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INTERIM REPORT

Quarterly Progress Report Covering Period July 1 Through September 29, 1978—The Study of Plutonium Oxide Leak Rates from Shipping Containers

November 1978

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INTERIM REPORT

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QUARTERLY PROGRESS REPORT

July 1 - September 29, 1978

STUDY OF PLUTONIUM OXIDE LEAK RATES FROM SHIPPING CONTAINERS

INTRODUCTION

This study was initiated in October, 1976, as outlined in the 189 research proposal submitted previously. Several tasks are to be undertaken in this study which, when combined, have the end objective of defining the leak rates of plutonium oxide powder from characterized leaks.

This is the eighth quarterly report of this work. Previous reports were issued as BNWL-2260-1, -2, -3, -4, -5, -6, and -7. Each task will be identified and the progress during the reporting period briefly described.

PROGRESS TO DATE

TASK A -- Review literature and theoretical work relating to transmission of particles through channels

Task objective has been fulfilled, and two reports issued: "Supporting Information for the Estimation of Plutonium Oxide Leak Rates Through Very Samll Apertures," by L.C. Schwendiman, BNWL-2198, and "Transport of Particles Through Gas Leaks -- A Review," by L.C. Schwendiman and S.L. Sutter, BNWL-2218, January 1977.

TASK B -- Investigate the relationship of gas flow rates, leak geometries, pressure and temperatures

Milestone 1. Review literature on topic.

Milestone 2. Report on technical literature.

These milestones were reached and a document, "Estimation of Gas Leak Rates Through Very Small Orifices and Channels," by H.J. Bomelburg, BNWL-2223, was issued.

Milestone 3. Select method and design apparatus for flow experiments.

Milestone 4. Fabricate and assemble apparatus.

Milestone 5. Test apparatus.

Milestone 6. Conduct first test.

Milestones 1 through 6 were completed in FY-1977.

Milestone 7. Complete test series (orifices). January 1978.

Milestone 8. Draft report. March 1978.

Milestone 9. Issue report.

The document, "Measured Airflow Rates Through Microorifices and Flow Prediction Capability," NUREG/CR-0066 (PNL-2611) was issued in July 1978.

Milestone 10. Fabricate microcapillaries.

Milestone 11. Complete test series. April 1978.

Milestone 12. Draft report.

A revised draft of a document, "Measured Airflow Rates Through Tubing of Fine Bore," is being circulated for internal review.

TASK C -- Measure transmission of a well-characterized simulant (UO_2 powder) through leaks characterized in Task B

Milestone 1. Pressure vessel for simulating container available for experiments. June 1978.

Milestone 2. Convert airflow apparatus. Completed January 1978.

Milestone 3. First experiment completed.

Initial experiments to measure the transmission of UO_2 when the leakpath is above (APLA) or below (UPL) the powder level were completed in the third quarter and further experiments continued into the fourth quarter of FY-1978.

- Leakpaths Above The Static Powder Level With Powder Agitation (APLA)

Seventy-two experiments were completed during this reporting period. Three of these experiments investigated individual orifices in pressure decay. Results of all the experiments for which the uranium measurements have been completed are shown in Table A-1 (see Appendix A). The quantity of depleted uranium dioxide (DUO) measured is reported as total μg DUO transmitted, μg DUO/min, and μg DUO/cc air.

-- Individual orifice or capillary experiments

Experiments were completed on single orifices and capillaries. The powder transmission rates (μg/min) continued to increase as a function of orifice diameter (Figure 1). Figure 2 plots capillary DUO powder flow as a function of pressure for three nominal capillary diameters at two lengths. Powder transmission rate increases with diameter are mixed and appeared to increase with length, i.e., at 1000 psig, the longer 150 μm diameter capillary had six times the flow the the shorter 150 μm diameter capillary. The two values for the longer 250 μm diameter (30, 500 psig) are in question because of plugging which was apparent when the experiment began. However, these data are too few to show a functional relationship. Further investigation will be

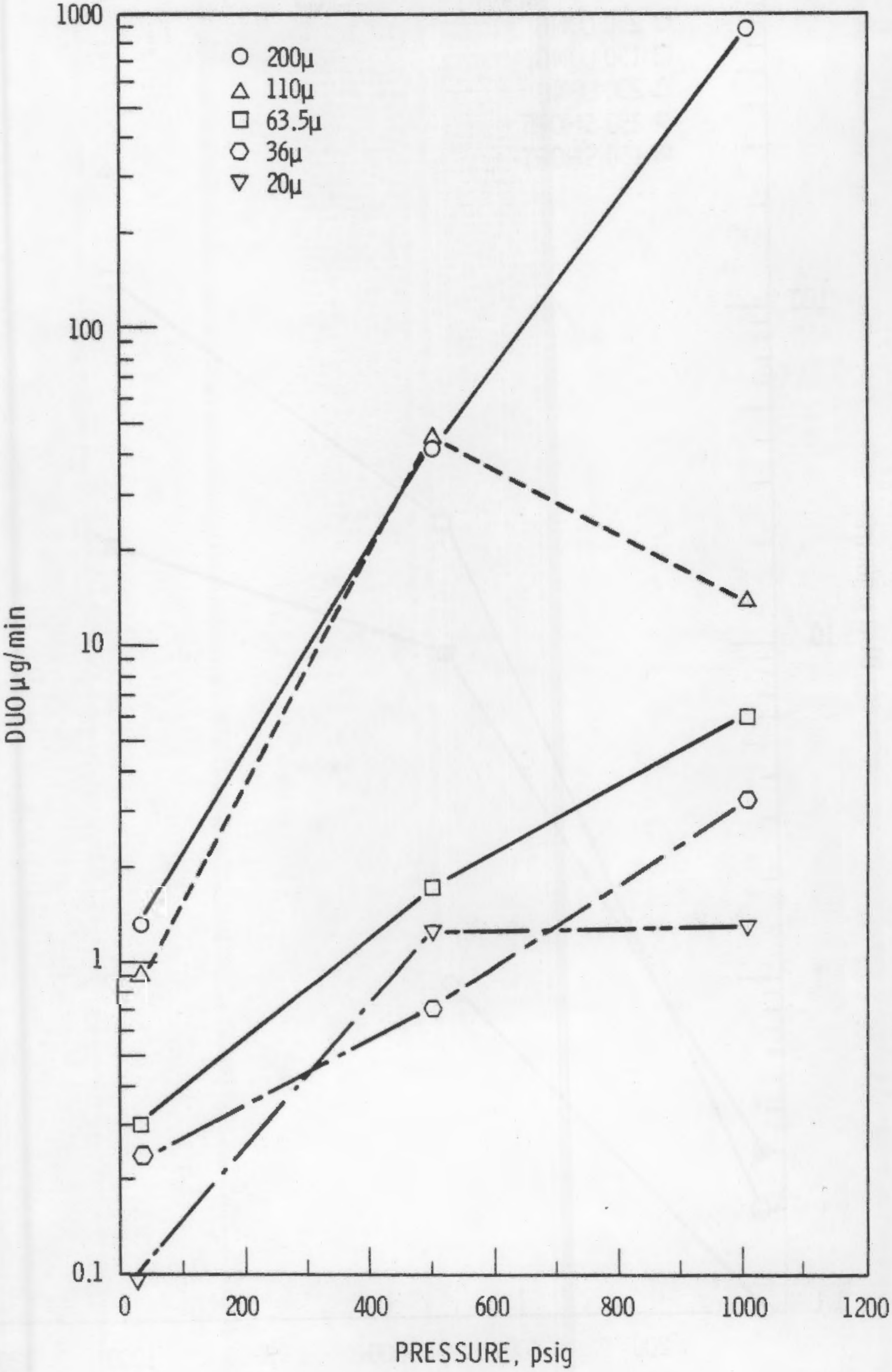

FIGURE 1 -- APLA Powder Leak Rates Through Orifices as a Function of Pressure

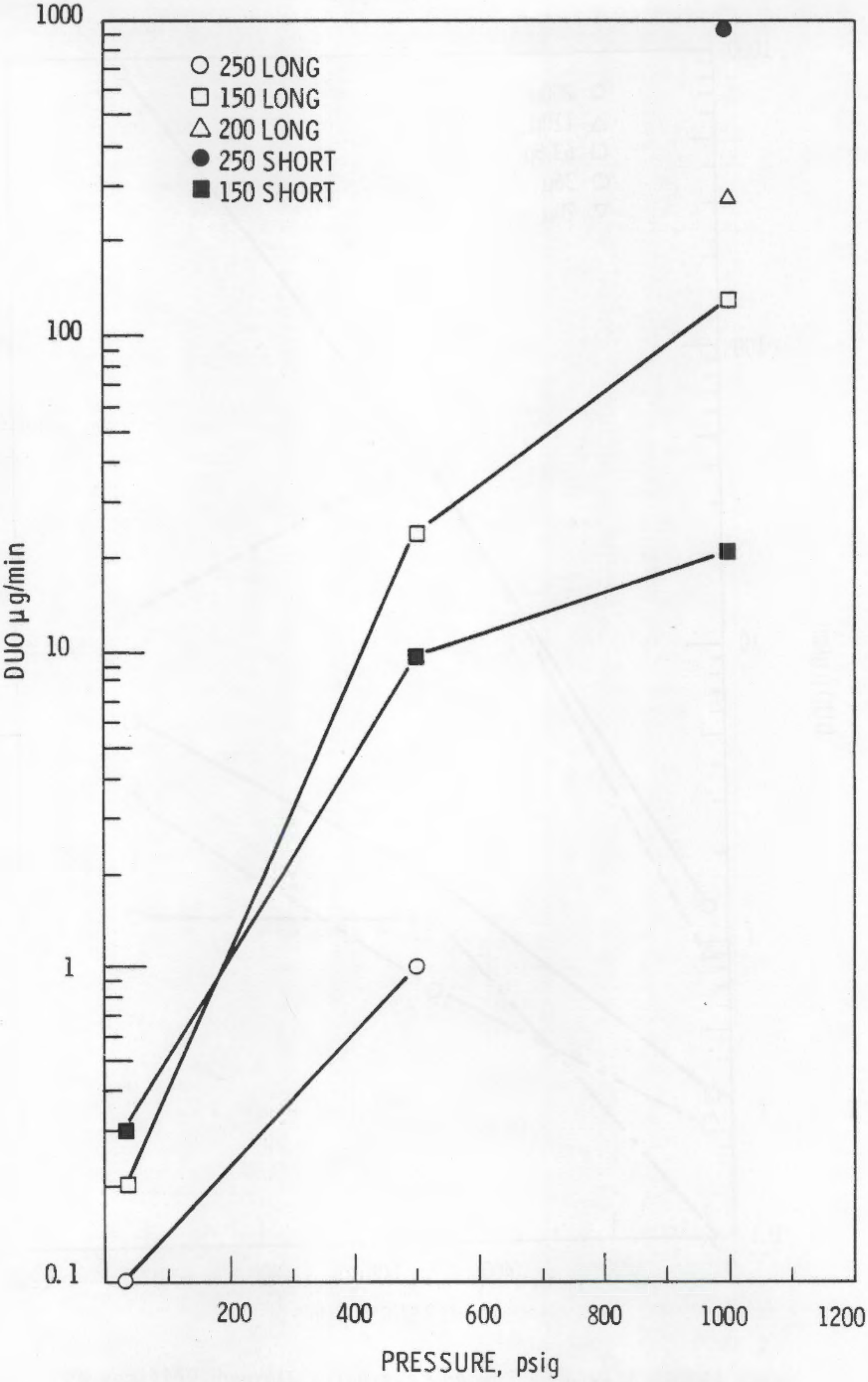

FIGURE 2 -- APLA Powder Leak Rates through Capillaries as a Function of Pressure

completed when replacements for broken and clogged capillaries are fabricated and characterized.

In the initial experiments, the known airflow rate at the designated pressure for the orifice or capillary was maintained by a vacuum. This compensated for the buildup of back pressure that would lower the flow rate below the desired value. Currently, a series of experiments have begun which do not use a vacuum to maintain flow; as a result, orifices exhibit a flow lower than the characterized airflow rate. Table I shows the percentage of deviation from the characterized orifice flow for two pressures.

TABLE I

UNAIDED AIRFLOW AS PERCENT OF CHARACTERIZED AIRFLOW RATE BY ORIFICE SIZE

psig	20 μm	36 μm	63.5 μm	110 μm	200 μm
1000	76,12	74,7	28	64	84
500	20	57	27	73	100

-- Multiple orifice and capillary experiments

Experiments are being performed to assess the anticipated standard deviation for individual powder transmission rates, for leakpaths of each nominal diameter under upstream conditions, and for changes in powder transmission as a function of time.

Multiple orifice runs showed as much as 100 percent standard deviation between samples. Table II compares the deviation between samples. There tends to be better agreement between samples at higher pressures and larger orifice diameters. This is the deviation between four samples for the nominal 20 μm and 36 μm diameter, 3 for the 63.5 μm and 110 μm, and 2 for the 200 μm.

TABLE II

VARIATION BETWEEN SAMPLES, TOTAL DUO TRANSMITTED AS PERCENT DEVIATION, SAME AEROSOLIZED POWDER

psig	20 μm	36 μm	63.5 μm	110 μm	200 μm
1000	65	55	50	29	10
500	35	29	6		
30	62	100	62		

The powder transmission does not seem to increase with time at 500 psig for the orifices tested. Fig. 3 is a bar graph comparing the total DUO transmitted for the longest sampling time of the multiple time increment experiments, the multiple uniform time samples, and the single orifice results. The 63.5 micron orifice that was sampled for 60 minutes at 1000 psig was the only one that showed a statistically significant increase in the amount of DUO transmitted above shorter time (10 min.) samples. The other orifices did not show an increase in DUO transmission with time. The results at 30 psig are mixed, and the potential deviation between samples make these results inconclusive.

The objective of this study is to correlate powder transmission with known gas leak rates. A finite amount of DUO powder seems to be transmitted in each cc of air as shown in the plot of μg/cc and airflow in Figure 4. If each cc of air transmitted contains a finite amount of uranium, then more DUO powder will be transmitted the higher the airflow rate. Figure 5 illustrates this trend by plotting of the transmission in μg/min as a function of airflow rate.

-- Pressure decay experiments

Six times as much DUO was transmitted through two nominal 63.5 μm orifices in a pressure decay experiment requiring 20 hours as through a single 63.5 μm orifice sampling for 10 minutes at 1000 psig. These experiments agitated the powder; the vessel was pressurized to 1000 psig and allowed to depressurize. There was no attempt to maintain a specific flow rate.

Three additional pressure decay experiments measured powder transmission under a decaying pressure regime. The estimated and required time to depressurize the vessel are shown in Table III. (The calculational methodology for the volume decay is shown in Appendix B.) The measured pressure decay is plotted in Figure 6.

TABLE III

TIME REQUIRED TO DEPRESSURIZE VESSEL

Diameter	Estimated Time, Min.	Required Time, Min.
100	75	132
125	48	85
200	19	27

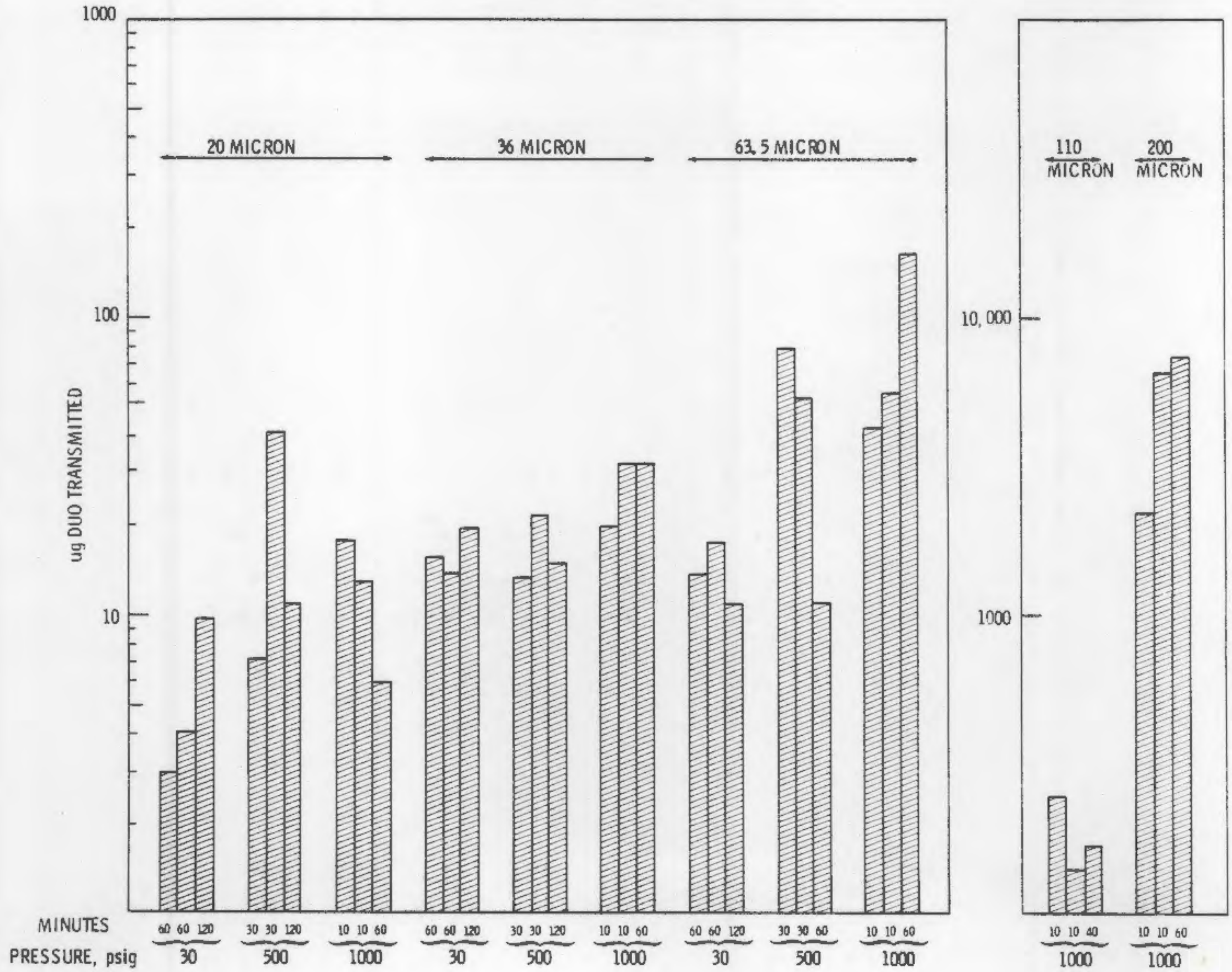

FIGURE 3 -- Total DUO Transmitted Through Orifices For Different Sampling Times

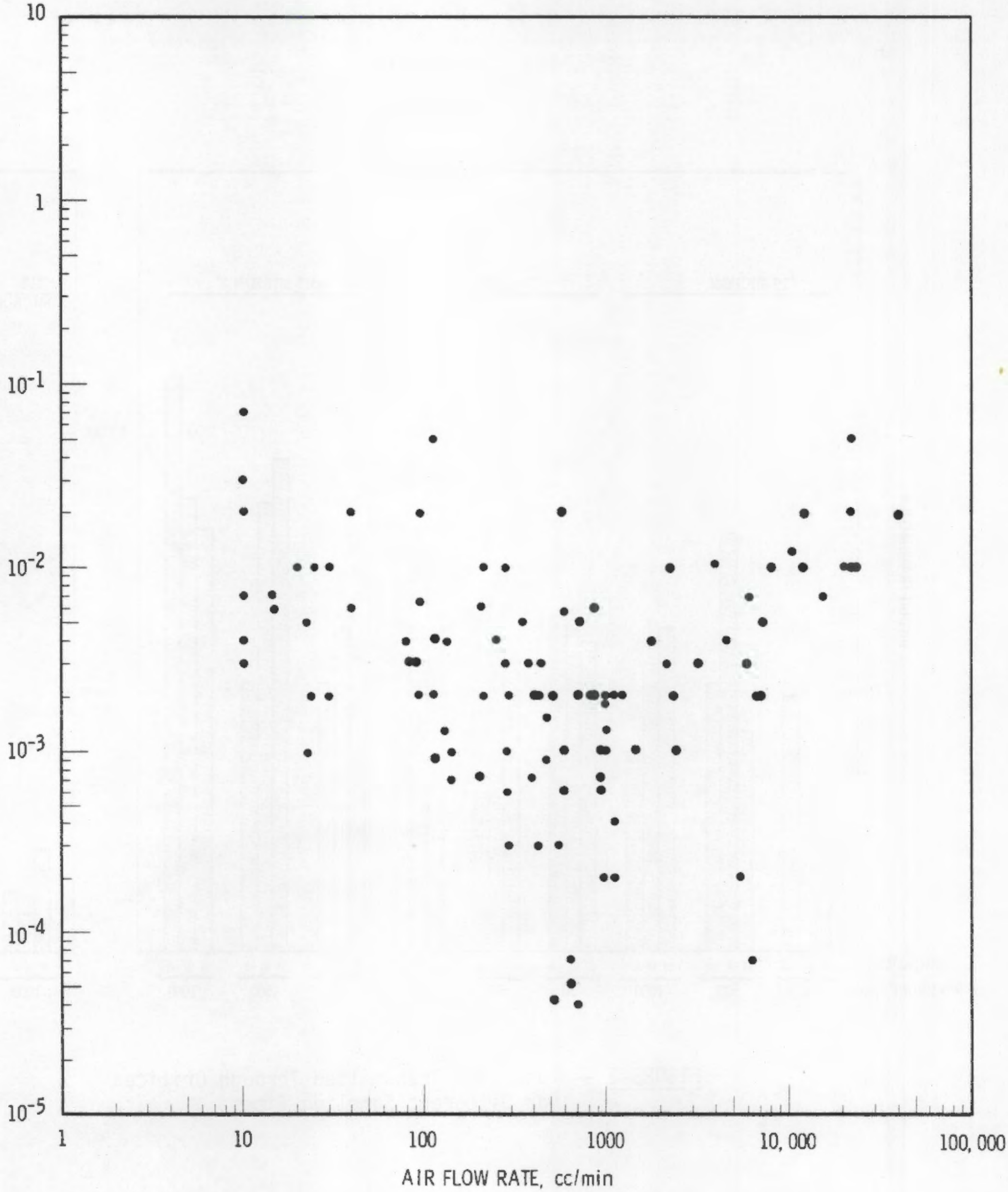

FIGURE 4 -- APLA Powder Flow Rates Through Characterized Leaks As a Function of Airflow Rate

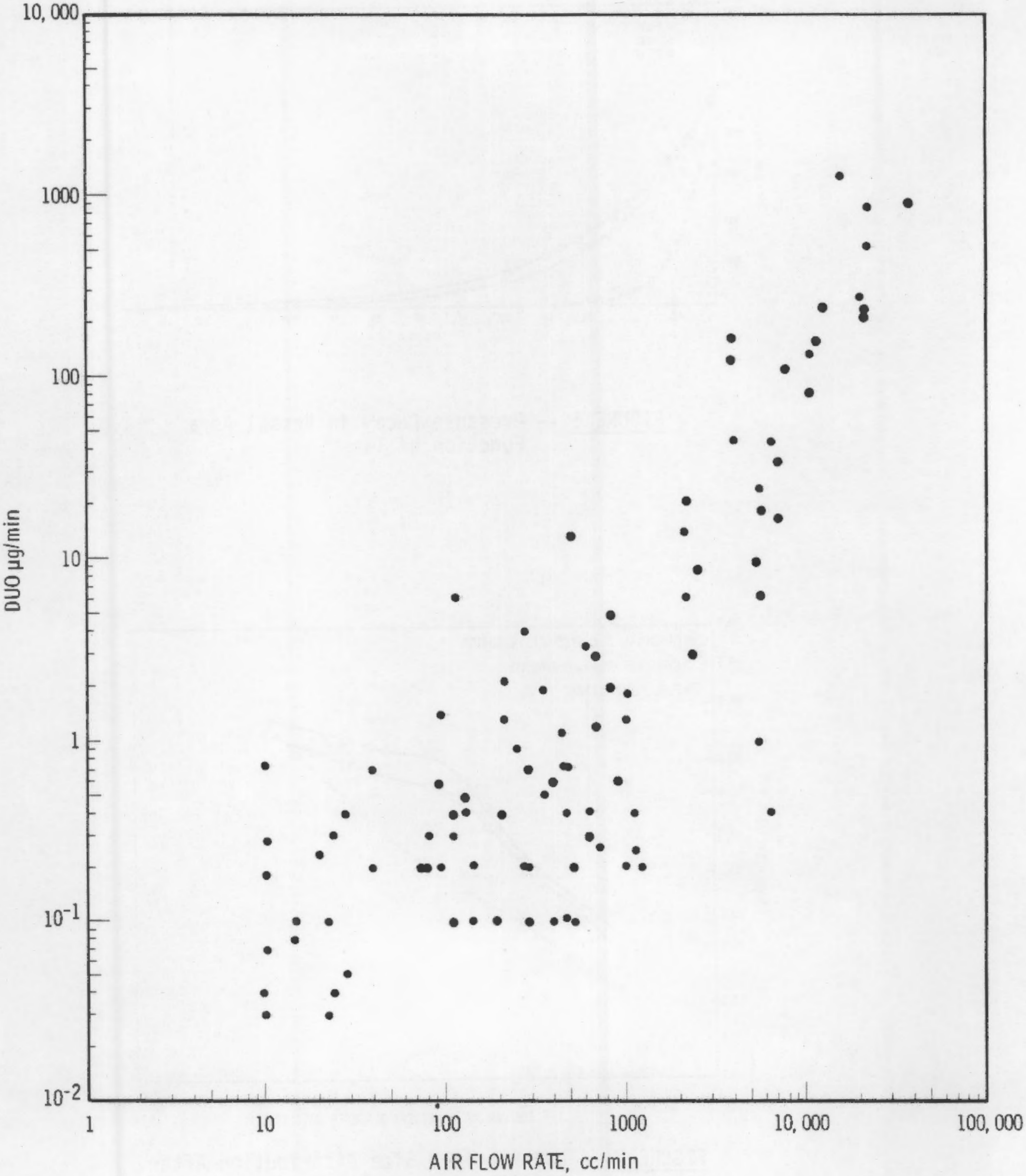

FIGURE 5 -- APLA Powder Flow Rates Through Characterized Leaks as a Function of Airflow Rates

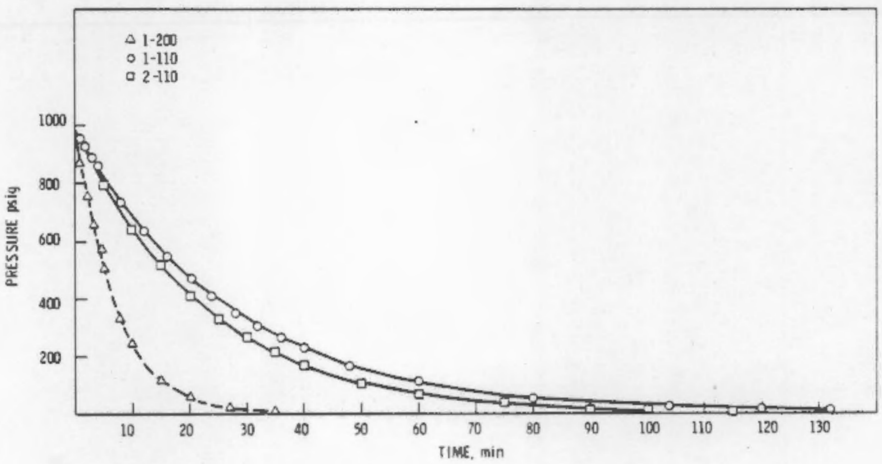

FIGURE 6 -- Pressure Decay in Vessel As a Function of Time

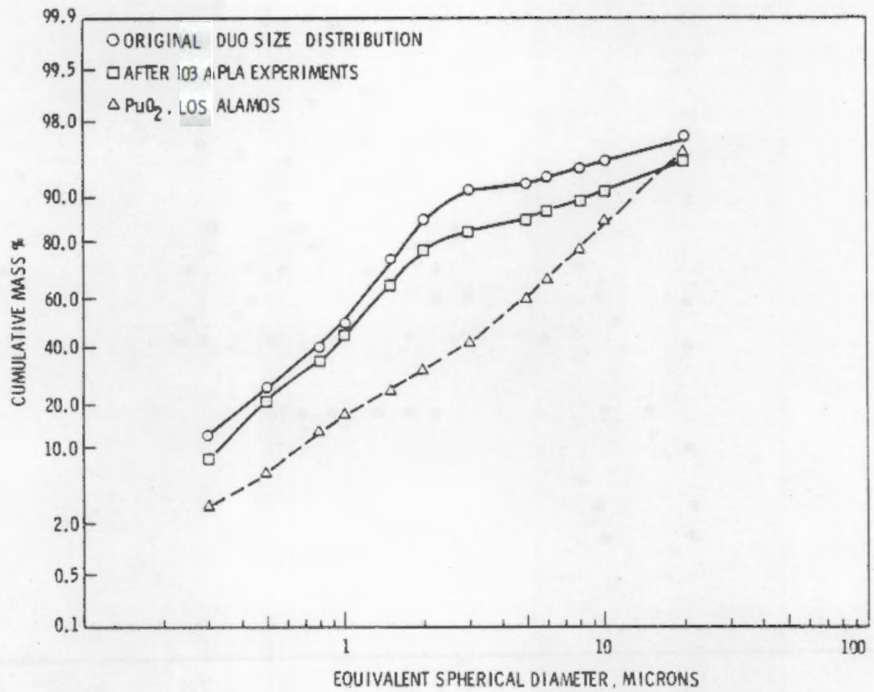

FIGURE 7 -- DUO Particle Size Distribution After 103 APLA Experiments

In event of an accident, several hours could elapse before a depressurized vessel with a minute break reaches ambient pressure, with no additional pressurization.

The DUO particle size did not change significantly during the APLA experiments. Figure 7 shows the DUO particle size distribution after 103 APLA experiments using the same bulk powder. Mass median diameter is now 1.1 μm, and there does not seem to be a significant depletion of fine particles by the aerosolization techniques.

- Leakpath Under the Powder Level (UPL)

Measurements of the DUO transmitted through leakpaths under the powder level are tabulated in Table A-2 (see Appendix A). The transmission rates for all nominal orifice sizes under 200 μm appeared to maximize at approximately 100 psig, decrease at 500 psig, and to increase at 1000 psig.(1) Powder transmission rates appear to increase with increasing diameter for the capillaries tested; all diameters were 182 μm or greater, as shown in plots in Figures 8 and 9. Agitation did not seem to be an important parameter. As the capillary length increased, the powder flow generally decreased. An exception was the 150 μm diameter at 1000 psig with no agitation, which was confirmed in reruns. This phenomenon will be investigated further when fabrication of more capillaries is completed.

TASK D -- Measure fuel grade PuO_2 leaks through a "standard leak" incorporated into a suitable container

Milestone 1. Design of experimental equipment.

Milestone 2. Assembly of experimental system.

Milestone 3. Simulant experiments.

Milestone 4. Transfer to glovebox.

Milestone 5. Conduct "hot experiments".

- "Standard Leak" Configuration

-- 5 μm Orifice

As discussed in the June 19, 1978, proposal for extended work (Proposal No. 585-J-4069R), the data at the bounding limits of each parameter must be adequately measured in order to determine the effects of the parametric interactions. Furthermore, to determine whether the relationships are linear or curvilinear, an internal data point must also be measured. Based on

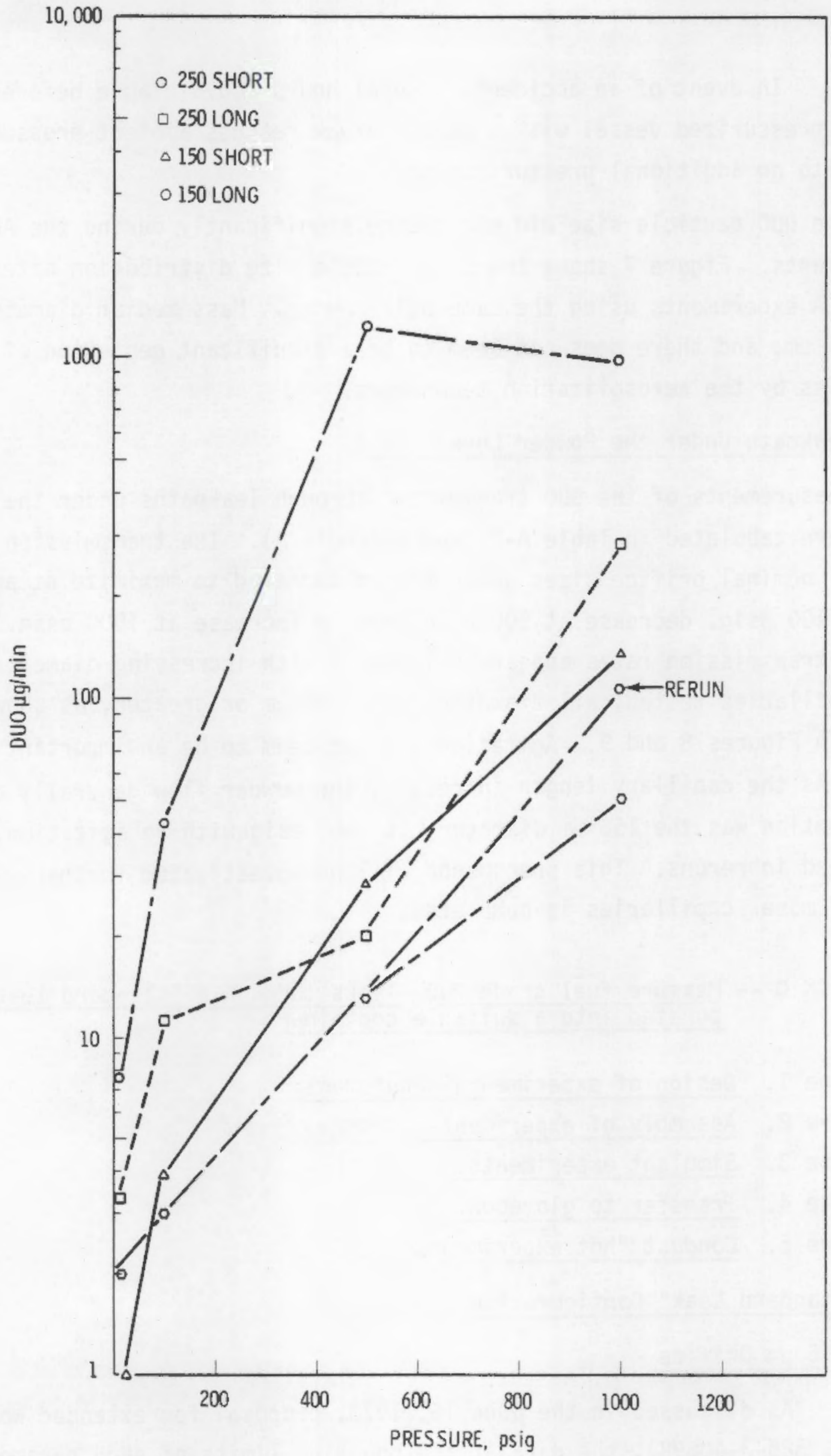

FIGURE 8 -- UPL Powder Leak Rates Through Capillaries As a Function of Pressure (Agitated)

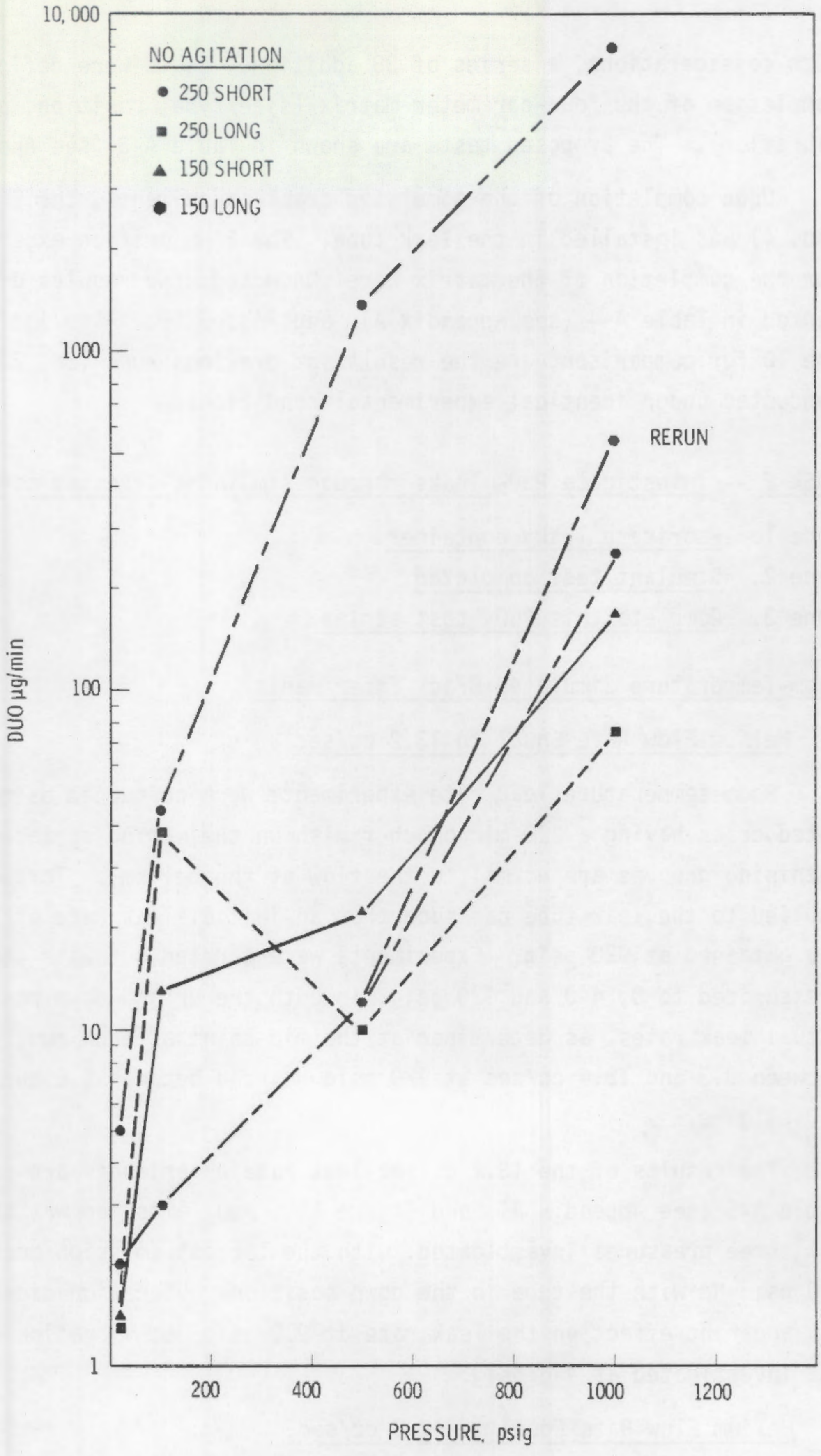

FIGURE 9 -- UPL Powder Leak Rates Through Capillaries As a Function of Pressure (No Agitation)

such considerations, a series of 38 additional tests were defined for the completion of the four-parameter matrix (size/type, position, pressure, vibration). The proposed tests are shown in Table A-3 (see Appendix A).

Upon completion of the simulated crack experiments, the 5 µm orifice (No. 4) was installed in the leak tube. The 5 µm orifice experiments required for the completion of the matrix were conducted, the results of which are presented in Table A-4 (see Appendix A) and Figure 10. Also included in Figure 10 for comparison, are the results of previous runs (28, 28a, 33, 33a) conducted under identical experimental conditions.

TASK E -- Investigate PuO_2 leaks through simulated defected containers

Milestone 1. Fabricate leaky container.

Milestone 2. Simulant test completed.

Milestone 3. Complete this PuO_2 test series.

- Room-Temperature Simulated Crack Experiments

-- Helium Flow Rate Equal to 13.2 cc/sec

Room-temperature leak rate experiments were conducted using the simulated crack having a 220-microinch finish on the mating surfaces (the machining grooves are normal to the flow of the helium). Torque was applied to the leak tube cap such that an initial leak rate of 13.2 cc/sec He was obtained at 920 psig. Experiments were carried out with the leak tube pressurized to 0, 440 and 920 psig, in both the up and down positions. The actual leak rates, as determined at the mid-point of each run, varied between 9.3 and 12.4 cc/sec at 920 psig He, and between 2.5 and 3.0 cc/sec at 440 psig He.

The results of the 13.2 cc/sec leak rate experiments are presented in Table A-5 (see Appendix A) and Figure 11. PuO_2 emission was observed at all three pressures investigated, with the largest emission occurring at 440 psig He with the tube in the down position. Vibration did not have any apparent effect on the leak rate at 920 psig He; vibration effects were not investigated at 440 psig.

-- Helium Flow Rate Equal to 17.3 cc/sec.

In these experiments, torque was applied to the leak tube cap to provide an initial leak rate of 17.3 cc/sec at 920 psig He. Actual leak rates

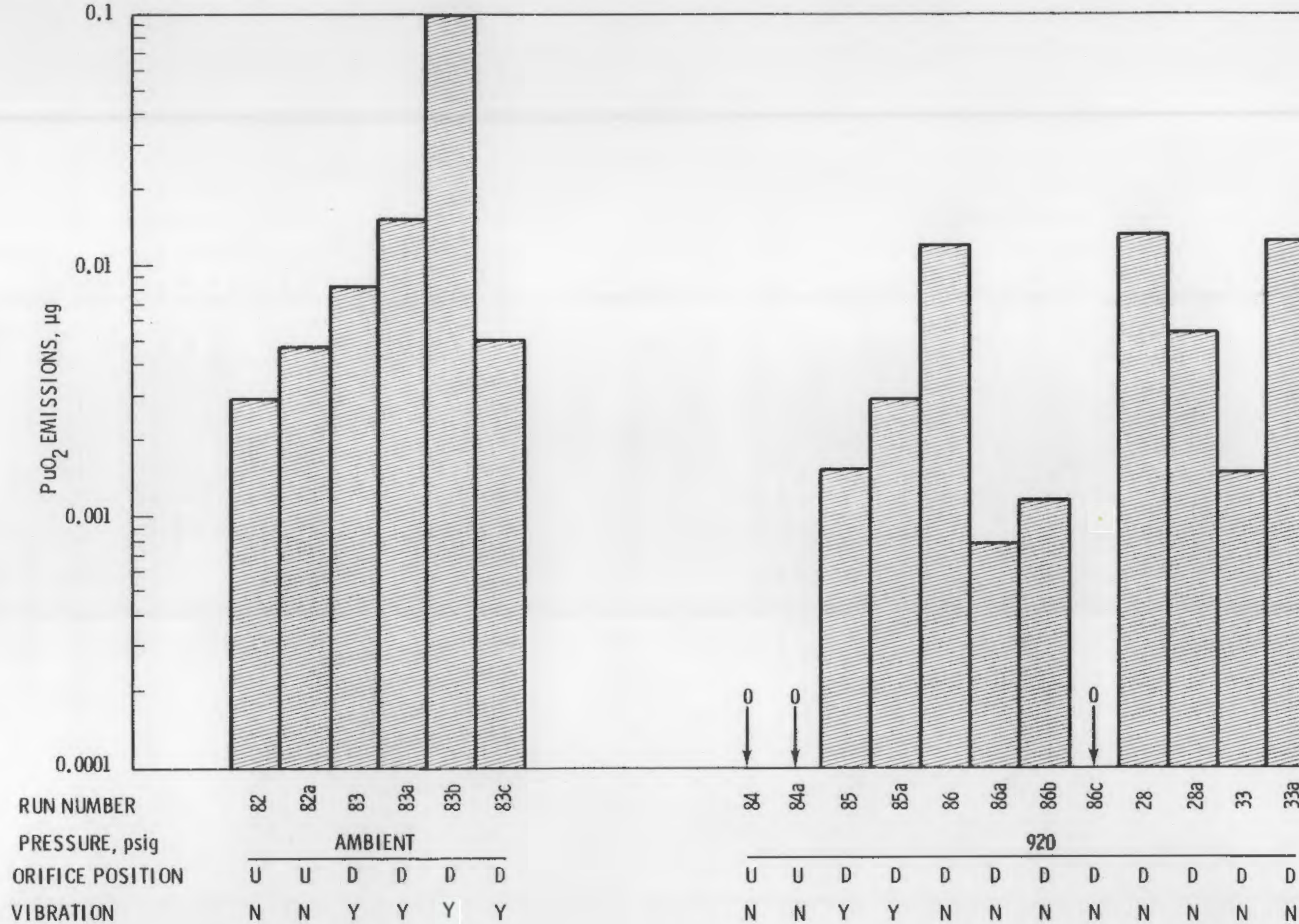

FIGURE 10 -- EFFECT OF EXPERIMENTAL CONDITIONS ON PuO_2 Emissions Through a 5-µm Orifice
(Note: Runs 28, 28a, 33 and 33a are previous runs show here only for comparison.)

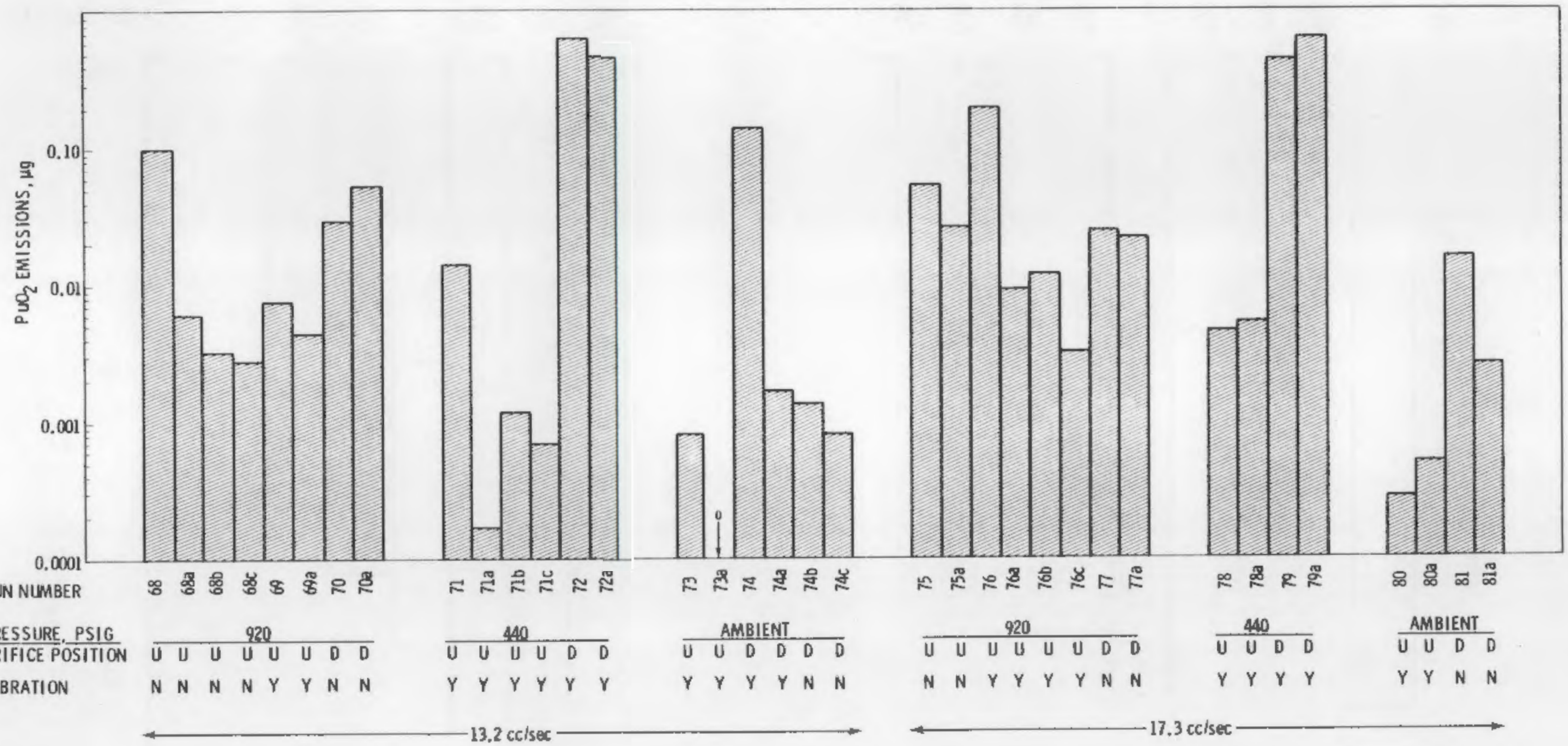

FIGURE 11 -- Effect of Experimental Conditions on PuO_2 Emissions through A Simulated Crack at Room Temperature With Two Initial He Flow Rates

varied from 8.25 to 16.3 cc/sec at 920 psig, but were a consistent 2.6 cc/sec at 440 psig. Consistent with observations at 13.2 and 9.8 cc/sec, the largest PuO_2 emission occurred at 440 psig with the leak tube in the down position. These data are presented in Table A-6 (see Appendix A) and Figure 11.

-- Summary of Simulated Crack Experiments

The experiments conducted during this reporting period complete the current series of simulated crack experiments. Additional experiments may be planned pending a statistical analysis of these data. Although the analysis has been initiated, a detailed discussion of the results and their interpretation is not feasible at this time.

The simulated crack experiments were conducted at initial helium leak rates of 9.8, 11.4, 11.6, 13.2, and 17.3 cc/sec at 920 psig. The results of experiments at the first three leak rates were presented in the Seventh Quarterly Progress Report (April - June, 1978). The parametric matrix of experimental conditions presented in Table A-7 (see Appendix A) serves as a summary of the completed experiments. A total of 92 experiments have been conducted.

The standard deviation and the mean amount of PuO_2 leaked are listed in Table A-8 (see Appendix A) as are the coordinates of these data points. Each set of numbers in the table corresponds to a single set of experimental conditions, under which two or more tests were conducted. Consistent with observations made for the orifice data (Proposal No. 585-3-4069R), the standard deviation for a given experimental condition is directly proportional to the amount of PuO_2 leaked, as shown in Figure 12. Further statistical analysis and data interpretation are in progress.

• Future Work

The statistical analysis and data interpretation of the simulated crack data will continue. Experiments to complete the four-parameter matrix will continue.

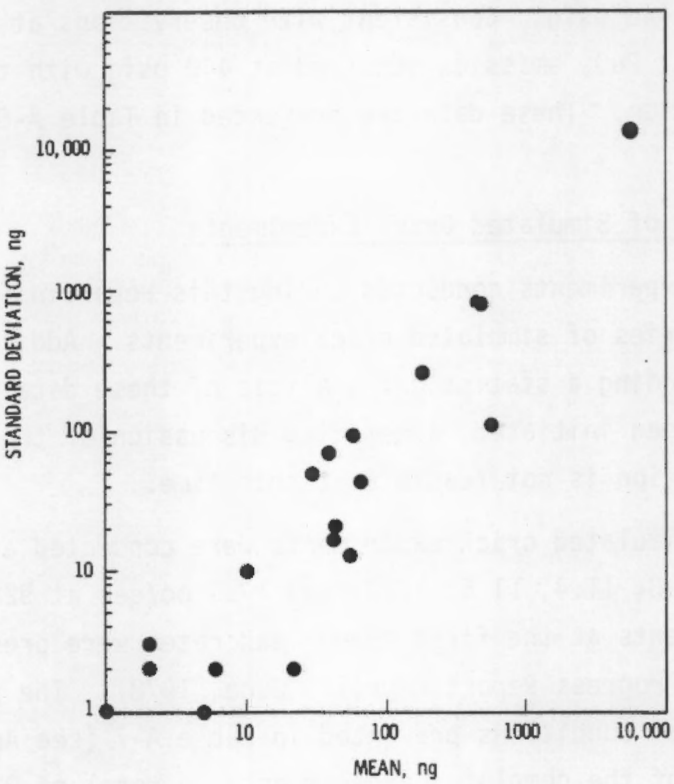

FIGURE 12 -- Standard Deviation Versus Mean For Simulated Crack Experiments

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(1) L.C. Schwendiman, et al. Quarterly Progress Report, April 1 through June 30, 1978 -- Study of Plutonium Dioxide Leak Rates from Shipping Containers, PNL-2260-7, Battelle, Pacific Northwest Laboratory, Richland, Washington 99352, August 29, 1978.

(2) H.J. Bomelburg. Estimation of Gas Leak Rates Through Very Small Orifices and Channels, BNWL-2223, Battelle, Pacific Northwest Laboratories, Richland, Washington 99352.

APPENDIX A

TABLES

TABLE A-1 -- Depleted Uranium Dioxide Transmitted Through Well Characterized Leaks

APLA	ORIFICE OR CAPILLARY DESIGNATION	MEASURED DIAMETER µm	CHAMBER PRESSURE psig	TIME min	AIR FLOW cc/min	TRANSMITTED[4] DUO, µg	DUO µg/min	DUO µg/cc
1	1-110	100	1000	20	7100[2]	5.23 ± 1.6	0.26	4×10^{-5}
2	1-200	200	1000	20	16400[2]	$2.5 \times 10^{4} \pm 8.7 \times 10^{3}$	1.25×10^{3}	8×10^{-3}
3[1]	1-110	100	1000	10	2100[2]	140 ± 42	14	7×10^{-3}
4	2-110	125	500	30	4300-3800[3]	1330 ± 410	44	1×10^{-2}
5	2-200	200	500	30	6200[2]	1300 ± 340	43	7×10^{-3}
6	2-63.5	61	1000	10	2100	55.6 ± 17	6	3×10^{-3}
7								
7-1	1-20	22	500	10	111	60.7 ± 18	6	5×10^{-2}
7-2	1-20a	23	500	30	133	16.4 ± 4.9	0.5	3.8×10^{-3}
7-3	2-20	20	500	60	94	36.7 ± 11	0.6	6.5×10^{-3}
7-4	3-20	23	500	120	140	10.6 ± 3.2	0.1	7.1×10^{-4}
8	2-20	20	1000	10	210	13.2 ± 4	1.3	6×10^{-3}
9	2-36	33	1000	10	580	33.1 ± 9.9	3.3	6×10^{-3}
10	2-63.5	61	500	30	1000	54.7 ± 16	1.8	2×10^{-3}
11	3-36	38	500	30	470	21.7 ± 6.5	0.7	2×10^{-3}
12	2-20	20	500	30	94	42.8 ± 13	1.4	2×10^{-2}
13	1-200	200	1000	10	22000	5090 ± 2600	509	2×10^{-2}
14	250 A	274	500	30	5400[2]	30.4 ± 9.1	1	2×10^{-4}
15	150 A	189	1000	10	10500	1280 ± 660	128	1.2×10^{-2}
16	2-200	200	1000	10	22000	8730 ± 4400	873	4×10^{-2}
17	1-200	200	30	60	1000	80.3 ± 24	1.3	1×10^{-3}
18	1-110	100	30	60	245	56.3 ± 17	0.9	4×10^{-3}
19	1-63.5	66	30	60	80	17.8 ± 5.3	0.3	4×10^{-3}

(1) DUPLICATE OF 1 BECAUSE OF POOR PRESSURE CONTROL IN RUN 1

(2) LESS THAN DESIRED FLOW

(3) DROPPED 1 MINUTE INTO RUN

(4) THE ± IS THE UNCERTAINTY IN THE URANIUM ANALYSIS AT THE 2σ CONFIDENCE LEVEL

TABLE A-1 (Continued)

APLA	ORIFICE OR CAPILLARY DESIGNATION	MEASURED DIAMETER µm	CHAMBER PRESSURE psig	TIME min	AIR FLOW cc/min	TRANSMITTED[4] DUO,µg	DUO µg/min	DUO µg/cc
20								
20-1	3-30	33	500	10	350	19.3 ± 5.8	1.9	5×10^{-3}
20-2	1-36	43	500	30	435	32.2 ± 9.7	1.1	3×10^{-3}
20-3	2-36	33	500	60	285	10.3 ± 3.1	0.2	6×10^{-4}
20-4	3-36	38	500	120	470	15 ± 4.5	0.1	3×10^{-4}
21	1-200	~200	500	30	6400 [2]	12.8 ± 3.8	0.4	7×10^{-5}
22								
22-1	3-30	33	500	30	350	10.5 ± 3.2	0.5	1×10^{-3}
22-2	1-36	43	500	30	435	20.4 ± 6.1	0.7	2×10^{-3}
22-3	2-36	33	500	30	285	12.3 ± 3.7	0.4	1×10^{-3}
22-4	3-36	38	500	30	470	11.3 ± 3.4	0.4	9×10^{-4}
23	250 A	274	1000	10	0-1000 [2]	12.7 ± 3.8	1.3	1.3×10^{-3}
24								
24-1	1-20	22	500	30	111	7.9 ± 2.4	0.3	2×10^{-3}
24-2	2-20	20	500	30	94	5.5 ± 1.6	0.2	2×10^{-3}
24-3	3-20	23	500	30	140	4.5 ± 1.3	0.2	1×10^{-3}
24-4	1-20 a	23	500	30	133	10.9 ± 3.3	0.4	3×10^{-3}
25								
25-1	1-63.5	66	500	30	1100	75.6 ± 23	2.5	2×10^{-3}
25-2	2-63.5	61	500	30	1000	78.7 ± 24	2.6	3×10^{-3}
25-3	3-63.5	65	500	30	1200	87.3 ± 26	2.9	2×10^{-3}
26	150 B	176	500	30	5600	720 ± 330	24	4×10^{-3}
27								
27-1	1-63.5	66	500	10	1100	4 ± 1.2	0.4	4×10^{-4}
27-2	2-63.5	61	500	30	1000	6.1 ± 1.8	0.2	2×10^{-4}
27-3	3-63.5	65	500	60	1200	10.8 ± 3.2	0.2	2×10^{-4}
28	200 B	231	1000	10	20000	2690 ± 1100	269	1×10^{-2}

TABLE A-1 (Continued)

APLA	ORIFICE OR CAPILLARY DESIGNATION	MEASURED DIAMETER µm	CHAMBER PRESSURE psig	TIME min	AIR FLOW cc/min	TRANSMITTED[4] DUO, µg	DUO µg/min	DUO µg/cc
29								
29-1	1-20	22	1000	10	275	36.5 ± 11	4.0	1×10^{-2}
29-2	1-20 a	23	1000	10	275	9.2 ± 2.8	0.9	3×10^{-3}
29-3	2-20	20	1000	10	210	20.9 ± 6.3	2.1	1×10^{-2}
29-4	3-20	23	1000	10	290	6.0 ± 1.8	0.6	2×10^{-3}
30								
30-1	1-20	22	1000	10	275	6.8 ± 2	0.7	3×10^{-3}
30-2	1-20 a	23	1000	20	275	3.3 ± 1.2	0.2	7×10^{-4}
30-3	2-20	20	1000	30	210	13.2 ± 3.9	0.4	2×10^{-3}
30-4	3-20	23	1000	60	290	5.8 ± 1.7	0.1	3×10^{-4}
31								
31-1	1-20	22	30	10	10	7.3 ± 2.2	0.73	7×10^{-2}
31-2	1-20a	23	30	30	10.3	8.5 ± 2.5	0.28	3×10^{-2}
31-3	2-20	20	30	60	9.5	10.9 ± 3.3	0.18	2×10^{-2}
31-4	3-20	23	30	120	14.5	9.8 ± 2.9	0.08	6×10^{-3}
32	1-36	43	30	60	20	14.2 ± 4.3	0.24	1×10^{-2}
33								
33-1	1-20	22	30	60	10	< 1.6 ± 1.6	< 0.03	$< 3 \times 10^{-3}$
33-2	1-20a	23	30	60	10.3	2.4 ± 1.6	0.04	4×10^{-3}
33-3	2-20	20	30	60	9.5	< 1.6 ± 1.6	< 0.03	$< 3 \times 10^{-3}$
33-4	3-20	23	30	60	14.5	6.0 ± 1.8	0.1	7×10^{-3}
34	250 A	274	30	60	1180 (5)	2.4 ± 1.6	0.04	3×10^{-5}
35								
35-1	3-30	33	30	10	28	3.8 ± 1.6	0.4	1×10^{-2}
35-2	1-36	43	30	30	22	2.9 ± 1.6	0.1	5×10^{-3}

(5) Through flow was achieved wire could not be run through, appears plugged after run

TABLE A-1 (Continued)

APLA	ORIFICE OR CAPILLARY DESIGNATION	MEASURED DIAMETER µm	CHAMBER PRESSURE psig	TIME min	AIR FLOW cc/min	TRANSMITTED [4] DUO, µg	DUO µg/min	DUO µg/cc
35 (CONT'D)								
35-3	2-36	33	30	60	24	2.6 ± 1.6	0.04	2×10^{-3}
35-4	3-36	38	30	120	39	20.1 ± 6	0.2	5×10^{-3}
36	1-20	22	30	60	10	4.1 ± 1.6	0.07	7×10^{-3}
37	250 B	274	30	60	520	5.9 ± 1.8	0.1	2×10^{-4}
38 38-1	3-30	33	30	60	28	3.1 ± 1.6	0.05	2×10^{-3}
38-2	1-36	43	30	60	22	2.0 ± 1.6	0.03	1×10^{-3}
38-3	2-36	33	30	60	24	17.5 ± 5.3	0.3	1×10^{-2}
38-4	3-36	38	30	60	39	43.7 ± 1.3	0.7	2×10^{-2}
39								
39-1	1-63.5	66	1000→0	1200	--	303 ± 91	0.3	--
39-2	2-63.5	61	1000→0	1200	--	49.8 ± .5	0.04	--
39-3	3-63.5	65	1000→0	1200	--	326 ± 98	0.3	--
40								
40-1	1-63.5	66	1000	10	2300	43.2 ± 13	4.3	2×10^{-3}
40-2	2-63.5	61	1000	10	860 (2)	20.3 ± 6.1	2.0	2×10^{-3}
40-3	3-63.5	65	1000	10	1760 (2)	76.8 ± 23	7.7	4×10^{-3}
41	150 S	182	1000	10	14600	212 ± 64	21.2	1×10^{-3}
42								
42-1	1-63.5	66	1000	10	200 (2)	17.8 ± 5.3	2	1×10^{-2}
42-2	2-63.5	61	1000	30	1450 (2)	61.9 ± 19	2	1×10^{-3}
42-3	3-63.5	65	1000	60	2400	167 ± 50	3	1×10^{-3}
43	150 S	182	500	30	5600	290 ± 87	9.7	2×10^{-3}
44	150 B	176	30	60	520	12.4 ± 3.7	0.2	4×15^{-4}

TABLE A-1 (Continued)

APLA	ORIFICE OR CAPILLARY DESIGNATION	MEASURED DIAMETER μm	CHAMBER PRESSURE psig	TIME min	AIR FLOW cc/min	TRANSMITTED (4) DUO,μg	DUO μg/min	DUO μg/cc
45	150 S	182	30	60	640	18.0 ± 5.4	0.3	5×10^{-4}
46								
46-1	3-30	33	1000	10	695	11.5 ± 3.5	1.2	2×10^{-3}
46-2	1-36	43	1000	20	840	97.3 ± 29	4.9	6×10^{-3}
46-3	2-36	33	1000	30	580	10.7 ± 3.2	0.4	6×10^{-4}
46-4	3-36	38	1000	60	920	32.6 ± 9.8	0.5	6×10^{-4}
47								
47-1	3-30	33	1000	10	695	33.6 ± 10	3.4	5×10^{-3}
47-2	1-36	43	1000	10	840	20.5 ± 6.2	2.0	2×10^{-3}
47-3	2-36	33	1000	10	580	1.35×10^3 ± 510 (6)		
47-4	3-36	38	1000	10	920	6.3 ± 1.9	0.6	7×10^{-4}
48								
48-1	1-63.5	66	30	30	80	6.19 ± 1.9	0.2	3×10^{-3}
48-2	2-63.5	61	30	60	88	15.3 ± 4.6	0.3	3×10^{-4}
48-3	3-63.5	65	30	120	109	11.0 ± 3.3	0.09	9×10^{-4}
49								
49-1	1-63.5	66	30	57	80	12.2 ± 3.7	0.2	3×10^{-3}
49-2	2-63.5	61	30	57	88 (7)	4.3 ± 1.7	0.08	9×10^{-4}
49-3	3-63.5	65	30	57	109	25 ± 7.5	0.4	4×10^{-3}
50	100 B	99	1000	10	3140	87.8 ± 26	8.8	3×10^{-3}
51								
51-1	1-110	100	1000	15	7100	259 ± 78	17.3	2×10^{-3}
51-2	2-110	125	1000	30	500 (2)	401 ± 120	13.4	2×10^{-3}
51-3	3-110	100	1000	40	5800	250 ± 75	6.3	1×10^{-3}

(6) This orifice inadequately sealed, leaked duo (results omitted)

(7) Lost flow after 30 minutes

TABLE A-1 (Continued)

APLA	ORIFICE OR CAPILLARY DESIGNATION	MEASURED DIAMETER µm	CHAMBER PRESSURE psig	TIME min	AIR FLOW cc/min	TRANSMITTED (4) DUO, µg	DUO µg/min	DUO µg/cc
52	100 B	99	1000	10	400 (8)	6.2 ± 1.9	0.6	2×10^{-3}
53								
53-1	1-110	100	1000	10	7100	350 ± 110	35	5×10^{-3}
53-2	2-110	125	1000	10	2200 (2)	211 ± 63	21.1	1×10^{-2}
53-3	3-110	100	1000	10	5800	187 ± 56	187	3×10^{-3}
54	100 B	99	500	30	195 (2)	4.07 ± 1.7	0.1	7×10^{-4}
55	250 S	276	1000	10	38800	$9.21 \times 10^3 \pm 360$	921	2×10^{-2}
68								
68-1	1-200	200	1000	10	23,600 (9)			
68-2	2-200	200	1000	10	22,000	2120 ± 820	212	1×10^{-2}
68-3	3-200	200	1000	10	22,000	2350 ± 900	235	1×10^{-2}
69	200 S	228	500	30	8000	3340 ± 130	111	1×10^{-2}
72								
72-1	1-200	200	500	10	12200	2380 ± 910	238	2×10^{-2}
72-2	2-200	310 (10)	500	30	11200	1960 ± 760	65	6×10^{-3}
72-3	3-200	200	500	60	11000			
74								
74-1	1-200	200	500	30	12200	3480 ± 1300	116	1×10^{-2}
74-2	2-200	310 (11)	500	30	11200	2420 ± 930	81	7×10^{-3}
74-3	3-200	200	500	30	11000			
76								
76-1	1-200	200	1000	10	4000 (2)	1690 ± 660	169	4×10^{-2}
76-2	2-200	310 (11)	1000	30	22000	$4.31 \times 10^4 \pm 1.6 \times 10^4$	1436	7×10^{-2}
76-3	3-200	200	1000	60	4000-7000 (2)	7460 ± 2800	124	2×10^{-2}

(8) Incorrect flow

(9) Plugged immediately

(10) Plugged after run; enlarged to 310µm square during cleaning

(11) 310µ m, flow not correct, result not used

TABLE A-2 -- Depleted Uranium Dioxide Transmission Rates for Leak Paths Under the Powder Level

UPL	ORIFICE OR CAPILLARY DESIGNATION	MEASURED DIAMETER, µm	CHAMBER PRESSURE psig	AGITATION	LENGTH OF RUN min	AIR FLOW cc/min	TRANSMITTED(3) DUO, µg	DUO µg/min	DUO µg/cc
1	2-200	200	1000	NO	5	12200-21000	$3.54 \times 10^3 \pm 1.3 \times 10^3$	(1)	(1)
2	2-200	200	1000	NO	5	13800	$1.61 \times 10^3 \pm 5.9 \times 10^2$	3.2×10^2	2×10^{-2}
3	2-200	200	1000	YES	5	6200	$4.89 \times 10^3 \pm 1.7 \times 10^3$	9.8×10^2	2×10^{-1}
4	2-200	200	5	NO	60	16.6	6.96 ± 2.1	0.1	7×10^{-3}
5	2-200	200	5	YES	60	18.2	4.05 ± 1.2	0.1	4×10^{-3}
6	2-110	125	1000	NO	20	4600	118 ± 35	5.9	1×10^{-3}
7	2-110	125	1000	YES	20	8000	133 ± 40	6.7	8×10^{-4}
8	2-110	125	15	YES	60	76	37.2 ± 11	0.6	8×10^{-3}
9	2-110	125	15	NO	60	18	25.2 ± 7.5	0.4	2×10^{-2}
10	2-63.5	61	1000	NO	20	1900	58.9 ± 18	2.9	2×10^{-3}
11	2-63.5	61	1000	YES	20	2000	111 ± 33	5.6	3×10^{-3}
12	2-63.5	61	15	NO	60	18	51.5 ± 1.5	1.0	5×10^{-2}
13	2-63.5	61	15	YES	60	16	17.4 ± 5	0.3	2×10^{-2}
14	2-36	33	1000	NO	20	31	14.8 ± 4	0.7	2×10^{-2}
15	2-36	33	1000	YES	20	26	72.5 ± 22	3.6	1×10^{-2}
16	2-36	33	15	NO	120	0.3	4.5 ± 1.8	0.04	1×10^{-1}
17	2-36	33	15	YES	120	1.1	12.6 ± 3.8	0.1	9×10^{-2}
18	2-20	20	1000	NO	20	30	82.4 ± 25	4.0	1×10^{-1}
19	2-20	20	1000	YES	20	61	11.2 ± 3.4	0.6	1×10^{-2}
20	2-20	20	15	YES	120	ND(2)	21.2 ± 6	0.2	
21	2-20	20	15	NO	120	ND	13.6 ± 4	0.1	
22	2-200	200	500	NO	20	6500	812 ± 220	40.6	6×10^{-3}
23	2-200	200	500	YES	20	5750	1960 ± 330	98.0	2×10^{-2}
24	2-110	125	500	NO	20	3250	150 ± 45	7.5	2×10^{-3}

(1) ALMOST ALL DUO EXPELLED IMMEDIATELY

(2) ND, NOT DETECTABLE, LESS THAN 0.2 cc/min

(3) THE ± IS THE UNCERTAINTY IN THE URANIUM ANALYSIS AT THE 2σ CONFIDENCE LEVEL

TABLE A-2 (Continued)

UPL	ORIFICE OR CAPILLARY DESIGNATION	MEASURED DIAMETER, μm	CHAMBER PRESSURE psig	AGITATION	LENGTH OF RUN, min	AIR FLOW cc/min	TRANSMITTED[3] DUO, μg	DUO μg/min	DUO μg/cc
25	2-110	125	500	YES	20	2550	86.3 ± 26	4.3	2×10^{-3}
26	2-63.5	61	500	NO	30	470	71.8 ± 22	2.4	5×10^{-3}
27	2-63.5	61	500	YES	30	275	37.0 ± 11	1.2	4×10^{-3}
28	2-36	33	500	NO	60	225	20.4 ± 6	0.3	1×10^{-3}
29	2-36	33	500	YES	60	75	36.1 ± 11	0.6	8×10^{-3}
30	2-20	20	500	NO	60	14	15.0 ± 5	0.3	6×10^{-3}
31	2-20	20	500	YES	60	0.75	13.0 ± 4	0.2	3×10^{-1}
32	250 B	274	1000	NO	5	32500	379 ± 110	75.8	2×10^{-3}
33	250 B	274	1000	YES	10	32000	2830 ± 400	283	9×10^{-3}
34	150 B	176	1000	NO	5	9600	1270 ± 220	254	3×10^{-2}
35	150 B	176	1000	YES	10	7400	498 ± 120	50	7×10^{-3}
36	250 B	274	500	NO	30	14100	311 ± 98	10	7×10^{-4}
37	250 B	274	500	YES	30	11500	585 ± 140	20	2×10^{-3}
38	150 B	176	500	NO	30	3950	374 ± 100	12	3×10^{-3}
39	150 B	176	500	YES	30	5400	395 ± 120	13	2×10^{-3}
40	250 B	274	15	YES	60	410	1950 ± 300	33	8×10^{-2}
41	250 B	274	15	NO	60	28	78.3 ± 23	1.3	4×10^{-2}
42	150 B	176	15	YES	60	29	122 ± 37	2	7×10^{-2}
43	150 B	176	15	NO	60	50	129 ± 39	2	4×10^{-2}
44	2-200	200	100	NO	30	820	740 ± 400	25	3×10^{-2}
45	2-200	200	100	YES	30	485	578 ± 320	19	3×10^{-2}
46	2-110	125	100	NO	30	325	464 ± 140	15	5×10^{-2}
47	2-110	125	100	YES	30	280	120 ± 36	4	1×10^{-2}
48	2-63.5	61	100	NO	30	26.6	68.4 ± 21	2.3	9×10^{-2}

TABLE A-2 (Continued)

UPL	ORIFICE OR CAPILLARY DESIGNATION	MEASURED DIAMETER, μm	CHAMBER PRESSURE psig	AGITATION	LENGTH OF RUN, min	AIR FLOW cc/min	TRANSMITTED[3] DUO, μg	DUO μg/min	DUO μg/cc
49	2-63.5	61	100	YES	30	66.4	190 ± 57	6.3	0.1
50	2-36	33	100	NO	30	6.8	139 ± 42	4.6	0.7
51	2-36	33	100	YES	30	15	69 ± 21	2.3	0.2
52	2-20	20	100	NO	30	ND	97.4 ± 29	3.2	
53	2-20	20	100	YES	30	ND	59.2 ± 18	2.0	
54	250 B	274	100	NO	30	1550	1160 ± 600	38.7	3×10^{-2}
55	250 B	274	100	YES	30	2780	338 ± 100	11.3	4×10^{-3}
56	150 B	176	100	NO	30	ND	94 ± 28	3	
57	150 B	176	100	YES	30	900	90.6 ± 27	3	3×10^{-3}
58	150 S	182	100	NO	30	660	395 ± 12	13.2	2×10^{-2}
59	150 S	182	100	YES	30	1180	118 ± 35	3.9	3×10^{-3}
60	250 S	276	100	NO	30	660	1330 ± 580	44	7×10^{-2}
61	250 S	276	1000	NO	10	19900	$7.92 \times 10^4 \pm 3.4 \times 10^4$	7920	0.4
62	250 S	276	500	NO	10	20200	$1.36 \times 10^4 \pm 5.6 \times 10^3$	1360	7×10^{-2}
63	250 S	276	500	YES	10	13900	$1.22 \times 10^4 \pm 5 \times 10^3$	1220	9×10^{-2}
64	150 S	182	1000	NO	10	10800	1690 ± 730	169	2×10^{-2}
65	150 S	182	1000	YES	10	12200	1330 ± 580	133	1×10^{-2}
66	150 S	182	500	NO	30	4200	666 ± 320	22	5×10^{-3}
67	150 S	182	500	YES	30	6800	852 ± 380	28.4	4×10^{-3}
68	150 S	182	15	NO	60	67	85.8 ± 26	1.4	2×10^{-2}
69	2-200	200	15	NO	60	90	618 ± 190	10.3	1×10^{-1}
70	2-220	200	15	YES	60	210	567 ± 170	9.5	5×10^{-2}
71	150 S	182	15	YES	60	28	61.5 ± 18	1	4×10^{-2}
72	250 S	276	15	YES	60	96	454 ± 140	7.6	8×10^{-2}
73	250 S	276	15	NO	60	210	302 ± 91	5	2×10^{-2}
74	250 S	276	100	YES	50	1280	$2.15 \times 10^3 \pm 650$	43	3×10^{-3}
75	250 S	276	1000	YES	10	40500	$9.78 \times 10^3 \pm 3.7 \times 10^3$	978	2×10^{-2}
76	2-20[4]	20	1000	NO	10	57	22.3 ± 6.7	2.2	4×10^{-2}
77	2-20[4]	20	1000	YES	10	27	25.7 ± 7.7	2.6	1×10^{-1}
78	150 B[4]	176	1000	YES	10	1100	$1.05 \times 10^3 \pm 420$	105	1×10^{-2}
79	150 B[4]	176	1000	NO	10	11000	$5.46 \times 10^3 \pm 2 \times 10^3$	546	5×10^{-2}

(4) RERUNS

TABLE A-3 -- ADDITIONAL TESTS PROPOSED TO ADEQUATELY DEFINE PARAMETRIC RELATIONS

Position:	Up			Down		
Pressure:	Ambient	440 psig	920 psig	Ambient	440 psig	920 psig
With Vibration						
5-μm Orifice	√*	-	√	2	-	2
10-μm Orifice	-	√	-	-	2	-
20-μm Orifice	2	-	4	2	-	2
Without Vibration						
5-μm Orifice	2	-	2	√	-	2
10-μm Orifice	-	4	-	-	4	-
20-μm Orifice	2	-	2	2	-	2
Total Added Experiments = 38						

* √ = parametric point adequately defined by previous tests.

TABLE A-4 SUMMARY OF PuO_2 LEAK RATE EXPERIMENTS USING A 5-μm ORIFICE

Run Number	Tube Position	Helium Pressure, psig	Vibration	Helium Leak Rate[b], cc/sec	Quantity of PuO_2 Detected, μg[a]			
					Inlet Nozzle	Final Filter	Total	Net Total[c]
B56[d]	Sideways	–	–	–	0.00060	0.00079	0.00139	--
B57[d]	Sideways	–	–	–	0.00073	0.00035	0.00108	--
Pu82	Up	0	No	–	0.00111	0.00313	0.00424	0.00301
Pu82a	Up	0	No	–	0.00129	0.00465	0.00594	0.00471
Pu83	Down	0	Yes	–	0.00236	0.00712	0.00948	0.00825
Pu83a	Down	0	Yes	–	0.00662	0.01014	0.01676	0.01553
Pu83b	Down	0	Yes	–	0.00782	0.09217	0.09999	0.09876
Pu83c	Down	0	Yes	–	0.00588	0.00054	0.00643	0.00520
Pu84	Up	920	No	0.4	0.00022	0.00069	0.00091	0.0
Pu84a	Up	920	No	0.4	0.00048	0.00030	0.00078	0.0
Pu85	Down	920	Yes	0.4	0.00099	0.00180	0.00279	0.00156
Pu85a	Down	920	Yes	1.7	0.00260	0.00155	0.00415	0.00292
Pu86	Down	920	No	3.9	0.00090	0.01253	0.01344	0.01221
Pu86a	Down	920	No	0.9	0.00045	0.00155	0.00200	0.00077
Pu86b	Down	920	No	0.4	0.00182	0.00057	0.00239	0.00116
Pu86c	Down	920	No	0.4	0.00045	0.0	0.00045	0.0

(a) Based on a specific activity of 0.096 Ci/g for the PuO_2 powder.

(b) Helium leak rate determined by pressure decay method at the midpoint of the run.

(c) The net total is the amount above the average containment box background of 0.00124 μg.

(d) Containment box background.

TABLE A-5 SUMMARY OF ROOM-TEMPERATURE PuO_2 LEAK RATE EXPERIMENTS USING A SIMULATED CRACK[(a)]

Run Number	Tube Position	Helium Pressure, psig	Vibration	Helium Leak Rate, cc/sec[(c)]	Quantity of PuO_2 Detected, μg[(b)]: Inlet Nozzle	Final Filter	Total	Net Total[(d)]
B-52(e)	Sideways	-	-	-	0.00035	0.00031	0.00066	-
B-53(e)	Sideways	-	-	-	0.00028	0	0.00028	-
Pu 68	Up	920	No	12.4	0.01082	0.09195	0.10278	0.10231
Pu 68a	Up	920	No	11.3	0.00004	0.00632	0.00636	0.00589
Pu 68b	Up	920	No	9.6	0.00120	0.00256	0.00376	0.00329
Pu 68c	Up	920	No	10.0	0	0.00333	0.00333	0.00286
Pu 69	Up	920	Yes	11.1	0.00031	0.00795	0.00826	0.00779
Pu 69a	Up	920	Yes	9.3	0.00109	0.00392	0.00501	0.00454
Pu 70	Down	920	No	9.5	0.00633	0.02405	0.03038	0.02991
Pu 70a	Down	920	No	9.7	0.00452	0.05006	0.05458	0.05411
Pu 71	Up	440	Yes	3.0	0.00083	0.00400	0.00483	0.00436
Pu 71a	Up	440	Yes	2.6	0.00018	0.00046	0.00064	0.00017
Pu 71b	Up	440	Yes	2.6	0.00042	0.00125	0.00168	0.00121
Pu 71c	Up	440	Yes	2.6	0.00090	0.00026	0.00116	0.00069
Pu 72	Down	440	Yes	2.6	0.08613	0.56607	0.65220	0.65173
Pu 72a	Down	440	Yes	2.6	0.07166	0.41948	0.49114	0.49067
Pu 73	Up	Ambient	Yes	-	0.00081	0.00050	0.00132	0.00085
Pu 73a	Up	Ambient	Yes	-	0.00013	0	0.00013	0
Pu 74	Down	Ambient	No	-	0.01986	0.12725	0.14711	0.14664
Pu 74a	Down	Ambient	No	-	0.00035	0.00187	0.00223	0.00176
Pu 74b	Down	Ambient	No	-	0.00071	0.00117	0.00187	0.00140
Pu 74c	Down	Ambient	No	-	0.00088	0.00043	0.00131	0.00084

(a) The simulated crack has a 220-μin.finish perpendicular to the helium flow. The helium leak rate was initially 13.2 cc/sec at 920 psig. All runs were for ten minutes.
(b) Based on a specific activity of 0.096 Ci/g for the PuO_2 powder.
(c) The leak rate was determined by the pressure decay method at the midpoint of the run.
(d) The net total is the amount above the average containment box background of 0.00047 μg.
(e) Containment box background runs.

TABLE A-6 SUMMARY OF ROOM TEMPERATURE PuO_2 LEAK RATE EXPERIMENTS USING A SIMULATED CRACK[(a)] WITH AN INITIAL He FLOW RATE OF 17.3 cc/sec AT 920 psig

Run Number	Tube Position	Helium Pressure, psig	Vibration	Helium Leak Rate, cc/sec[(c)]	Quantity of PuO_2 Detected, μg[(b)]			
					Inlet Nozzle	Final Filter	Total	Net Total[(d)]
B 54[(e)]	Sideways	--	--	--	0.00050	0.00040	0.00090	--
B 55[(e)]	Sideways	--	--	--	0	0.00104	0.00104	--
Pu 75	Up	920	No	15.8	0.00096	0.05731	0.05827	0.05737
Pu 75a	Up	920	No	16.3	0.00202	0.02667	0.02868	0.02778
Pu 76	Up	920	Yes	15.8	0.01367	0.18926	0.20293	0.20203
Pu 76a	Up	920	Yes	16.3	0.00128	0.00933	0.01061	0.00971
Pu 76b	Up	920	Yes	8.25	0.00002	0.01363	0.01365	0.01261
Pu 76c	Up	920	Yes	8.25	0.00093	0.00374	0.00467	0.00363
Pu 77	Down	920	No	16.3	0.00424	0.02171	0.02595	0.02505
Pu 77a	Down	920	No	16.3	0.00398	0.01969	0.02367	0.02277
Pu 78	Up	440	Yes	2.6	0.00030	0.00548	0.00578	0.00474
Pu 78a	Up	440	Yes	2.6	0.00097	0.00553	0.00651	0.00547
Pu 79	Down	440	Yes	2.6	0.10042	0.35852	0.45894	0.45790
Pu 79a	Down	440	Yes	2.6	0.12144	0.52779	0.64923	0.64819
Pu 80	Up	Ambient	Yes	--	0.00096	0.00036	0.00133	0.00029
Pu 80a	Up	Ambient	Yes	--	0.00076	0.00081	0.00157	0.00053
Pu 81	Down	Ambient	No	--	0.00314	0.01456	0.01770	0.01666
Pu 81a	Down	Ambient	No	--	0.00035	0.00346	0.00381	0.00277

(a) The simulated crack has a 220 μ in finish perpendicular to the flow of the helium. The helium leak rate was initially 17.3 cc/sec at 920 psig. All runs were for ten minutes.
(b) Based on a specific activity of 0.096 Ci/g for the PuO_2 powder.
(c) The leak rate was determined by the pressure decay method at the midpoint of the run.
(d) The net total is the amount above the containment box background.
(e) Containment box background runs. B54 was used for runs Pu 75-76a and Pu 77-77a. B55 was used for all other runs.

TABLE A-7 PARAMETRIC MATRIX OF BCL PuO_2 EXPERIMENTS USING SIMULATED CRACK

Leak Rate[a], cc/sec	Position: Pressure: Up Ambient	Up 440 psig	Up 920 psig	Down Ambient	Down 440 psig	Down 920 psig
With Vibration						
9.8	2	3	2	2	2	-
11.4	2	3	2	-	2	-
11.6	2	2	4	-	4	-
13.2	2	4	2	-	2	-
17.3	2	2	4	-	2	-
Without Vibration						
9.8	-	-	2	2	-	2
11.4	-	-	2	2	-	2
11.6	-	-	4	2	-	6
13.2	-	-	4	4	-	2
17.3	-	-	2	2	-	2
TOTAL EXPERIMENTS = 92						

(a) Leak rate at 920 psig using pressure decay method; determined prior to runs.

TABLE A-8 ARITHMETIC MEAN VALUE OF PuO_2 POWDER LEAKED AND THE STANDARD DEVIATION FOR EACH EXPERIMENTAL CONDITION USING THE SIMULATED CRACK CONFIGURATION*
(Mean/Standard Deviation)

Leak Rate, cc/sec	Position: Pressure:	Up Ambient	Up 440 psig	Up 920 psig	Down Ambient	Down 440 psig	Down 920 psig
With Vibration							
9.8		2/3	1/1	4/2	0/0	65/44	-
11.4		1/0	0/0	0/0	-	0/0	-
11.6		0/0	0/1	441/872	-	469/853	-
13.2		0/1	2/2	6/2	-	571/114	-
17.3		0/0	5/1	57/97	-	553/134	-
Without Vibration							
9.8		-	-	3/0	0/0	-	1/1
11.4		-	-	0/0	0/0	-	0/0
11.6		-	-	180/265	1/1	-	5955/14124
13.2		-	-	29/50	38/73	-	42/17
17.3		-	-	43/21	10/10	-	24/2

* Mean and standard deviation in nearest ng.

APPENDIX B

APPENDIX B

Calculation of Time Required to Depressurize the APLA Vessel

The volume flow rate through an orifice can be written[2]:

$$q_a = \alpha A \psi \frac{P}{\rho_a} \sqrt{\frac{2}{RT}} \tag{1}$$

where

q_a = volume flow rate at ambient conditions

α = orifice coefficient

A = geometric cross section of orifice

ψ = dependence of flow on ratio of specific heats and pressure ratio (0.484)

P = upstream pressure

ρ_a = ambient air density

R = gas constant for air, $2.87 \times 10^6 \frac{cm^2}{°K\ sec^2}$

T = temperature, °K

The rate of change of mass in the container is:

$$\frac{dM}{dt} = -m_r \tag{2}$$

where

M = mass in the vessel

m_r = mass flow rate out of the vessel

Also:

$$M = \rho_a V = \frac{PV}{RT} \tag{3}$$

where V is the volume of the vessel, and

$$m_r = \rho_a q_a \tag{4}$$

$$\therefore \quad \frac{d}{dt}\left(\frac{PV}{RT}\right) = -\rho_a\, \alpha A \psi \frac{P}{\rho_a} \sqrt{\frac{2}{RT}} \tag{5}$$

The only variable inside the pressure vessel, which is a function of time, is the pressure. Therefore, rearranging terms:

$$\frac{1}{P}\frac{dP}{dt} = -K \qquad (6)$$

where:

$$K = \frac{\alpha \pi D^2}{4V} \psi \sqrt{2RT} \qquad (7)$$

D is the orifice diameter

Integrating the above equation

$$\int_{P_i}^{P_f} \frac{dP}{P} = -K \int_{0}^{t_f} dt \qquad (8)$$

one obtains

$$\frac{P_f}{P_i} = e^{-Kt_f} \qquad (9)$$

where the subscripts f denote the final values and i the initial values.

Solving for t_f one can determine the time it takes to reach any particular pressure.

$$t_f = \frac{1}{K} \ln\left(\frac{P_i}{P_f}\right) \qquad (10)$$

It should be remembered that this time is based on the assumption that everything is a constant except the pressure. In particular, the exit flow function, ψ, is taken at its maximum value in the sample calculation given.

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