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Milliwatt Generator Project

April 1986–March 1988

Los Alamos

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April 1986–March 1988

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LIST OF ABBREVIATIONS

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

MILLIWATT GENERATOR PROJECT

April 1986 – March 1988

by

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ABSTRACT

This report covers progress on the Milliwatt Generator Project from April 1986 through March 1988. 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 radioisotope 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. du Pont de Nemours and Co. (Inc.), Savannah River Plant (fuel); Monsanto Research Corporation, Mound Facility (metal hardware); and General Electric Company, Neutron Devices Department (RTGs). 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, 27 lots (5.72 kg) of SRP feed powder were processed through the MWG fuel-processing line to obtain 4.96 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 $19\,600\text{ n/s} \cdot \text{g}^{238}\text{Pu}$. After ^{16}O exchange and other processing, the average neutron emission rate of the fuel lots was $4\,060\text{ n/s} \cdot \text{g}^{238}\text{Pu}$.

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
171	629	402792	17 200	4 040
172	631	402802	17 100	4 580
174	636	403821	17 900	4 420
175	631	402800	16 100	3 930
176	637	403827	20 300	4 230
177	004	8604-013	18 800	3 830
178	004	8604-014	12 300	3 500
179	007	8605-027	18 400	3 880
180	004	8604-015	19 200	4 380
181	004	8604-016	20 500	4 410
182	005	8604-017	14 500	4 020
183	005	8604-018	17 000	3 960
184	005	8604-019	15 200	3 710
185	005	8604-020	20 000	4 270
186	006	8604-021	17 200	3 570
187	006	8605-022	17 900	3 830
188	006	8605-023	20 500	3 950
190	006	8605-024	17 400	3 860
191	007	8605-026	19 800	3 920
192	007	8605-027	17 800	4 260
193	007	8605-029	17 000	3 950
194	007	8605-030	23 200	3 900
195	028	8704-117	27 000	4 530
196	028	8704-118	21 000	3 990
197	028	8704-119	26 200	4 320
199	029	8703-122	26 100	3 900
200	029	8705-125	32 900	4 350
Average			19 600 ± 4 400	4 060 ± 280

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 it had been processed at Los Alamos. The data indicate that fuel processing reduced the average calcium level by 210 ppm but increased the average iron and silicon levels by 70 ppm and 45 ppm, respectively.

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 those of the Los Alamos analyses. Excellent agreement exists between the SRP and Los Alamos results. The ²³⁸Pu enrichment averaged 84.40% compared with 83.96% for fuel processed from April 1984 through March 1986.¹

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

Element	Specification (ppm)	As Received (ppm)	As Processed (ppm)
Ag	25	8	10
Al	175	60	75
B	10	<5	<5
Ba	25	<6	<6
Bi	25	<6	<6
Ca	315	310	100
Cd	25	<3	<3
Co	50	<13	<13
Cr	150	80	95
Cu	50	<13	<13
Fe	500	140	210
Mg	50	<13	<13
Mn	50	<13	<13
Ni	100	30	10
Pb	50	25	<13
Si	250	120	165
Sn	50	<13	<13
Zn	100	<25	<25

Table III. Plutonium Isotopic Contents of Feed Lots

Feed		Plutonium Isotope (wt %)				
Lot	Analyst	238	239	240	241	242
171	SRP	83.82	13.78	1.94	0.37	0.10
	LANL	83.89	13.73	1.93	0.36	0.09
172	SRP	83.54	13.94	2.02	0.41	0.09
	LANL	83.67	13.85	1.99	0.40	0.09
174	SRP	83.70	13.85	1.98	0.38	0.09
	LANL	83.68	13.84	2.00	0.39	0.09
175	SRP	83.52	13.96	2.02	0.41	0.09
	LANL	83.65	13.87	2.00	0.40	0.09
176	SRP	83.80	13.89	1.82	0.39	0.09
	LANL	82.07	15.44	2.03	0.36	0.09
177	SRP	84.60	13.22	1.83	0.30	0.05
	LANL	84.48	13.23	1.83	0.40	0.05
178	SRP	84.59	13.22	1.83	0.30	0.05
	LANL	84.53	13.21	1.82	0.39	0.05
179	SRP	85.67	12.37	1.58	0.34	0.04
	LANL	85.69	12.36	1.58	0.34	0.04
180	SRP	84.57	13.24	1.83	0.30	0.05
	LANL	84.42	13.30	1.84	0.39	0.05

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

Feed		Plutonium Isotope (wt %)				
Lot	Analyst	238	239	240	241	242
181	SRP	84.57	13.24	1.83	0.30	0.05
	LANL	84.46	13.26	1.83	0.39	0.05
182	SRP	84.98	12.90	1.73	0.36	0.04
	LANL	84.94	12.91	1.73	0.37	0.05
183	SRP	84.96	12.92	1.73	0.36	0.04
	LANL	84.88	12.96	1.75	0.37	0.05
184	SRP	84.96	12.92	1.73	0.36	0.04
	LANL	84.89	12.94	1.74	0.37	0.05
185	SRP	84.95	12.93	1.73	0.36	0.04
	LANL	84.92	12.93	1.74	0.37	0.05
186	SRP	85.23	12.71	1.67	0.34	0.04
	LANL	85.17	12.76	1.68	0.35	0.04
187	SRP	85.23	12.71	1.67	0.34	0.04
	LANL	85.17	12.75	1.68	0.35	0.05
188	SRP	85.22	12.73	1.67	0.34	0.04
	LANL	85.18	12.75	1.68	0.35	0.04
190	SRP	85.22	12.73	1.67	0.34	0.04
	LANL	85.17	12.77	1.68	0.34	0.04
191	SRP	85.56	12.48	1.60	0.32	0.04
	LANL	85.52	12.51	1.60	0.33	0.04
192	SRP	85.59	12.45	1.59	0.33	0.04
	LANL	85.60	12.44	1.59	0.33	0.04
193	SRP	85.58	12.45	1.59	0.33	0.04
	LANL	85.59	12.46	1.59	0.32	0.04
194	SRP	85.58	12.45	1.59	0.33	0.04
	LANL	85.54	12.49	1.60	0.32	0.04
195	SRP	83.24	14.31	2.02	0.31	0.12
	LANL	83.17	14.35	2.03	0.32	0.13
196	SRP	83.23	14.32	2.02	0.31	0.12
	LANL	83.18	14.36	2.02	0.32	0.13
197	SRP	83.23	14.32	2.02	0.31	0.12
	LANL	83.18	14.35	2.03	0.31	0.13
199	SRP	83.13	14.39	2.04	0.31	0.13
	LANL	83.13	14.39	2.04	0.31	0.13
200	SRP	83.15	14.38	2.04	0.31	0.13
	LANL	83.11	14.40	2.04	0.31	0.13
SRP Average		84.50	13.29	1.81	0.34	0.07
		±0.90	±0.70	±0.17	±0.03	±0.03
LANL Average		84.40	13.36	1.82	0.35	0.07
		±0.99	±0.80	±0.17	±0.03	±0.03

III. PRODUCTION OF HEAT SOURCES

During this report period, a total of 250 MC2893A heat sources (4.0 W) and 166 MC3599 heat sources (4.5 W) were accepted by the Department of Energy. The average thermal power of the MC2893A heat sources was 4.016 ± 0.006 W, and the average thermal power of the MC3599 units was 4.514 ± 0.007 W.

Acceptance rates for strength member and clad welding for MC2893A and MC3599 units were 98% – 100% during this reporting period. The acceptance rate (92%) for MC3599 liner welding was lower than that (99%) for MC2893A liner welding because the additional fuel loading caused greater plutonium contamination in the welding area. Fabrication summaries showing the various causes for rejection of MC2893A and MC3599 units are given in Tables IV and V, respectively.

Table IV. MC2893A Heat Source Fabrication Summary

Liner Assembly	Fabricated	261
	Rejected	2 ^a
	Yield	99%
Strength Member Assembly	Fabricated	278
	Rejected	1 ^b
	Yield	99%
Clad Assembly	Fabricated	254
	Rejected	4 ^c
	Yield	98%

^a1 — Insufficient weld penetration.

1 — High direct alpha count in weld area.

^b1 — Failed dye penetrant inspection.

^c2 — Visual appearance.

1 — Oversize diameter.

1 — Insufficient weld penetration.

Table V. MC3599 Heat Source Fabrication Summary

Liner Assembly	Fabricated	158
	Rejected	13 ^a
	Yield	92%
Strength Member Assembly	Fabricated	156
	Rejected	0
	Yield	100%
Clad Assembly	Fabricated	169
	Rejected	3 ^b
	Yield	98%

^a8 — High direct alpha count in weld area.

3 — Visual appearance.

2 — Insufficient weld penetration.

^b1 — Visual appearance.

1 — Insufficient weld penetration.

1 — Used incorrect hardware.

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, four MC2893A 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 glove box atmosphere at the time of fabrication, is summarized in Table VI.

Table VI. MC2893A Pressure-Burst Test Units

Unit No.	Pellet No.	Welding Atmosphere Impurities (ppm)		
		Oxygen	Nitrogen	Water
3956	MPT-12H	1	48	3
4479	MPT-13H	1	48	3
4491	MPT-14	1	48	3
4499	MPT-11H	1	18	3

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 years and at 600°C for times ranging from 2 to 15 years.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.

A 4.0-W compatibility test unit (LASL-132) that had been heat-treated at 700°C for 4 years was destructively examined. The Hastelloy-C clad on this unit had a dark oxidation layer as a result of its heat treatment in air. The liner, strength member, and clad of a similar compatibility test unit (LASL-131), which had been heat-treated at 700°C for 2 years, failed in a impact test.¹

Metallography of LASL-132 revealed that the liner had breached as a result of intergranular cracking (Fig. 1). The liner showed an increase in oxygen content in the dome region from 117 ppm in as-fabricated T-111 to 890 ppm after heat treatment. The average hardness in this region increased from 232 to 412 VHN (Table VII). These values are similar to those for LASL-131 (1100 ppm oxygen and 404 VHN).

Oxygen analyses and hardness values for the strength member of LASL-132 showed no evidence of oxygen transfer from the fuel to the strength member after 4 years at 700°C (Table VII). This confirms the results of LASL-131—that the yttrium addition and the T-111 liner are quite effective in preventing oxygen diffusion into the T-111 strength member at temperatures considerably above the heat source's operating temperature of about 450°C.

A 4.5-W compatibility test unit (LASL-142) that had been heat-treated at 600°C for 4 years was impacted (side on) at 151 m/s and 450°C. The impact face of the unit is shown in Fig. 2. As in LASL-53, which was heat-treated at 600°C for 2 years before impact testing,³ the clad partially bonded to the strength member along the impact face, and the liner and strength member appeared to have failed as a result of shear and bending stresses at impact (Fig. 3). Many cracks appeared in the liner near the breach (Fig. 4).

Fig. 1. Breach of the liner of LASL-132, showing intergranular cracking.

Table VII. Compatibility Test Results

Unit No.	Assembly	Oxygen (ppm)			Hardness (VHN)		
		Dome	Body	Weld + Cap	Dome	Body	Weld
132	Liner	890	340	120	412	436	266
	SM	85	90	60	220	236	245
142	Liner	300	190	90	277	267	254
	SM	80	85	90	274	252	252

Fig. 2. Impact face of LASL-142, showing extent of failure.

Fig. 3. Longitudinal section of liner and strength member of LASL-142 after impact at 151 m/s and 450°C. Clad is bonded to strength member along impact face. As polished. 4.5×

Fig. 4. Cracking in liner of LASL-142 in region near breach. Etched. 100×

Chemical analyses and hardness values of the liner and strength member of LASL-142 are shown in Table VII. These results were similar to previous results¹ for LASL-52 and LASL-53, which were heat-treated at 600°C for 2 years. Average oxygen content of the dome and body (sidewall) regions of the LASL-142 liner were 245 ppm compared with 400 ppm for LASL-52 and 240 ppm for LASL-53. Average hardness of the dome and body regions of the LASL-142 liner were 272 VHN compared with 267 VHN for LASL-52 and 232 VHN for LASL-53.

Although both LASL-53 and LASL-142 failed as a result of 150 m/s impacts, there has been little indication from average oxygen content (58–82 ppm) and average hardness values (235–263 VHN) of the strength members of the three units heat treated at 600°C that the mechanical properties of the strength member were degraded by diffusion of oxygen from the fuel. Some changes in the mechanical properties of the strength member could have occurred as a result of the prolonged heat treatments, however.

VI. SURVEILLANCE UNITS

Five MC2893 units, manufactured at MF during 1977–1979, three MC2893A units, manufactured at LANL during 1982–1983, and 10 MC3599 units, manufactured at LANL during 1982–1984, were destructively examined. Four of the units were impact tested. Identification of these 18 units, along with the tests and analyses performed, are shown in Table VIII. Although the condition of the strength member 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.

Four of the MC3599 units were impact tested at 147 to 152 m/s and 450°C. Photographs of two of the impacted units are shown in Figs. 5–6. All the clads failed in the weld region on impact. All of the strength members, although severely deformed in the dome region (see Subsection VI.B) were unbreached and all of the liners were breached.

Table VIII. Surveillance Units Tested and Examined

Fabrication		Type	Origin	Impact Test	Metallography	Liner Oxygen and Hardness	Fines Analysis
Unit	Date						
MAD-0090	11/77	2893	MF	—	X	X	X
MAD-0413	3/78	2893	MF	—	X	X	—
MAD-0512	5/78	2893	MF	—	X	X	—
MAD-0787	9/78	2893	MF	—	X	X	—
MAD-1048	1/79	2893	MF	—	X	X	X
UAS-0068	5/82	2893A	LANL	—	X	X	—
UAS-0345	3/83	2893A	LANL	—	X	X	—
UAS-0386	5/83	2893A	LANL	—	X	X	X
UAS-0107	8/82	3599	LANL	—	X	X	X
UAS-0109	8/82	3599	LANL	X	X	X	X
UAS-0115	9/82	3599	LANL	—	X	X	—
UAS-0296	1/83	3599	LANL	—	X	X	X
UAS-0297	1/83	3599	LANL	X	X	X	—
UAS-0353	3/83	3599	LANL	—	X	X	X
UAS-0398	5/83	3599	LANL	—	X	X	—
UAS-0755	3/84	3599	LANL	X	X	X	—
UAS-0957	7/84	3599	LANL	X	X	X	—
UAS-1190	9/84	3599	LANL	—	X	X	—

Fig. 5. UAS-0109 after side-on impact at 147 m/s and 450°C. A, Impact face; B, Side view.

Fig. 6. UAS-0755 after side-on impact at 151 m/s and 450°C. A, Impact face; B, Side view.

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 shows the diametral deformations of the four MC3599 impacted units. Including the one previously examined impacted MC3599 unit,¹ the average deformations of MC3599 units have been $-25.5 \pm 1.2\%$ and $+15.9 \pm 1.1\%$. These deformations are higher than the average of the 14 MC2893 units impacted thus far ($-23.7 \pm 1.8\%$ and $+14.0 \pm 1.8\%$). The MC3599 units contain $\sim 1.2\text{g}$ more PuO_2 fuel than the MC2893 units.

Table IX. Diametral Deformations of MC3599 Surveillance Units Impacted at ~ 150 m/s and 450°C

Unit	Impact Velocity (m/s)	$\Delta H(\%)$	$\Delta W(\%)$	Clad Condition	SM Condition
UAS-0109	147	-25.6	+16.0	Breach	Intact
UAS-0297	150	-24.9	+14.4	Breach	Intact
UAS-0755	151	-24.5	+16.4	Breach	Intact
UAS-0957	152	-27.5	+17.3	Breach	Intact
Average		-25.6	+16.0		

B. Metallography

Longitudinal sections of the four 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. 7–14. All units deformed similarly and all demonstrated the ductile nature of the strength member.

Fig. 7. Longitudinal section of impacted unit UAS-0109. As polished. 5×

Fig. 8. Deformation of liner and strength member at bottom of impact surface in UAS-0109. Etched. 50×

Fig. 9. Longitudinal section of impacted unit UAS-0297. As polished. 4.9×

Fig. 10. Deformation of liner and strength member at bottom of impact surface on UAS-0297. Etched. 50×

Fig. 11. Longitudinal section of impacted unit UAS-0755. As polished. 4.7×

Fig. 12. Deformation of liner and strength member at bottom of impact surface on UAS-0755. Etched. 50×

Fig. 13. Longitudinal section of impacted unit UAS-0957. As polished. 4.8×

Fig. 14. Deformation of liner and strength member at bottom of impact surface on UAS-0957. Etched. 50×

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. As usual, some variation in the angle between the impact face and the surface of the strength member cap was observed. In these four impacted units, this angle varied between 85.6 and 90 degrees. Minimum thicknesses of the strength members (measured only in the longitudinal sections shown) varied between 0.26 mm and 0.40 mm. No correlation between these impact angles and the minimum strength member thickness for these and seven previously examined units¹ was found.

Cracks in liners of nonimpacted units were observed in MAD-0512 (Fig. 15), UAS-0068 (Fig. 16), and UAS-0353 (Fig. 17). The cracks were predominantly intergranular but intragranular cracks were also observed. In some of the liners, chemical interaction of the PuO₂/yttrium mixture was observed at the bottom of the T-111 liner (dome area). Typical interactions are shown in Fig. 18.

C. Oxygen Analyses and Microhardness Measurements of Liners

The oxygen contents of the five MC2893 liners for the dome, body, and weld-plus-cap regions averaged 195, 150, and 70 ppm, respectively (Table X). There was no significant difference between these values and those for 30 previously examined MC2893 surveillance units, which averaged 225, 280, and 95 ppm for the same regions. The oxygen contents of the three MC2893A liners for the same regions averaged 280, 215, and 115 ppm, respectively. The oxygen contents of the 10 MC3599 liners for the same regions averaged 230, 150, and 85 ppm, respectively.

Microhardness measurements taken in dome and body regions of the five MC2893 and the three MC2893A liners averaged 278 ± 42 VHN, showing little difference from the average hardness of 274 VHN for 12 MC2893 liners measured during 1984–1986.¹ The microhardness of 12 MC3599 liners, including two previously examined,¹ averaged 291 ± 17 VHN.

Fig. 15. Cracking in liner of MAD-0512. Etched. 100×

Fig. 16. Cracking in liner of UAS-0068. Etched. 50×

Fig. 17. Cracking in liner of UAS-0353. Etched. 50×

Fig. 18. Typical fuel-clad chemical interaction at the bottom (dome area) of liners. A, UAS-0109; B, UAS-0296. Etched. 100×

Table X. Oxygen Contents and Microhardnesses of the T-111 Liners of Surveillance Units						
Unit	Oxygen Content (ppm)			Hardness of Liner (VHN)		
	Dome	Body	Weld and Cap	Dome	Body	Weld
MAD-0090	280	210	120	406	285	313
MAD-0413	260	230	85	186	248	220
MAD-0512	120	120	70	286	283	257
MAD-0787	95	115	45	277	287	269
MAD-1048	<u>215</u>	<u>80</u>	<u>50</u>	<u>250</u>	<u>271</u>	<u>249</u>
MC2893 Average ^a	195	150	70	281	275	262
UAS-0068	275	230	115	275	263	267
UAS-0345	260	310	100	287	284	266
UAS-0386	<u>310</u>	<u>110</u>	<u>130</u>	<u>272</u>	<u>280</u>	<u>264</u>
MC2893A Average ^a	280	215	115	278	276	266

Table X. Oxygen Contents and Microhardnesses of the T-111 Liners of Surveillance Units (continued)

Unit	Oxygen Content (ppm)			Hardness of Liner (VHN)		
	Dome	Body	Weld and Cap	Dome	Body	Weld
UAS-0107	270	320	100	269	300	280
UAS-0109	230	100	110	300	289	273
UAS-0115	560	130	90	302	300	272
UAS-0296	200	120	80	284	286	277
UAS-0297	170	100	85	316	297	278
UAS-0353	180	90	100	297	295	277
UAS-0398	150	140	90	303	286	276
UAS-0755	300	130	65	301	292	278
UAS-0957	110	230	65	296	290	290
UAS-1190	110	145	85	266	251	259
MC3599 Average ^a	230	150	85	293	289	276

^aTo nearest 5 ppm.

D. Fines Analyses

One impacted MC3599 unit and six nonimpacted MC2893, MC2893A, and MC3599 units were cut open to characterize the amount of PuO₂ fines (<20 μm) in these surveillance units. Respirable fines, which in the case of PuO₂ would be about 3 μm in diameter, were categorized as those particles that were less than 5 μm in diameter. The results are shown in Table XI.

The nonimpacted MC2893 and MC2893A units yielded an average of 0.32 g of fines smaller than 20 μm. This mass is near the average of 0.26 ± 0.16 g for 13 similar units manufactured in 1977 and 1978 and analyzed in 1982 through 1986.^{1,2,3} The respirable fines from these nonimpacted units averaged 0.09 g, also slightly higher than the average of the 13 previously examined MC2893 and MC2893A units (0.06 ± 0.05 g).

The three nonimpacted MC3599 units yielded an average of 0.21 g of fines smaller than 20 μm and 0.06 g of respirable fines. These results are comparable to those of the MC2893 and MC2893A units previously examined.

The impacted MC3599 unit yielded 1.26 g of respirable fines, above the average of seven previously examined impacted MC2893 units (0.99 ± 0.30 g). However, the amount of fines smaller than 20 μm was 3.31 g, below the average of 3.79 ± 0.25 g for the impacted MC2893 units.

Table XI. PuO₂ Fines from Surveillance Units

Unit	Type	Impacted	Amount (g)			
			<5 μm	5–10 μm	10–20 μm	<20 μm
MAD-0090	2893	No	0.12	0.16	0.28	0.56
MAD-1048	2893	No	0.07	0.09	0.06	0.22
Average			0.10	0.12	0.17	0.39
UAS-0386	2893A	No	0.07	0.05	0.06	0.18
UAS-0107	3599	No	0.06	0.11	0.06	0.23
UAS-0296	3599	No	0.02	0.02	0.02	0.06
UAS-0353	3599	No	0.09	0.16	0.10	0.35
Average			0.06	0.10	0.06	0.21
UAS-0109	3599	Yes	1.26	1.60	0.45	3.31

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