level specifications for three elements. The aluminum impurity specification limit was raised from 70 ppm to 175 ppm, the calcium specification limit was increased from 250 ppm to 315 ppm, and the silicon specification limit was increased from 100 ppm to 250 ppm.

3. Isotopic Data. The plutonium isotopic contents for the fuel lots are listed in Table III. The SRP isotopic contents in Table III have been corrected (decayed) to the same dates as the Los Alamos analyses. There is excellent agreement between the SRP and Los Alamos results. The ²³⁸Pu enrichment averaged 84.91% compared with 83.51% for fuel processed during the period April 1982 through March 1983.¹

III. PRODUCTION OF HEAT SOURCES

During the past year, DOE accepted a total of 206 MC2893A heat sources (4.0 W) and 72 MC3599 heat sources (4.5 W). The average thermal power of the MC2893A heat sources was 4.003 ± 0.011 W. The average power of the MC3599 units was 4.500 ± 0.012 W.

Acceptance rates of heat-source components during this report period were 99% for liner assemblies, 93% for strength members, and 94% for clad assemblies. Table IV presents a fabrication summary showing the various causes for rejection.

TABLE III. Plutonium Isotopic Contents of Fuel Lots

Feed Lot	Analyst	Plutonium Isotope (wt%)				
		238	239	240	241	242
101	SRP	83.15	14.31	2.03	0.37	0.14
	LANL	83.21	14.25	2.02	0.38	0.14
102	SRP	85.09	12.84	1.66	0.33	0.08
	LANL	85.09	12.85	1.66	0.32	0.08
103	SRP	85.09	12.84	1.66	0.33	0.08
	LANL	85.06	12.84	1.66	0.34	0.09
104	SRP	84.86	13.08	1.67	0.31	0.08
	LANL	84.94	13.00	1.66	0.30	0.09
105	SRP	84.81	13.09	1.69	0.33	0.08
	LANL	84.80	13.07	1.70	0.34	0.09
106	SRP	84.81	13.09	1.69	0.33	0.08
	LANL	84.84	13.04	1.69	0.34	0.09
107	SRP	84.81	13.09	1.69	0.33	0.08
	LANL	84.78	13.07	1.71	0.34	0.09
108	SRP	84.88	13.03	1.70	0.31	0.08
	LANL	84.78	13.10	1.70	0.32	0.09
109	SRP	85.19	12.76	1.65	0.31	0.08
	LANL	85.02	12.93	1.65	0.32	0.08
110	SRP	84.97	12.90	1.71	0.34	0.08
	LANL	85.02	12.87	1.69	0.34	0.08
111	SRP	85.67	12.40	1.56	0.30	0.06
	LANL	85.68	12.39	1.56	0.31	0.06
112	SRP	85.02	12.80	1.73	0.37	0.07
	LANL	85.06	12.76	1.73	0.37	0.07
113	SRP	85.19	12.69	1.69	0.35	0.07
	LANL	85.24	12.67	1.68	0.35	0.07
114	SRP	85.02	12.78	1.74	0.37	0.08
	LANL	85.00	12.80	1.74	0.37	0.08
115	SRP	85.01	12.81	1.74	0.37	0.07
	LANL	85.00	12.78	1.75	0.38	0.09
116	SRP	84.61	13.18	1.78	0.36	0.08
	LANL	84.62	13.15	1.79	0.36	0.08
117	SRP	84.93	12.91	1.74	0.34	0.08
	LANL	84.65	13.15	1.77	0.35	0.08
118	SRP	84.93	12.91	1.74	0.34	0.08
	LANL	84.63	13.16	1.77	0.35	0.08

TABLE III. (continued)

Feed		Plutonium Isotope (wt%)				
Lot	Analyst	238	239	240	241	242
119	SRP	84.77	13.09	1.72	0.34	0.08
	LANL	84.62	13.14	1.78	0.36	0.10
120	SRP	84.77	13.09	1.72	0.34	0.08
	LANL	84.64	13.13	1.77	0.36	0.09
122	SRP	85.16	12.77	1.67	0.32	0.08
	LANL	85.17	12.77	1.66	0.31	0.08
123	SRP	85.32	12.68	1.63	0.30	0.07
	LANL	85.09	12.82	1.68	0.32	0.09
124	SRP	85.16	12.77	1.67	0.32	0.08
	LANL	85.15	12.78	1.67	0.32	0.09
125	SRP	84.95	12.97	1.69	0.32	0.07
	LANL	84.90	12.98	1.72	0.33	0.08
126	SRP	85.15	12.78	1.68	0.31	0.08
	LANL	85.17	12.78	1.67	0.31	0.08
127	SRP	85.31	12.69	1.63	0.29	0.07
	LANL	85.14	12.79	1.68	0.31	0.08
128	SRP	85.31	12.69	1.63	0.29	0.07
	LANL	85.12	12.83	1.67	0.31	0.07
129	SRP	85.31	12.69	1.63	0.29	0.07
	LANL	85.10	12.83	1.68	0.31	0.08
SRP Average		84.97	12.92	1.70	0.33	0.08
		±0.42	±0.33	±0.08	±0.02	±0.01
LANL Average		84.91	12.95	1.71	0.34	0.08
		±0.41	±0.31	±0.08	±0.02	±0.01

IV. PRESSURE-BURST TEST UNITS

New production MC2730A and MC3500 RTGs are evaluated over their life spans of 25 and 20 years, respectively, to determine the effects of extended storage at high and low temperatures on both the RTG and the heat source. As a part of this evaluation, Los Alamos fabricates both MC2893A and MC3599 pressure-burst units for subsequent testing at MF.

The pressure-burst capsule consists of a strength-member assembly containing a tantalum pellet to simulate the volume of the liner assembly and fuel. The strength-member cap is provided with a tantalum tube (1.52 mm in diameter, 101.6 mm long, with a 0.25-mm orifice) that is electron-beam welded through the center of the cap. This tube is used to pressurize the strength-member assembly with helium, after which the tube is sealed. For these units, the amount of helium introduced is such that a preset pressure of 35.8 MPa. (5190 psi) is attained when the assembly is heated to 1010°C.

TABLE IV. Heat-Source Fabrication Summary

Liner Assembly	Fabricated	364
	Rejected	5 ^a
	Yield	99%
Strength-Member Assembly	Fabricated	338
	Rejected	23 ^b
	Yield	93%
Clad Assembly	Fabricated	297
	Rejected	19 ^c
	Yield	94%

^a2 - Weld contaminated with fuel

1 - Lack of weld penetration

1 - Failed dye penetrant

1 - Hardware defect

^b9 - Blowout of weld overlap area

4 - Incorrect rotational speed

3 - Excessive weld underbead

3 - Lack of penetration

2 - No record of heat treatment

1 - Excessive weld fillet

1 - Visual appearance

^c6 - Excessive fillet

5 - Lack of weld penetration

4 - Oversize diameter

1 - Low thermal output

1 - High direct alpha count

1 - Wrong torch angle

1 - Visual appearance

During the past year, 10 MC2893A and 8 MC3599 pressure-burst test units were welded and shipped to MF for testing. Data for these units, including the impurity levels of oxygen, nitrogen, and water in the welding glove-box atmospheres at the time of fabrication, are summarized in Table V.

V. COMPATIBILITY STUDIES

Both 4.0-W and 4.5-W heat sources are being heat treated at 600°C for times ranging between 2 and 15 years.¹ We will use these tests to characterize the effects on alloy T-111 from long-term exposure to PuO_{2,x}. Some of the test units will be subjected to impact testing.

A Los Alamos 4.0-W compatibility test unit (LASL-53), which had been heat treated at 600°C for 2 years, was impacted (side-on) at 150 m/s at a temperature of 450°C. To protect the clad from oxidation, we encapsulated LASL-53 in Hastelloy X during the 2-year heat treatment.

The impact face of the clad is shown in Fig. 1. The clad appeared to fail in a brittle manner. Cracks were observed on the impact face, and the clad impact surface broke away from the

TABLE V. Pressure-Burst Test Units

Unit No.	Type	Pellet	Welding Atmosphere Impurities (ppm)		
			Oxygen	Nitrogen	Water
LPBA-02	2893A	TP-107	7	89	7
LPBA-03	2893A	TP-108	7	89	7
LPBA-04	2893A	TP-109	7	89	7
LPBA-05	2893A	TP-110	7	89	7
LPBA-06	2893A	TP-111	<1	85	48
LPBA-07	2893A	TP-112	<1	85	48
LPBA-08	2893A	TP-113	<1	85	48
LPBA-09	2893A	TP-085	15	23	6
LPBA-10	2893A	TP-086	15	23	6
LPBA-11	2893A	TP-087	15	23	6
LPB-01	3599	LTP-02	2	11	5
LPB-02	3599	LTP-03	2	11	5
LPB-03	3599	LTP-04	2	11	5
LPB-04	3599	LTP-05	3	12	11
LPB-05	3599	LTP-06	3	12	11
LPB-06	3599	LTP-07	3	12	11
LPB-07	3599	LTP-08	3	12	11
LPB-08	3599	LTP-09	<1	85	48

Fig. 1. Impact face of LASL-53, showing extent of failure. Clad at impact face has separated from the remainder of the clad and is partially bonded to the strength member. Strength member is breached in the dome region. 2X.

remainder of the clad. In addition, the clad partially bonded to the strength member along the impact face (Fig. 2). A major breach occurred in the dome region, in which the liner and the strength member appeared to have failed as a result of shear and bending stresses at impact (Figs. 2-3). Figures 4 and 5 show the clad failures in the dome and cap regions, respectively, in directions 90° from that of Fig. 1. Figure 5 shows the complete separation along the weld interface of the clad cap from the clad body.

Chemical analyses and hardness values of the liner, strength member, and clad (Table VI) indicated that the alloys were not significantly affected by the diffusion of oxygen from the fuel. Oxygen contents and hardness values of both the liner and the strength member were somewhat below values obtained from LASL-52, which was heat treated at the same conditions as LASL-53 but was not impact tested.¹ Hardness profiles for the liner and strength member of LASL-53 are shown in Figs. 6 and 7, respectively. One unusual feature found by metallography was the existence of numerous defects in the liner body (Fig. 8), but no effects on the results of the test were observed.

Although the unit failed as a result of the impact, there was no indication that the mechanical properties of the strength member were degraded by diffusion of oxygen from the fuel. Interaction between the fuel and T-111 was confined to the liner. Some changes in the mechanical properties of the strength member could have occurred as a result of the 600°C heat treatment, however. The brittle behavior of the Hastelloy-C cladding might also be related to this extended heat treatment.

Fig. 2. Longitudinal section of liner and strength member of LASL-53 after impact. Clad at impact face partially bonded to the strength member. 4X.

Fig. 3. Breach of both liner and strength member in the dome region of LASL-53. As polished. 50X.

Fig. 4. Clad failure in dome region of LASL-53 after impact. 2X.

Fig. 5. Clad failure in cap region of LASL-53, showing remaining strength member as a result of cap separation. 2X.

VI. IMPACT TESTING

To determine the contribution of the cladding to the ability of the MWG heat source to withstand the 150-m/s impact test at 450°C, an as-fabricated but unclad MWG unit (SM-2693) was impact tested. The strength member of SM-2693 did not breach. A longitudinal section is shown in Fig. 9. Deformation was greatest in the dome area at the impact face and appeared to be similar to the deformation of previously tested as-fabricated MWG units.²

Oxygen and nitrogen levels in various areas of the liner and strength member were found to be the same (30-80 ppm) as for units incorporating a clad (Table VII). The test indicated that MWG units are capable of withstanding a 150-m/s impact at 450°C without the added strength of the clad.

TABLE VI. Compatibility Test Results for LASL-53

Assembly	Oxygen (ppm)			Nitrogen (ppm)			Hardness (VHN)			
	Dome	Body	Weld + Cap	Dome	Body	Weld + Cap	Dome	Body	Cap	Weld
Liner	150	330	120	10	15	25	215	250	257	235
SM	60	55	45	15	15	10	230	240	259	255
Clad	30	35	30	---	---	---	---	---	---	---

Fig. 6. Hardness profile for the liner of LASL-53.

Fig. 7. Hardness profile for the strength member of LASL-53.

Fig. 8. Defects in the liner of LASL-53 along impact face. As polished. 50X.

Fig. 9. Longitudinal section of unclad heat source SM-2693 impacted side-on at 450°C and 150 m/s. As polished. 4X.

TABLE VII. Oxygen and Nitrogen Analyses for Impacted Unclad MWG Unit SM-2693

Assembly	Oxygen (ppm)			Nitrogen (ppm)		
	Dome	Body	Weld + Cap	Dome	Body	Weld + Cap
Liner	40	30	80	55	45	50
Strength Member	60	35	60	70	55	40

VII. SURVEILLANCE UNITS

Nine MC2893 units manufactured at MF in 1977-78 and one MC3599 unit manufactured at Los Alamos in 1981 were destructively examined. Four of the MC2893 units were impact tested. Identification of these 10 units, along with the tests and analyses performed, are shown in Table VIII.

A. Impact Tests

Four of the MC2893 units were impact tested at 148-150 m/s and 450°C. Typical photographs of the impact faces and side views (90° from the impact face) of the units after impact are shown in Figs. 10-13. All the clads failed in the weld region on impact over approximately one-third to one-half the circumference. No external alpha count was found and subsequent examinations confirmed that the strength members were unbreached.

Diametral deformations of the impacted units were characterized by the relative decreases in the original diameters parallel to the impact direction and the increases in width of the impact faces relative to the original diameters. Table IX gives the diametral deformations of the four impacted units. Average diametral deformations were $-22.7 \pm 0.7\%$ and $+12.9 \pm 0.5\%$. These deformations were somewhat lower than those of seven previously impacted MF units,^{1,2} which averaged $-24.5 \pm 1.4\%$ and $+15.3 \pm 1.7\%$.

TABLE VIII. Surveillance Units Tested and Examined

Fabrication		Type	Fabricator	Impact Test	Metallography	Liner	Fines Analysis
Unit	Date					Oxygen & Hardness	
MAD-0193	12/77	2893	MF	---	X	X	---
MAD-0218	1/78	2893	MF	X	X	X	---
MAD-0374	3/78	2893	MF	---	X	X	X
MAD-0446	4/78	2893	MF	---	X	X	X
MAD-0461	4/78	2893	MF	X	X	X	---
MAD-0472	4/78	2893	MF	---	X	X	X
MAD-0683	7/78	2893	MF	X	X	X	---
MAD-0696	7/78	2893	MF	---	X	X	X
MAD-0751	8/78	2893	MF	X	X	X	---
UAS-0008	7/81	3599	LANL	---	X	X	X

Fig. 10. Impact face of MAD-0461 after side-on impact at 149 m/s and 450°C.

Fig. 11. Side view of MAD-0461 after impact at 149 m/s and 450°C.

Fig. 12. Impact face of MAD-0683 after side-on impact at 150 m/s and 450°C.

Fig. 13. Side view of MAD-0683 after impact at 150 m/s and 450°C.

**TABLE IX. Diametral Deformations of MC2893 Surveillance Units
Impacted at 148-150 m/s and 450°C**

Unit	Velocity (m/s)	$\Delta H(\%)$	$\Delta W(\%)$	Clad	SM
MAD-0218	148	-22.1	+13.5	Breach	Intact
MAD-0461	149	-22.0	+12.4	Breach	Intact
MAD-0683	150	-23.1	+13.2	Breach	Intact
MAD-0751	148	-23.5	+12.5	Breach	Intact
Average		-22.7	+12.9		

B. Metallography

Cross sections of the four impacted MC2893 units are shown in Figs. 14-17. Although the outward appearances of the impacted strength members were quite similar, the cross sections revealed some differences in the amount of deformation of the liners. For MAD-0218, there was considerably less thinning of the wall of the strength member than in the other three units.

The greater strength at the top of the unit because of the greater thickness of the strength-member cap results in considerable bending in the bottom of the unit in side-on impact testing. In this area, the mechanical deformation results in extreme thinning of the strength member. Figure 18 shows liner and strength-member deformation in this area of MAD-0751. The deformation reduced the thickness of the strength member of MAD-0751 in this area to 0.25 mm.

Fig. 14. Cross section of impacted unit MAD-0218. As polished. 4X.

Fig. 15. Cross section of impacted unit MAD-0461. As polished. 4X.

Fig. 16. Cross section of impacted unit MAD-0683. As polished. 4X.

Fig. 17. Cross section of impacted unit MAD-0751. As polished. 4X.

Fig. 18. Deformation of liner and strength member at bottom of impact surface in MAD-0751. Etched. 50X.

In MAD-0683 (Fig. 16), a break in the liner at the liner-cap weld was observed. A photomicrograph after etching (Fig. 19) shows the intergranular nature of the fracture. Electron-microprobe analysis of the weld area revealed plutonium and yttrium contamination in the weld.

Chemical interaction of the PuO_2 /yttrium mixture with the T-111 liner at the bottom of the liner (dome area) is shown in Fig. 20. Approximately 40% of the thickness of the liner appears to be affected by diffusion of oxygen into the T-111. Semicircular affected areas ("halos") were also observed within these interaction zones.

The MC3599 unit manufactured at Los Alamos (UAS-0008) was also destructively examined. The only features of interest were small cracks in the liner weld (Fig. 21). Etching revealed that the cracks were intergranular (Fig. 22). Electron-microprobe analysis of the weld area showed that plutonium and yttrium were associated with the cracks. Subsequently, the liner welding procedure was changed to incorporate a gauge that would ensure that the liner shim is at least 1.14 mm (0.045 in.) from the weld area before the liner cap is welded.

C. Oxygen Analyses and Microhardness Measurements of Liners

The oxygen contents of the nine MC2893 liners averaged 180, 270, and 75 ppm for the dome, body, and weld-plus-cap regions, respectively (Table X). These values are lower than those of eight previously examined¹ MC2893 surveillance units, which averaged 320, 450, and 155 ppm for the same regions. However, microhardness measurements taken in the body regions of the nine liners averaged 259 ± 9 VHN, which was not significantly higher than the average value (253 ± 15 VHN) for the eight previously examined¹ MC2893 surveillance units. No correlation between oxygen content and hardness of the body regions of the liners was evident.

Fig. 19. Liner fracture in weld area of impacted unit MAD-0683. Etched. 100X.

(a) MAD-0374.

(b) MAD-0472.

Fig. 20. Bottom (dome area) of liners showing effect of fuel-clad chemical interaction. Fueled surface is at top. Etched. 100X.

Fig. 21. Cracks in liner weld of UAS-0008. As polished. 50X.

Fig. 22. Cracks in liner weld of UAS-0008. Etched. 100X.

TABLE X. Oxygen Contents and Microhardnesses of the T-111 Liners of Surveillance Units

Unit	Oxygen Content (ppm)			Hardness of Body Region (VHN)
	Dome	Body	Weld + Cap	
MAD-0193	270	360	110	267
MAD-0218	390	870	100	246
MAD-0374	210	410	60	262
MAD-0446	200	110	95	265
MAD-0461	95	110	65	254
MAD-0472	50	60	70	250
MAD-0683	80	90	60	273
MAD-0696	210	260	50	255
MAD-0751	130	160	55	258
Average	180	270	75	259
UAS-0008	260	160	100	282

The oxygen contents of the dome, body, and weld-plus-cap regions of the MC3599 unit were 260, 160, and 100 ppm, respectively. The average oxygen content of the dome and body regions (210 ppm) was virtually the same as the average (225 ppm) for the MC2893 units. However, the average hardness of the body region was slightly higher (282 VHN) than the hardness of any of the MC2893 units. None of these results indicates that the liners of these surveillance units have undergone significant losses of mechanical strength or ductility as a result of oxygen diffusion from the fuel. Alloy T-111 containing 2000 ppm oxygen has been reported¹ to have a VHN of 259. At 1204°C, this amount of oxygen in T-111 results in little loss of ductility and somewhat increased ultimate tensile and yield strength compared with T-111 containing lower amounts of oxygen.³

D. Fines Analysis

Four nonimpacted MC2893 units and one nonimpacted MC3599 unit were cut open to characterize the amount of fines (<20 μm) in surveillance units. The results are shown in Table XI. A range of 0.10-0.53 g and an average of 0.40 g of fines smaller than 20 μm were found in the MC2893 units. The MC3599 unit yielded 0.26 g. The amount of <20- μm fines from six MC2893 units manufactured in 1977-78 that were analyzed in 1983¹ averaged 0.22 g.

Respirable fines, which in the case of PuO_2 would be $\sim 3 \mu\text{m}$ in diameter, were categorized as those particles that were less than 5 μm in diameter. The respirable fines in the four MC2893 units ranged from 0.03 g to 0.14 g and averaged 0.11 g. The MC3599 unit yielded 0.06 g. These amounts represented an increase from the six MC2893 units manufactured in 1977 and analyzed in 1983,¹ which averaged 0.04 g of respirable fines.

TABLE XI. PuO₂ Fines from Nonimpacted Surveillance Units

Unit	Type	Origin	Amount (g)			
			<5 μm	5-10 μm	10-20 μm	>20 μm
MAD-0374	2893	MF	0.14	0.19	0.20	0.53
MAD-0446	2893	MF	0.14	0.12	0.20	0.46
MAD-0472	2893	MF	0.13	0.16	0.21	0.50
MAD-0696	2893	MF	0.03	0.02	0.05	0.10
Average			0.11	0.12	0.17	0.40
UAS-0008	3599	LANL	0.06	0.09	0.11	0.26

VIII. INCONEL WELD DEVELOPMENT

Inconel-600 is being considered as a substitute material for the Hastelloy-C clad in the MWG program because Inconel-600 has nearly the same composition and properties as Hastelloy-C but is more readily obtained. Los Alamos received 15 sets of Inconel-600 clad hardware from MF and began a weld development program for this material. After weld parameters had been defined, three clad units (I022, I023, and I024) were submitted for metallographic examination of the weld areas. The weld penetration and quality were excellent. A photomicrograph of the I022 weld is shown in Fig. 23. The oxygen levels in the welds of I022, I023, and I024 were 20, 40, and 40 ppm, respectively.

Fig. 23. Inconel weld I022. Etched. 100X. (Apparent porosity caused by pullout during polishing.)

IX. QUALITY ASSURANCE

On June 2, 1983, Los Alamos/QA personnel conducted an audit of the MWG fuel-processing area to verify compliance with the requirements established in ANSI N45.2 (Quality Assurance Program Requirements for Nuclear Facilities), HS-QA-PD-1 Rev. 4, (Heat Source Quality Assurance Program Plan), and the Los Alamos MST-9 Quality Assurance Manual. On June 9, 1983, representatives from DOE/ALO conducted a QA survey on the production and quality processes applied to the manufacture of the MC2893A and MC3599 heat sources. The survey included review and evaluation of design and process information control, manufacturing procedures and equipment, inspection procedures and equipment, quality information, material control, nonconformances, and calibrations. A rating of "excellent" was assigned to this survey. On March 21, 1984, Los Alamos/QA personnel conducted an audit of the MWG impact testing and metallographic examination activities of groups MST-5 and MST-11. These activities were evaluated for compliance with the requirements established in ANSI N45.2, HS-QA-PD-1, and the MST-9 Quality Assurance Manual. The audit resulted in 5 findings and 10 observations, but none was of sufficient significance to affect quality of the product.

REFERENCES

1. G. H. Rinehart and T. W. Latimer, "Milliwatt Generator Project, April 1982-March 1983," Los Alamos National Laboratory report LA-11217-PR (May 1988).
2. W. J. Maraman (Compiler), "Milliwatt Generator Project, April-September 1981," Los Alamos National Laboratory report LA-9170-PR (December 1981).
3. D. E. Etter and W. H. Smith, "Effect of Oxygen Contamination on the Tensile Properties of T-111 (Tantalum - 8 Tungsten - 2 Hafnium) at 1204°C," Journal of the Less-Common Metals 27, 109-122 (1972).