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Milliwatt Generator Project

April 1984–March 1986

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Milliwatt Generator Project

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LIST OF ABBREVIATIONS

LANL	Los Alamos National Laboratory
MF	Mound Facility
MWG	Milliwatt Generator
RTG	Radioisotopic Thermoelectric Generator
SRP	Savannah River Plant
VHN	Vickers Hardness Number

MILLIWATT GENERATOR PROJECT
April 1984–March 1986

by

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ABSTRACT

This report covers progress on the Milliwatt Generator Project from April 1984 through March 1986. Activities included fuel processing and characterization, production of heat sources, fabrication of pressure-burst test units, compatibility studies, impact testing, and examination of surveillance units.

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 (RTGs) 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 subsequent examination of compatibility and surveillance units.

II. FUEL PROCESSING AND CHARACTERIZATION

A. Processing

During the report period, 36 lots (8.12 kg) of SRP feed powder were processed through the MWG fuel-processing line to obtain 7.03 kg of fuel granules.

B. Characterization

1. Neutron Emission. 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 $17\,800 \pm 1\,800$ n/s·g ^{238}Pu . After ^{16}O exchange and other processing, the average neutron emission rate of the fuel lots was $4\,320 \pm 320$ n/s·g ^{238}Pu .

2. Spectrochemical. 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 reduced the average calcium level by 350 ppm. Small changes in aluminum and silicon impurity levels were also seen after processing: the average aluminum content decreased by 40 ppm and the average silicon content increased by 20 ppm.

3. Isotopic. The plutonium isotopic contents for the fuel lots are listed in Table III. The SRP isotopic contents in the table have been corrected (decayed) to the same dates as the Los Alamos analyses. Excellent agreement exists between the SRP and Los Alamos results. The ^{238}Pu enrichment averaged 83.96% compared with 84.91% for fuel processed from April 1983 through March 1984.¹

III. PRODUCTION OF HEAT SOURCES

During this report period, a total of 566 MC2893A heat sources (4.0 W) and 276 MC3599 heat sources (4.5 W) were accepted by DOE. The average thermal power of the MC2893A heat sources was 4.001 ± 0.013 W, and the average thermal power of the MC3599 units was 4.503 ± 0.013 W.

During the first 10 months of this report period, the strength member acceptance rate was 91%. In February 1985, following consultations with MF personnel, the welding parameters were modified to reduce the amount of weld overlap during the ramp-down period. After this change was made, the strength member acceptance rate increased to 99% for the rest of the reporting period. Overall liner and clad acceptance rates were 97%. Fabrication summaries showing the various causes for rejection of MC2893A and MC3599 units are given in Tables IV and V, respectively.

TABLE I. Neutron Emission Rate Data for Feed Lots

Lot Numbers			Neutron Emission Rate (n/s · g ^{238}Pu)	
LANL	SRP		As	As
Lot	Lot	Run	Received	Processed
130	625	311771	19 200	4 380
131	626	312778	19 200	4 470
132	627	401780	17 700	3 720
134	627	401782	17 700	4 470
135	628	401785	18 100	4 480
136	628	401786	17 800	4 370
137	630	402796	17 800	4 960
139	633	403808	17 700	4 500
140	633	403809	17 900	4 660
141	633	403807	19 200	4 060
142	633	403810	18 100	4 770
143	634	403811	18 200	4 650

(cont.) TABLE I. Neutron Emission Rate Data for Feed Lots

Lot Numbers			Neutron Emission Rate (n/s · g ²³⁸ Pu)	
LANL	SRP		As	As
Lot	Lot	Run	Received	Processed
144	635	403817	18 300	4 050
145	635	403816	18 100	3 980
147	634	403813	17 700	3 850
148	634	403812	17 500	4 840
149	636	403822	17 500	4 440
150	632	403805	17 300	4 430
151	629	402791	8 500	4 010
152	635	403818	17 700	4 320
153	631	402799	17 800	4 580
155	629	402788	17 700	3 650
156	631	402801	17 900	4 750
157	629	402790	17 300	4 100
158	632	403804	17 500	4 310
159	632	403806	17 700	4 120
160	636	403819	18 900	4 060
161	636	403820	18 600	4 470
162	637	403826	17 500	4 030
163	637	403823	18 300	4 400
164	637	403825	17 300	4 100
165	636	312777	17 800	4 210
166	636	307724	18 500	3 910
167	636	402787	18 200	4 770
168	626	312776	21 900	4 440
170	629	402789	17 100	4 160
			17 800	4 320
Average			±1 800	± 320

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

Element	Specification (ppm)	As	As
		Received (ppm)	Processed (ppm)
Ag	25	3	1
Al	175	100	60
B	10	<5	<5
Ba	25	<2	<2
Bi	25	<1	<1
Ca	315	430	80
Cd	25	<10	<10
Co	50	<3	<3
Fe	500	130	130
Cr	150	30	40
Mg	50	9	5

(cont.) **TABLE II. Average Impurity Levels Determined by Spectrochemical Analyses for Feed Lots**

Element	Specification (ppm)	As	As
		Received (ppm)	Processed (ppm)
Cu	50	2	1
Mn	50	4	4
Ni	100	20	6
Pb	50	15	<5
Si	250	60	80
Sn	50	5	5
Zn	100	<5	<5

Table III. Plutonium Isotopic Contents of Feed Lots

Feed		Plutonium Isotope (wt%)				
Lot	Analyst	238	239	240	241	242
130	SRP	85.31	12.69	1.64	0.29	0.07
	LANL	85.09	12.84	1.68	0.31	0.08
131	SRP	84.93	12.99	1.70	0.31	0.07
	LANL	84.88	13.01	1.72	0.32	0.07
132	SRP	84.34	13.40	1.83	0.36	0.08
	LANL	84.40	13.33	1.82	0.37	0.08
134	SRP	84.34	13.40	1.83	0.36	0.08
	LANL	84.42	13.32	1.82	0.36	0.08
135	SRP	83.86	13.72	1.93	0.40	0.09
	LANL	84.04	13.57	1.91	0.40	0.09
136	SRP	83.86	13.72	1.93	0.40	0.09
	LANL	84.01	13.59	1.91	0.40	0.09
137	SRP	83.87	13.65	1.96	0.42	0.10
	LANL	83.88	13.65	1.95	0.42	0.09
139	SRP	83.76	13.75	1.98	0.42	0.09
	LANL	83.79	13.74	1.97	0.41	0.09
140	SRP	83.76	13.75	1.98	0.42	0.09
	LANL	83.83	13.66	1.98	0.42	0.10
141	SRP	83.76	13.76	1.98	0.42	0.09
	LANL	83.74	13.77	1.98	0.42	0.10
142	SRP	83.76	13.76	1.98	0.42	0.09
	LANL	83.75	13.76	1.98	0.42	0.10

(cont.) Table III. Plutonium Isotopic Contents of Feed Lots

Feed		Plutonium Isotope (wt%)				
Lot	Analyst	238	239	240	241	242
143	SRP	84.00	13.59	1.93	0.40	0.08
	LANL	83.79	13.73	1.97	0.42	0.09
144	SRP	84.36	13.58	1.61	0.39	0.06
	LANL	83.88	13.68	1.94	0.40	0.10
145	SRP	84.36	13.58	1.61	0.39	0.06
	LANL	83.85	13.70	1.95	0.40	0.10
147	SRP	83.99	13.60	1.93	0.40	0.08
	LANL	83.80	13.74	1.96	0.41	0.09
148	SRP	83.98	13.61	1.93	0.40	0.08
	LANL	83.83	13.71	1.95	0.42	0.10
149	SRP	83.81	13.73	1.96	0.40	0.09
	LANL	83.81	13.73	1.96	0.41	0.09
150	SRP	83.70	13.79	2.00	0.42	0.09
	LANL	83.70	13.79	1.99	0.42	0.10
151	SRP	83.91	13.68	1.92	0.38	0.10
	LANL	83.94	13.65	1.92	0.39	0.10
152	SRP	84.34	13.61	1.61	0.38	0.06
	LANL	83.76	13.76	1.97	0.41	0.11
153	SRP	83.64	13.84	2.01	0.43	0.09
	LANL	83.73	13.75	1.99	0.43	0.10
155	SRP	83.90	13.69	1.93	0.38	0.10
	LANL	84.00	13.63	1.91	0.37	0.09
156	SRP	83.62	13.86	2.01	0.43	0.09
	LANL	83.72	13.79	1.99	0.41	0.09
157	SRP	83.89	13.71	1.93	0.38	0.10
	LANL	83.95	13.67	1.91	0.38	0.09
158	SRP	83.66	13.82	2.01	0.41	0.09
	LANL	83.70	13.80	1.99	0.42	0.10
159	SRP	83.66	13.82	2.01	0.41	0.09
	LANL	83.70	13.80	1.99	0.41	0.10

(cont.) Table III. Plutonium Isotopic Contents of Feed Lots

Feed Lot	Analyst	Plutonium Isotope (wt%)				
		238	239	240	241	242
160	SRP	83.77	13.77	1.97	0.40	0.09
	LANL	83.75	13.76	1.98	0.41	0.10
161	SRP	83.76	13.78	1.97	0.39	0.09
	LANL	83.76	13.77	1.97	0.40	0.09
162	SRP	83.88	13.81	1.81	0.41	0.09
	LANL	83.68	13.81	1.99	0.42	0.09
163	SRP	83.89	13.80	1.81	0.41	0.09
	LANL	83.71	13.81	1.98	0.40	0.09
164	SRP	83.90	13.79	1.81	0.41	0.09
	LANL	83.71	13.82	1.99	0.40	0.08
165	SRP	84.79	13.13	1.71	0.29	0.08
	LANL	84.72	13.15	1.74	0.31	0.08
166	SRP	84.25	13.47	1.86	0.34	0.07
	LANL	83.75	13.80	1.97	0.39	0.10
167	SRP	83.83	13.77	1.94	0.37	0.10
	LANL	83.88	13.73	1.92	0.37	0.10
168	SRP	84.78	13.14	1.72	0.29	0.07
	LANL	84.70	13.18	1.73	0.31	0.08
170	SRP	83.83	13.77	1.94	0.37	0.10
	LANL	83.88	13.73	1.93	0.36	0.09
SRP Average		84.01	13.62	1.88	0.39	0.09
		± 0.41	± 0.26	± 0.13	± 0.04	± 0.01
LANL Average		83.96	13.63	1.93	0.39	0.09
		± 0.36	± 0.24	± 0.08	± 0.03	± 0.01

TABLE IV. MC2893A Heat Source Fabrication Summary

Liner Assembly	Fabricated	571
	Rejected	14 ^a
	Yield	98%
Strength-Member Assembly	Fabricated	620
	Rejected	33 ^b
	Yield	95%

(cont.) **TABLE IV. MC2893A Heat Source Fabrication Summary**

Clad Assembly	Fabricated	586
	Rejected	19 ^c
	Yield	97%
^a 9 — Insufficient weld penetration		
3 — Visual appearance		
1 — Failed helium leak check		
1 — Failed dye penetrant inspection		
^b 26 — Insufficient weld penetration		
5 — Failed dye penetrant inspection		
2 — Visual appearance		
^c 6 — Excessive weld fillet		
5 — Oversize diameter		
4 — Defects in cap		
2 — Insufficient weld penetration		
1 — Low thermal power		
1 — Lapped dome of unit		

TABLE V. MC3399 Heat Source Fabrication Summary

Liner Assembly	Fabricated	308
	Rejected	14 ^a
	Yield	95%
Strength-Member Assembly	Fabricated	286
	Rejected	10 ^b
	Yield	97%
Clad Assembly	Fabricated	279
	Rejected	3 ^c
	Yield	99%
^a 8 — Insufficient weld penetration		
6 — Visual appearance		
^b 8 — Insufficient weld penetration		
1 — High direct alpha count		
1 — Failed ultrasonic inspection		
^c 2 — Insufficient weld penetration		
1 — Oversize diameter		

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. In addition, new lots of alloy T-111 are qualified by testing pressure-burst test units to ensure that the strength member will not be ruptured by internal helium pressure (caused by ^{238}Pu alpha decay) at the end of capsule life. As a part of these evaluations, 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 that contains 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 and 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 new production 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.

During this report period, 43 MC2893A and 24 MC3599 pressure-burst test units were welded and shipped to MF for testing. A description of these units, including the impurity levels of oxygen, nitrogen, and water in the welding glovebox atmosphere at the time of fabrication, is summarized in Tables VI and VII.

V. COMPATIBILITY STUDIES

Both 4.0- and 4.5-W heat sources are being heat treated at temperatures of 600°C to 900°C for 2 yr and at 600°C for times ranging from 2 to 15 yr.² These tests will be used to characterize the effects on alloy T-111 from long-term exposure to PuO_{2-x} . Some of these test units have been and will be subjected to impact testing.

TABLE VI. MC2893A Pressure-Burst Test Units

Unit No.	Pellet No.	Welding Atmosphere Impurities (ppm)		
		Oxygen	Nitrogen	Water
LPBA-12	TP-088	2	68	20
LPBA-13	TP-089	2	68	20
LPBA-14	TP-090	2	68	20
LPBA-15	S-23	1	4	15
LPBA-16	S-26	1	4	15
LPBA-31	S-09	2	12	2
LPBA-32	S-12	2	12	2
LPBA-33	S-13	2	12	2
LPBA-34	S-14	2	12	2
LPBA-35	S-15	2	12	2
LPBA-36	S-16	2	12	2
LPBA-37	S-17	2	12	2
LPBA-38	S-18	2	12	2
LPBA-39	S-19	1	29	2
LPBA-40	S-05	1	29	2
LPBA-41	120F	1	71	3
MPT11-32	S-27	1	4	15
MPT12-01	S-28	1	9	15
MPT12-02	S-30	1	9	15
MPT12-03	S-31	1	9	15

(cont.) TABLE VI. MC2893A Pressure-Burst Test Units

Unit No.	Pellet No.	Welding Atmosphere Impurities (ppm)		
		Oxygen	Nitrogen	Water
MPT12-04	S-32	1	9	15
MPT12-05	S-33	1	9	15
MPT12-06	S-34	1	9	15
MPT12-07	S-36	1	9	15
MPT12-08	S-38	1	9	15
MPT12-09	S-39	1	9	15
MPT12-10	S-40	1	9	15
MPT12-11	S-41	1	7	13
MPT12-12	S-42	1	7	13
MPT12-13	TP-099	1	7	13
MPT12-14	TP-100	1	7	13
MPT12-15	TP-101	1	7	13
MPT12-16	TP-102	1	7	13
MPT12-17	TP-103	1	7	13
MPT12-18	TP-104	1	7	13
MPT12-19	TP-105	1	7	13
MPT12-20	TP-106	1	7	13
MPT12-21	114F	1	7	13
MPT12-22	115F	1	7	13
MPT12-23	116F	1	9	15
MPT12-24	117F	1	4	15
MPT12-25	118F	1	4	15
MPT12-26	119F	1	4	15

TABLE VII. MC3599 Pressure-Burst Test Units

Unit No.	Pellet No.	Welding Atmosphere Impurities (ppm)		
		Oxygen	Nitrogen	Water
LPB-11	LTP-12	2	88	20
LPB-12	LTP-13	2	88	20
LPB-13	LTP-14	2	88	20
LPB-14	LTP-18	1	7	15
LPB-15	LTP-19	1	7	15
LPB-16	LTP-29	1	19	2
LPB-17	LTP-31	1	19	2
LPB-18	LTP-32	1	19	2
LPB-19	LTP-33	1	19	2
LPB-20	LTP-37	1	29	2
LPB-21	LTP-38	1	29	2
LPB-22	LTP-39	1	29	2
LPB-23	LTP-34	1	71	3
LPBA-17	LTP-20	1	8	15
LPBA-18	LTP-21	1	8	15
LPBA-19	LTP-22	1	8	15
LPBA-20	LTP-23	1	8	15
LPBA-21	LTP-24	1	8	15

(cont.) TABLE VII. MC3599 Pressure-Burst Test Units

Unit No.	Pellet No.	Welding Atmosphere Impurities (ppm)		
		Oxygen	Nitrogen	Water
LPBA-22	LTP-25	1	8	15
LPBA-23	LTP-26	1	8	15
LPBA-24	LTP-27	1	8	15
LPBA-25	LTP-28	1	8	15
MPT11-33	LTP-15	1	7	15
MPT11-34	LTP-17	1	7	15

A Los Alamos 4.0-W compatibility test unit (LASL-131), which had been heat treated at 700°C for 2 yr, was impacted (side on) at 148 m/s and 450°C. The Hastelloy-C clad on this unit had a dark oxidation layer as a result of its heat treatment in air.

The impact face of the unit is shown in Fig. 1. As in LASL-53, which was heat treated at 600°C for 2 yr before impact testing,¹ the clad appeared to fail in a brittle manner and a major break occurred in the dome region. The liner and strength member appeared to have failed as a result of shear and bending stresses at impact (Fig. 2). Many cracks appeared in the liner near the breach (Figs. 2 and 3).

Fig. 1. Impact face of LASL-131, showing extent of failure. Clad cap has separated from the clad assembly and is shown at left. Liner and strength member are breached in the dome region.

Fig. 2. Longitudinal section of liner and strength member of LASL-131 after impact at 148 m/s and 450°C. As polished. 4.2×

Chemical analyses and hardness values of the liner and strength member are shown in Table VIII. The liner showed an increase in average oxygen content in the body (sidewall) and dome regions from 117 ppm in as-fabricated T-111 to 990 ppm after heat treatment and the hardness increased from 232 to 404 VHN (Table VIII). As expected, these values were between those obtained for units heat treated for 2 yr at 600°C and at 900°C (Table IX).^{1,2} Of more importance, the test showed a lack of oxygen transfer from the fuel to the strength member after 2 yr at 700°C, confirming the previous results obtained at 600°C and 900°C—that a significant design margin exists for these heat sources operating at about 450°C.

Fig. 3. Cracks in liner section of LASL-131 near breach after impact. As polished. 100×

Table VIII. Compatibility Test Results for LASL-131					
Assembly	Oxygen (ppm)			Hardness (VHN)	
	Dome	Body	Weld + Cap	Dome	Body
Liner	1100	880	110	404	---
SM	45	100	60	---	252

TABLE IX. Effect of Temperature on Oxygen Content and Hardness of Liners and Strength Members after Two Years

No.	Impacted	Test Temp(°C)	Liner		Strength Member	
			Oxygen Content (ppm)	Average Hardness (VHN)	Oxygen Content (ppm)	Average Hardness (VHN)
LASL-52	No	600	400	267	70	253
LASL-53	Yes	600	240	233	60	235
LASL-131	Yes	700	990	404 ^a	75	252 ^a
LASL-51	No	900	4100	647 ^a	60	260

^aBody or dome region only.

VI. SURVEILLANCE UNITS

Twelve MC2893 units, manufactured at MF in 1977 and 1978, and one MC3599 unit, manufactured at Los Alamos in 1983, were destructively examined. Seven of the units were impact tested. Identification of these 13 units, along with the tests and analyses performed, are shown in Table X.

TABLE X. Surveillance Units Tested and Examined

Fabrication		Type	Fabricator	Impact Test	Metallo- graphy	Liner	Liner Hardness	Fines Analysis
Unit	Date					Oxygen Content		
MAD-0138	11/77	2893	MF	X	X	X	X	X
MAD-0202	12/77	2893	MF	X	X	X	X	X
MAD-0211	1/78	2893	MF	—	X	X	—	X
MAD-0244	1/78	2893	MF	X	X	X	X	X
MAD-0270	1/78	2893	MF	—	X	X	X	X
MAD-0394	3/78	2893	MF	X	X	X	X	-
MAD-0405	3/78	2893	MF	—	X	X	X	-
MAD-0432	4/78	2893	MF	—	X	X	X	-
MAD-0476	4/78	2893	MF	—	X	X	X	-
MAD-0575	5/78	2893	MF	X	X	X	X	-
MAD-0592	6/78	2893	MF	—	X	X	X	-
MAD-0973	12/78	2893	MF	X	X	—	X	-
UAS-0301	2/83	3599	LANL	X	X	X	X	X

Although the condition of the strength members is of primary importance in the evaluation of surveillance units, the liners, which show the greatest effects because of contact with the fuel, are also evaluated.

A. Impact Tests

Some of the surveillance units returned for destructive examination are impacted against hardened steel at nominal conditions of 150 m/s and 450°C. These testing conditions are sufficient to rupture the liner and clad and are nearly sufficient to rupture the strength member on as-fabricated MC2893 or MC3599 heat sources. Therefore, this impact test is not for qualification purposes; it only serves to show whether the strength member has remained ductile.

Six of the MC2893 units and the MC3599 unit were impact tested at 147 to 152 m/s and 450°C. Photographs of two impacted MC2893 units (MAD-0202 and MAD-0973) and the impacted MC3599 unit (UAS-0301) are shown in Figs. 4 through 8. All the clads failed in the weld region on impact. The strength member of MAD-0575 was breached as indicated by an external alpha count after testing; the other 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 XI shows the diametral deformations of the seven impacted units. The average diametral deformations of the six MC2893 units were $-24.5 \pm 2.3\%$ and $+14.1 \pm 2.1\%$. These average deformations were higher (but not significantly so) than eight previously impacted MF surveillance units impacted during 1981 through 1984,¹⁻³ which averaged $-23.2 \pm 1.1\%$ and $+13.9 \pm 1.7\%$. Unit UAS-0301, which was the first impacted MC3599 surveillance unit examined, showed diametral deformations of -25.1% and $+15.6\%$. This deformation was somewhat higher than the average of the 14 MC2893 units impacted thus far ($-23.7 \pm 1.8\%$ and $+14.0 \pm 1.8\%$) but within one standard deviation from the mean.

Fig. 4. Impact face of MAD-0202 (left) after side-on impact at 147 m/s and 450°C. Nonimpacted unit on right for comparison.

Fig. 5. Side view of MAD-0202 (left) after impact at 147 m/s and 450°C. Nonimpacted unit on right for comparison.

Fig. 6. Impact face of MAD-0973 (left) after side-on impact at 151 m/s and 450°C. Nonimpacted unit on right for comparison.

Fig. 7. Side view of MAD-0973 (left) after impact at 151 m/s and 450°C. Nonimpacted unit on right for comparison.

(a) Impact face.

(b) Side view.

Fig. 8. UAS-0301 after side-on impact at 152 m/s and 450°C.

TABLE XI. Diametral Deformations of Surveillance Units Impacted at ~150 m/s and 450°C

Unit	Impact Velocity (m/s)	ΔH (%)	ΔW (%)	Clad Condition	SM Condition
MAD-0138	152	-25.8	+16.4	Breach	Intact
MAD-0202	147	-22.6	+13.1	Breach	Intact
MAD-0244	150	-23.3	+13.8	Breach	Intact
MAD-0394	150	-22.6	+12.4	Breach	Intact
MAD-0575	150	-28.5	+16.8	Breach	Breach
MAD-0973	151	-24.0	+11.8	Breach	Intact
Average		-24.5	+14.1		
UAS-0301	152	-25.1	+15.6	Breach	Intact

TABLE XII. 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-0138	130	330	85	279
MAD-0202	140	240	85	303
MAD-0211	610	590	110	---
MAD-0244	85	80	95	237
MAD-0270	100	190	60	264
MAD-0394	190	120	45	240
MAD-0405	310	130	75	269
MAD-0432	200	185	75	274
MAD-0476	200	100	55	263
MAD-0575	120	140	65	324
MAD-0592	140	110	75	303
MAD-0973	---	---	---	259
Average ^a	200	200	75	274
UAS-0301	300	140	110	328

^aTo nearest 5 ppm.

TABLE XIII. PuO₂ Fines from Surveillance Units

Unit	Type	Impacted	Amount (g)			
			<5 μm	5-10 μm	10-20 μm	<20 μm
MAD-0211	2893	No	0.02	0.10	0.05	0.17
MAD-0270	2893	No	0.03	0.04	0.06	0.13
Average			0.03	0.07	0.05	0.15
MAD-0138	2893	Yes	1.57	2.09	0.49	4.15
MAD-0202	2893	Yes	0.84	2.37	0.77	3.98
MAD-0244	2893	Yes	1.17	1.31	1.22	3.70
Average			1.19	1.92	0.83	3.94
UAS-0301	3599	Yes	1.02	1.90	0.67	3.59

B. Metallography

Longitudinal sections of the seven impacted units (after removal of the clad), along with photomicrographs of the areas of greatest thinning of the strength members in these sections are shown in Figs. 9 through 22. All units deformed similarly and all demonstrated the ductile nature of the strength member.

Fig. 9. Longitudinal section of impacted unit MAD-0138 As polished 45×

Fig. 10. Deformation of liner and strength member at bottom of impact surface in MAD-0138 Etched. 50×

Fig. 11. Longitudinal section of impacted unit MAD-0202. As polished. 4.2X

Fig. 12. Deformation of liner and strength member at bottom of impact surface in MAD-0202. Etched. 50X

Fig. 13. Longitudinal section of impacted unit MAD-0244. As polished. 48×

Fig. 14. Deformation of liner and strength member at bottom of impact surface in MAD-0244 Etched 50×

Fig. 15. Longitudinal section of impacted unit MAD-0394. As polished. 4.5×

Fig. 16. Deformation of liner and strength member at bottom of impact surface in MAD-0394. Etched 50×

Fig. 17. Longitudinal section of impacted unit MAD-0575. As polished. 4.2×

Fig. 18. Deformation of liner and strength member at bottom of impact surface in MAD-0575. Etched. 50×

Fig. 19. Longitudinal section of impacted unit MAD-0973 As polished 45×

Fig. 20. Deformation of liner and strength member at bottom of impact surface in MAD 0973 Etched 50×

Fig. 21. Longitudinal section of impacted unit UAS-0301. As polished. 4.5×

Fig. 22. Deformation of liner and strength member at bottom of impact surface in UAS-0301. Etched. 50×

In some of the liners, chemical interaction of the PuO_2 /yttrium mixture was observed at the bottom of the T-111 liner (dome area). Typical interactions are shown in Fig. 24.

The greater strength at the top of the units, attributable to the 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 causes extreme thinning of both the liner and the strength member.

Some variation in the angle between the impact face and the surface of the strength-member cap were observed. In the seven impacted units, this angle varied between 85.0° and 89.7° . However, no correlation was found between this angle and the minimum thickness of the strength member (measured only in the longitudinal sections shown). Minimum thicknesses in these strength-member sections measured 0.19 to 0.57 mm.

In MAD-0575, the strength member was breached although the longitudinal section in Fig. 18 showed only a thinning of the strength member to 0.19 mm. Further examination of this unit at other locations revealed a break in the strength member at a thickness of 0.14 mm (Fig. 23).

Fig. 23. Area of breach in the strength member of MAD-0575 after impact at 150 m/s and 450°C . Etched. $100\times$

Fig. 24. Bottom (dome area) of the liner of MAD-0476 showing (a) continuous and (b) intermittent fuel-clad chemical interaction. Fueled surface is at top. Etched. 100×

C. Oxygen Analyses and Microhardness Measurements of Liners

The oxygen contents of the 12 MC2893 liners for the dome, body, and weld-plus-cap regions averaged 200, 200, and 75 ppm, respectively (Table XII). There was no significant difference between these values and those of 19 previously examined¹⁻³ MC2893 surveillance units, which averaged 235, 330, and 110 ppm for the same regions. Also, we have not observed any trend of increasing

oxygen contents of the liners as a function of time between 1981 and 1986. Because of the relatively high oxygen levels found in the liner (600 ppm average) of MAD-0211, the strength member of this unit was analyzed for oxygen. Oxygen contents for the MAD-0211 strength member were 70 to 75 ppm in the body, dome, and weld regions, which showed no increase over values for as-fabricated strength members. The average oxygen content (dome and body) of the liner of the MC3599 unit, 220 ppm, was virtually the same as the 200-ppm average for the MC2893 units and the 210-ppm average for the only previously examined MC3599 unit.¹

Microhardness measurements taken in the body regions of the 12 MC2893 liners averaged 274 ± 27 VHN. The average liner hardness has increased slightly as a function of time. The average liner hardness for units examined in 1982 and 1983² was 253 ± 15 VHN, increasing to 259 ± 9 VHN for units examined in 1983 and 1984.¹ This progressive hardness increase, if not a result of statistical variation, may be the result of heat and neutron effects because the oxygen contents have not increased. The hardness of the liner body region of the MC3599 unit (UAS-0301) was 328 VHN, which was also greater than that of a similar unit (UAS-0008) examined in 1983,¹ which exhibited a hardness of 282 VHN.

D. Fines Analysis

Three impacted and two nonimpacted MC2893 units were cut open to characterize the amount of fines ($<20 \mu\text{m}$) in these surveillance units. In addition, the fines from the impacted MC3599 unit were analyzed. The results are shown in Table XIII.

The nonimpacted MC2893 units yielded an average of 0.15 g of fines smaller than $20 \mu\text{m}$. This mass is less than the average of 0.29 ± 0.18 g for 10 similar units manufactured in 1977 and 1978 and analyzed in 1982 through 1984.^{1,2} Respirable fines, which in the case of PuO_2 would be about $3 \mu\text{m}$ in diameter, were categorized as those particles that were less than $5 \mu\text{m}$ in diameter. The respirable fines from the nonimpacted units averaged 0.03 g, below the average of the 10 previously examined MC2893 units (0.07 ± 0.05 g).^{1,2}

The three impacted MC2893 units averaged 3.94 g of fines smaller than $20 \mu\text{m}$ and 1.19 g of respirable fines. These amounts are slightly higher than those found for four impacted MC2893 units examined during 1981 through 1983,^{2,3} which averaged 3.67 ± 0.21 g and 0.84 ± 0.13 g, respectively. Unit UAS-0301 was the first MC3599 unit to be impact tested; it yielded 3.59 g of fines less than $20 \mu\text{m}$ and 1.02 g of respirable fines.

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