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GCR-ORR LOOP NO. 2 FILTER TESTS - II

F. A. Flint and A. M. Smith

Abstract

Tests of Cambridge absolute filters, Model S1-071, specified for use in the GCR-ORR Loop No. 2 as full-flow, primary coolant filters have been completed. D.O.P. (dioctylphthalate) efficiency tests were performed on three filters in the "as received" condition, on two filters following "canning" and thermal cycling, and on one of the "canned" filters following baking out. None of the three units met the design criteria of 99.97% efficiency for removal of 0.3 micron particles in the "as received" condition. The post-thermal cycle efficiencies of the "canned" filters were slightly higher than their respective "as received" efficiencies. At the completion of testing, the two filters "canned" for installation in the reactor facility had measured efficiencies of 99.885% and 99.93%. These values were judged acceptable for the intended application. The thermal cycling of the two "canned" filters and the subsequent baking out of one of these units demonstrated that a limited amount of off-gas products would be given off. Pressure drop tests were performed on the "canned" filters with instrument air (ambient temperature, atmospheric pressure) over a flow rate range of 150 to 530 lb/hr. Curves of pressure drop across each filter versus Reynolds number were plotted for air and helium.

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Introduction

The helium coolant of the GCR-ORR No. 2 in-pile loop[1] is to be filtered through a full-flow filter to remove solids which might damage the compressor impeller and gas bearings. In the expectation that this unit would be effective in limiting the spread of particulate radioactive material throughout the loop, a high-efficiency (absolute) filter media was specified. Tests have been conducted in experimental facilities of the Reactor Division to determine the adequacy of a proposed filter design.

Objective

The objective of the tests was to determine the following:

1. If the filter could be handled and mounted in its pressure vessel (canned) without damage, by exercising reasonable care
2. The efficiency of the filter in the "as received" condition; in the "canned" pre-thermal cycle condition; and in the "canned" post-thermal cycle conditions
3. If thermal cycling would impair the efficiency of the filter
4. If off-gas products would be given off during thermal cycling, and if such products would be given off repeatedly whenever the filter was heated.
5. The pressure drop across the filter at a helium (314.4 psia, 600°F) flow rate of 1000 lb/hr

Scope

Two of the three filters procured were "canned", and the following tests were performed:

A. Filter Efficiency Test

   1. Performed on the three filters in the "as received" condition
   2. Performed on two filters in the "canned" pre-thermal cycle condition

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[1] J. Zasler, Interim Design Report - GCR-ORR Loop No. 2, ORNL CF 61-5-39 (May 15, 1961).

3. Performed on two filters in the "canned" post-thermal cycle condition
4. Performed on one filter in the "canned" post-bake-out condition

B. Pressure Drop Test

Performed on two filters in the "canned" post-thermal cycle condition

C. Thermal Cycle Test

Performed on two filters in the "canned" condition

D. Bake-Out Test

Performed on one filter in the "canned" condition

Test Specimens

The filters tested were Cambridge absolute, Model S1-071 as shown in Figure 1. Each unit consisted of a cylindrical, 16 gauge, type 304 stainless steel shell, 10 3/4 inches in diameter and 12 inches long, containing a filter element made up of type CM-115E glass-asbestos filter paper and 1 1/2 mil corrugated stainless steel separators. The filter paper was arranged in a series of folds parallel to the flowstream with a corrugated stainless steel separator between each fold. The passages formed by the corrugations of the separators in the upstream folds directed the flowstream to the filter paper while the passages formed by the corrugations in the separators of the downstream folds served as escape routes.

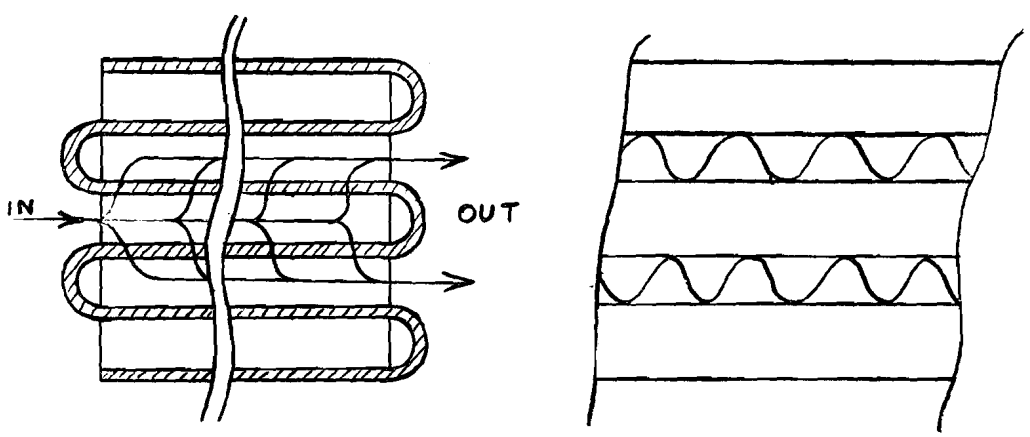

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Fig. 1. "Uncanned" Filter

The filtering element was sealed in the shell with fine fiber-glass, and the ends of the filter were covered with a heavy wire mesh screen of type 304 stainless steel as shown in Figures 2 and 3. Following efficiency testing in the "as received" condition, two of the filters were enclosed in pressure vessels, "canned", as shown in Figure 4. The "canned" filters were designated Filter Unit I and Filter Unit II respectively.

Test Equipment

A. Pressure drop and filter efficiency data were obtained in a test facility, as shown in Figure 5, composed of the following:

1. A filter mount provided with upstream and downstream pressure taps and probe holes
2. Air supply (4" instrument air header), pressure reducing valve, throttling valves, 6" orifice run, and the necessary manometers
3. Thermocouple (Chromel-Alumel), Potentiometer (Thermo Electric, Model 70200, serial D4758)
4. Air supply prefilter (Flander's Airpure, size C)
5. Aerosol contaminant and filter efficiency measuring equipment* for conducting D.O.P. (dioctylphthalate) filter efficiency tests
   a. Photometer (Phoenix Precision Instrument Company, Model JM-1000) as shown in Figure 6
   b. Light source voltage regulator (catalog LSR-1000 JM) as shown in Figure 7
   c. Pump (catalog SP-1000 JM) as shown in Figure 7
   d. Aerosol contaminant containers as shown in Figure 8

B. Test equipment for the thermal cycling and bake-out tests consisted of the following:

1. An electrically heated furnace with control panel
2. A vacuum pump, two Hastings vacuum gauges and a liquid nitrogen cold trap

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*Filter efficiency measuring equipment was supplied and operated by the Inspection Engineering Department of the Oak Ridge National Laboratory.

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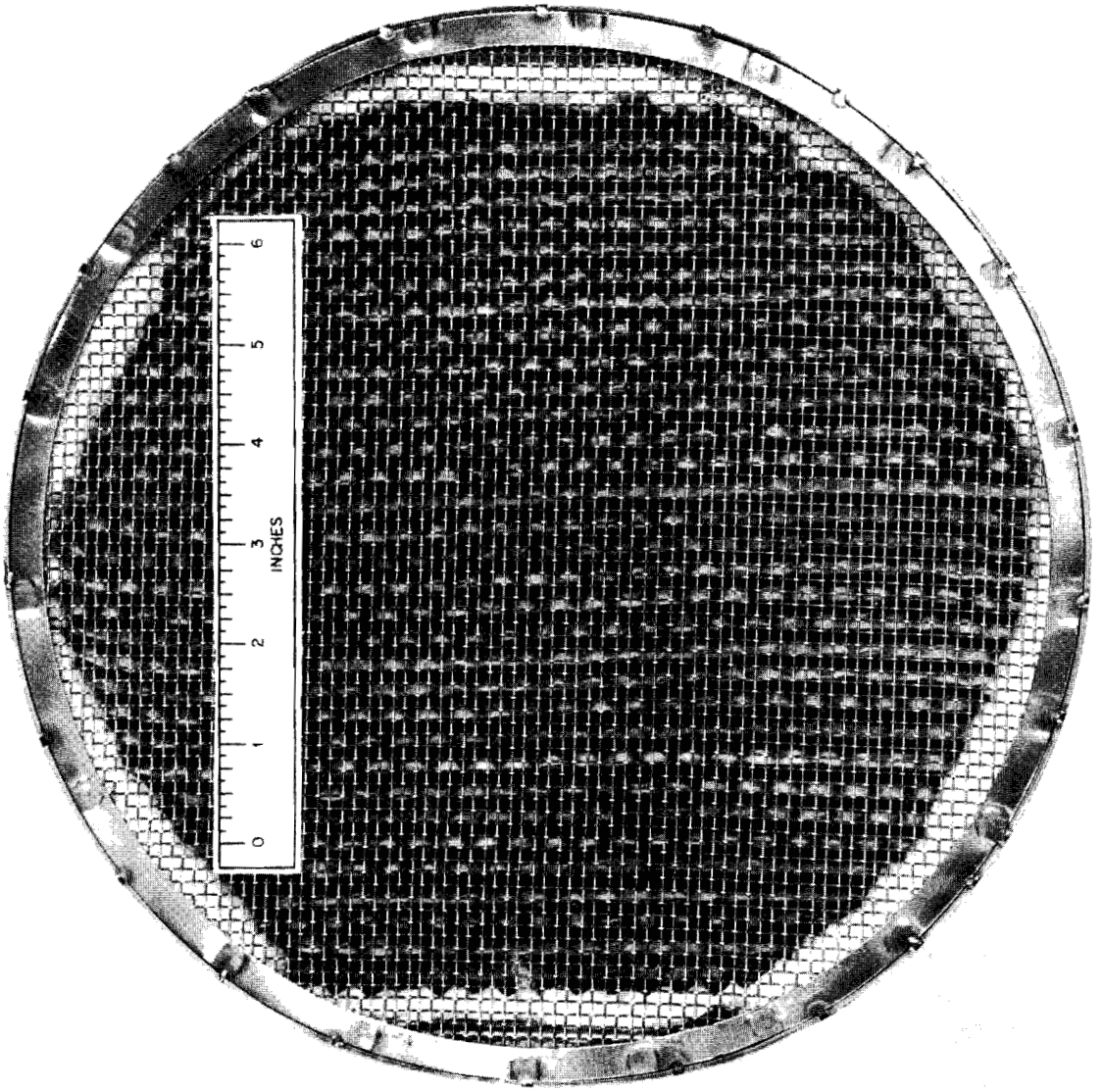

Fig. 2. Upstream End, "Uncanned" Filter.

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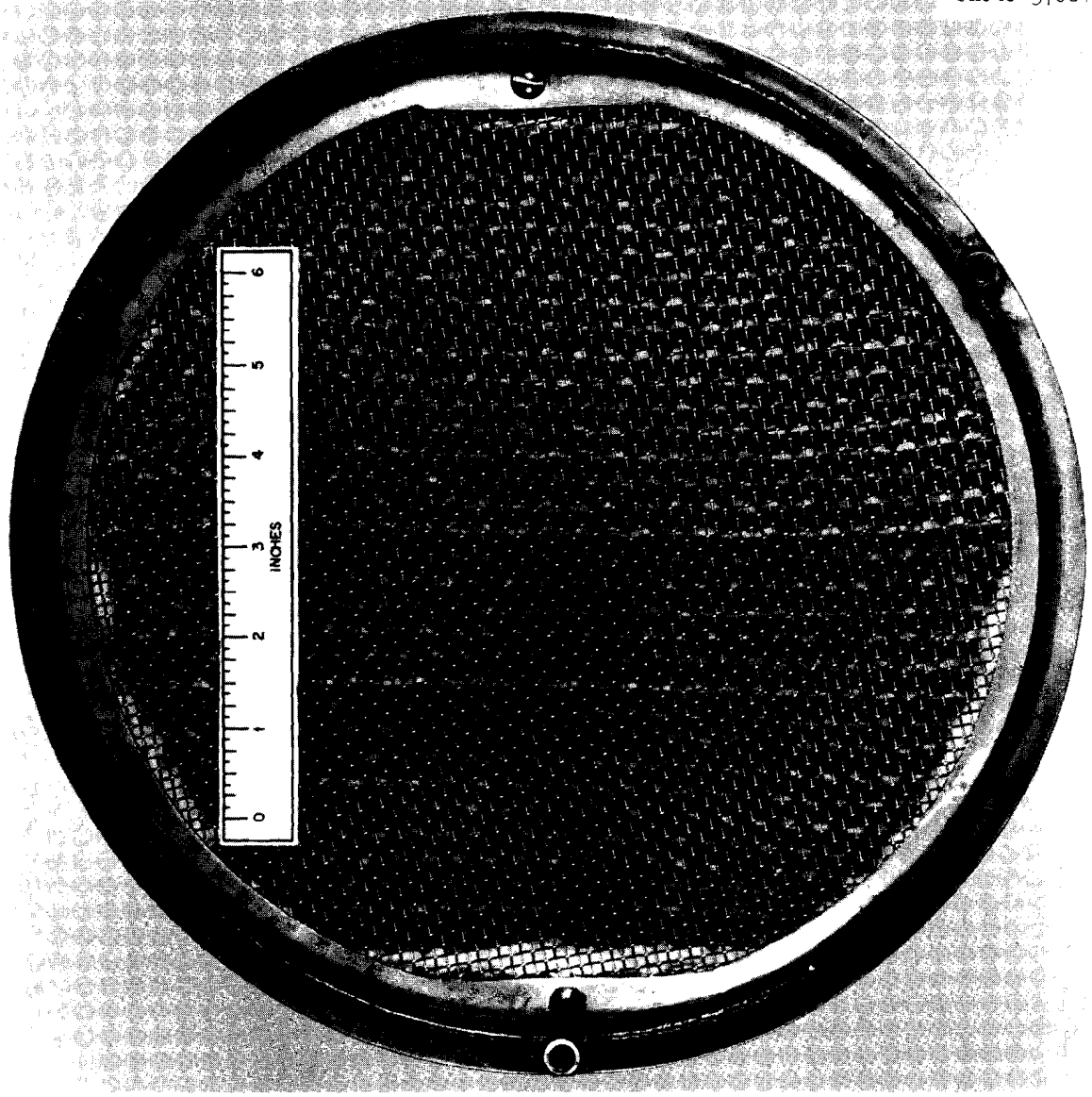

Fig. 3. Downstream End, "Uncanned" Filter.

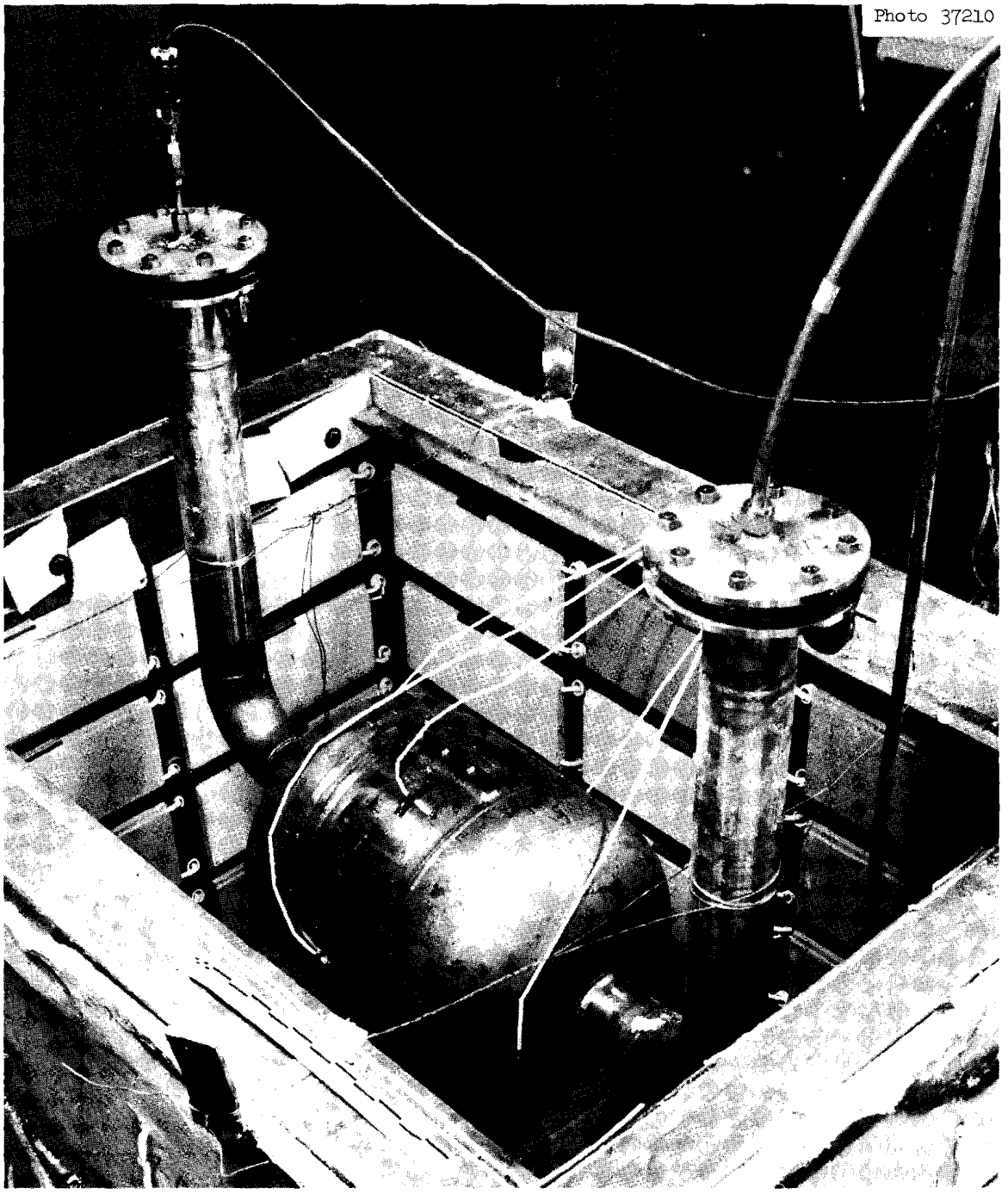

Fig. 4. "Canned" Filter Installed in Furnace.

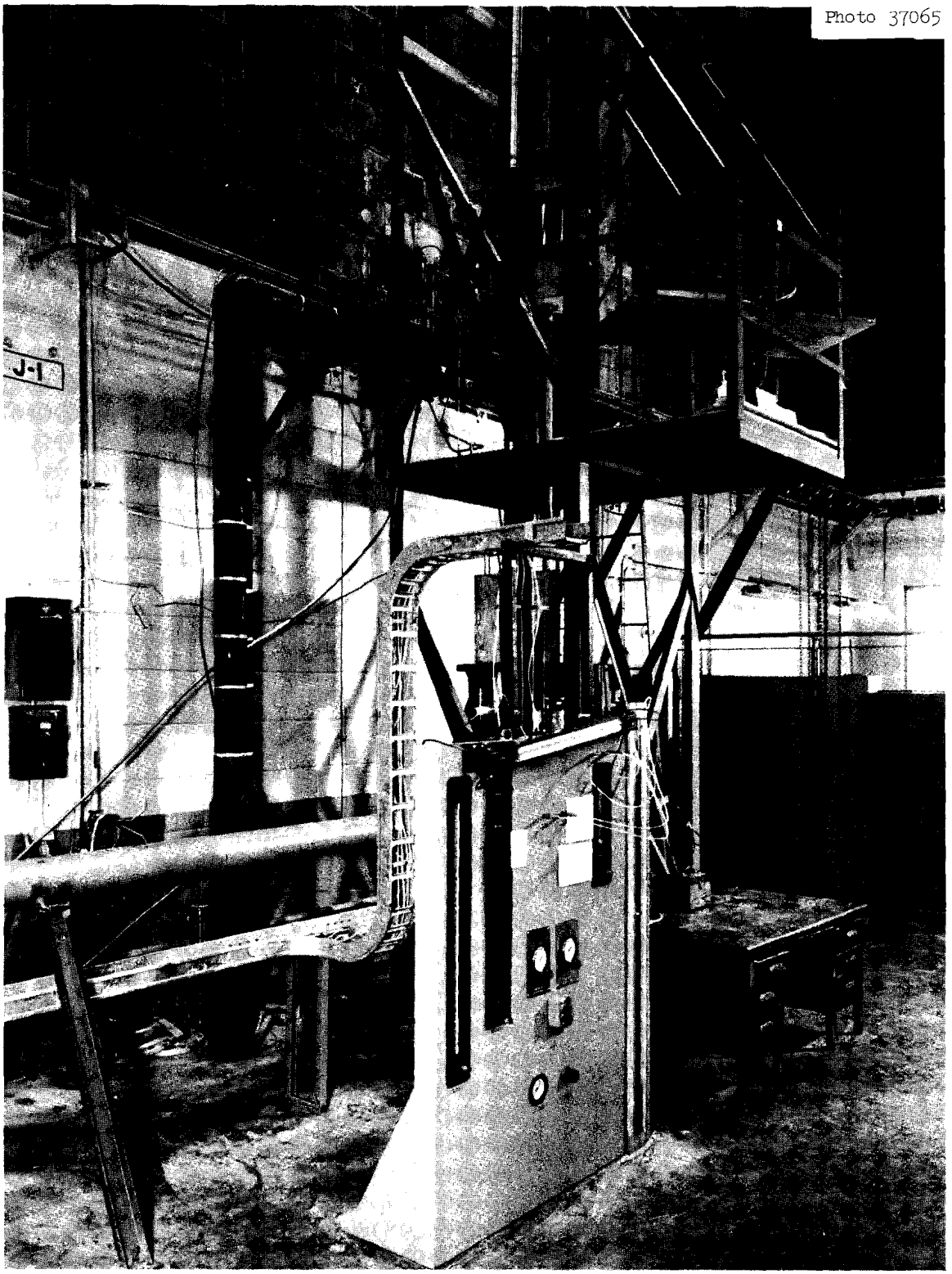

Fig. 5. Filter Test Rig.

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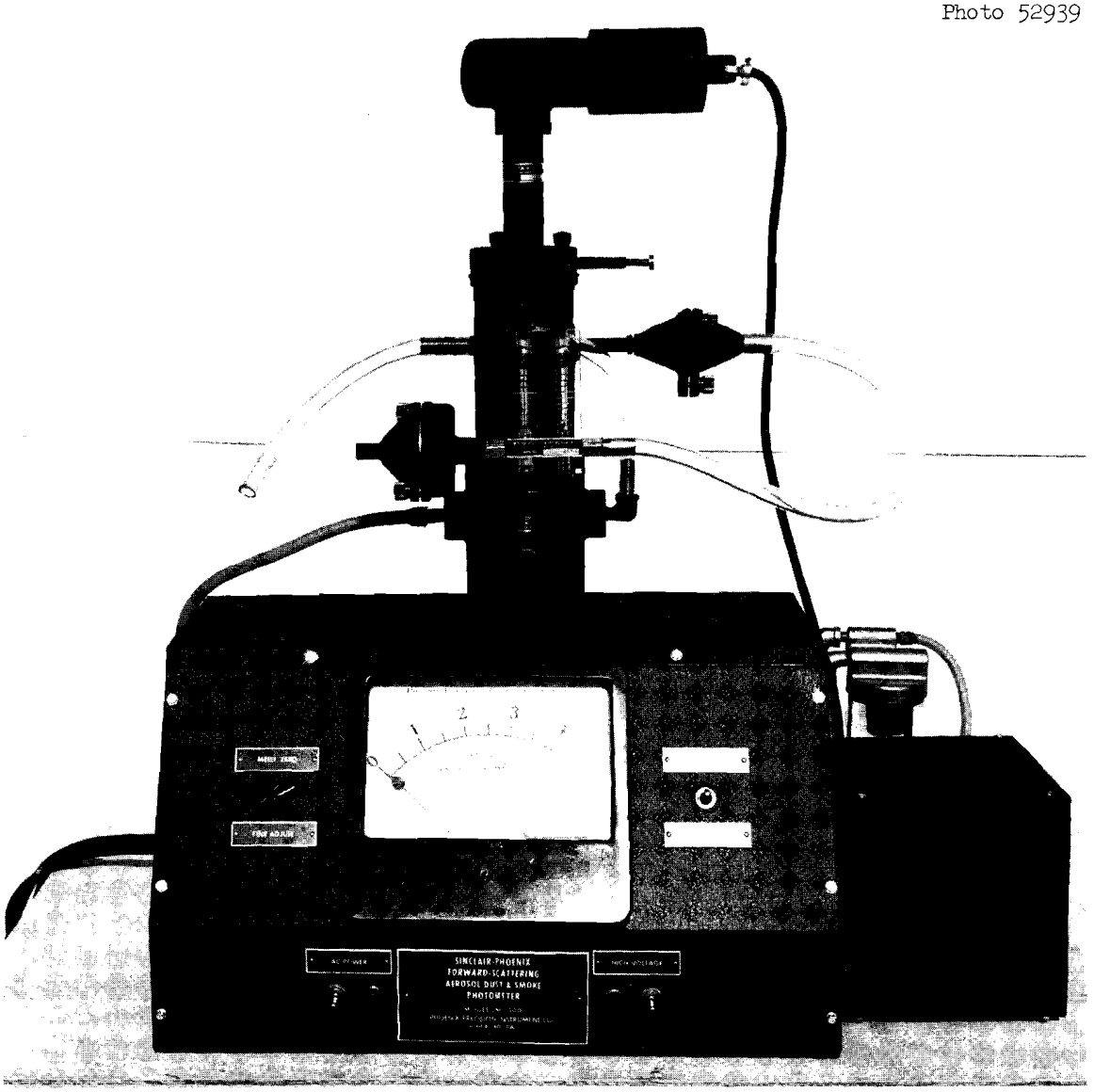

Fig. 6. Photometer.

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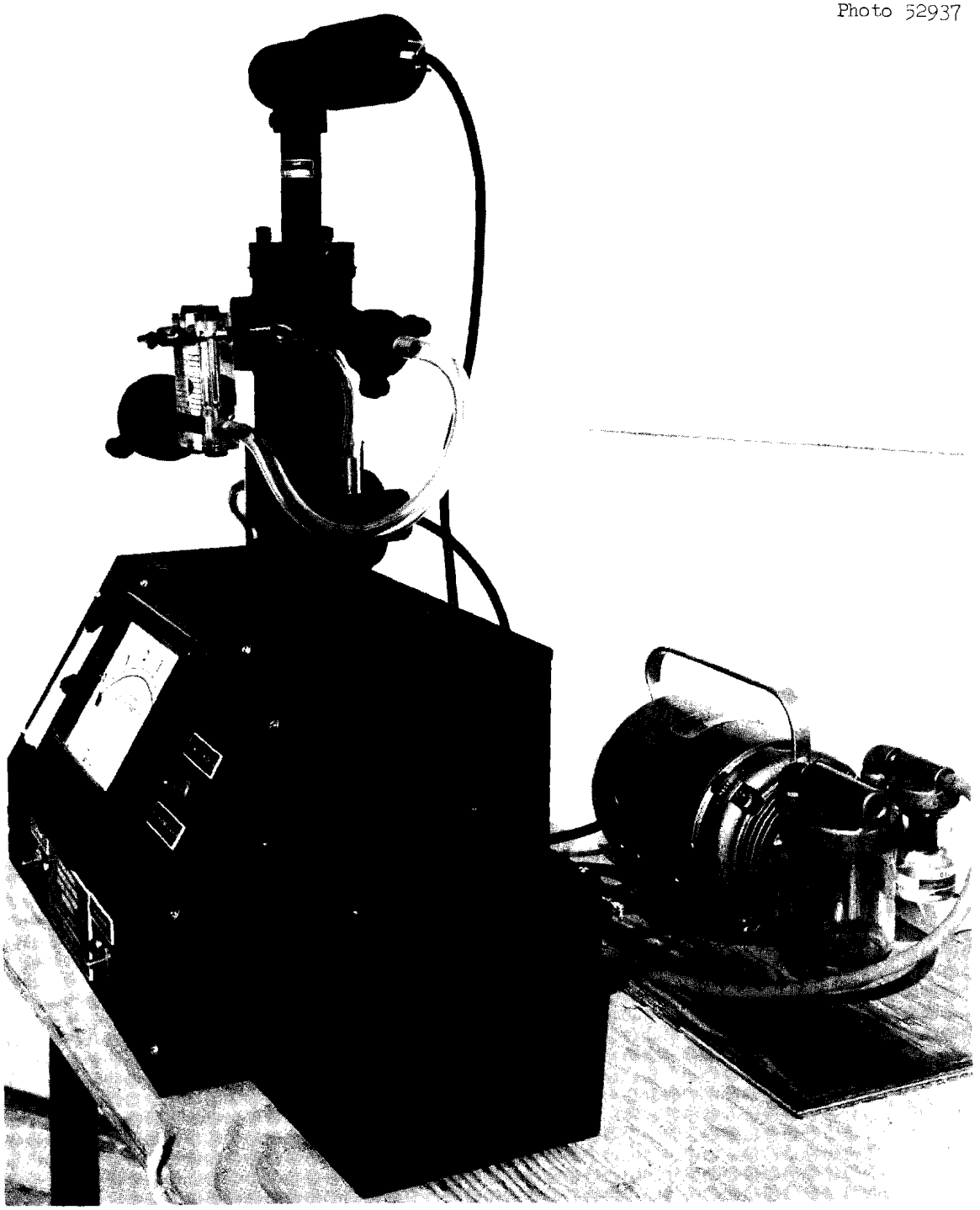

Fig. 7. Photometer, Voltage Regulator, and Pump.

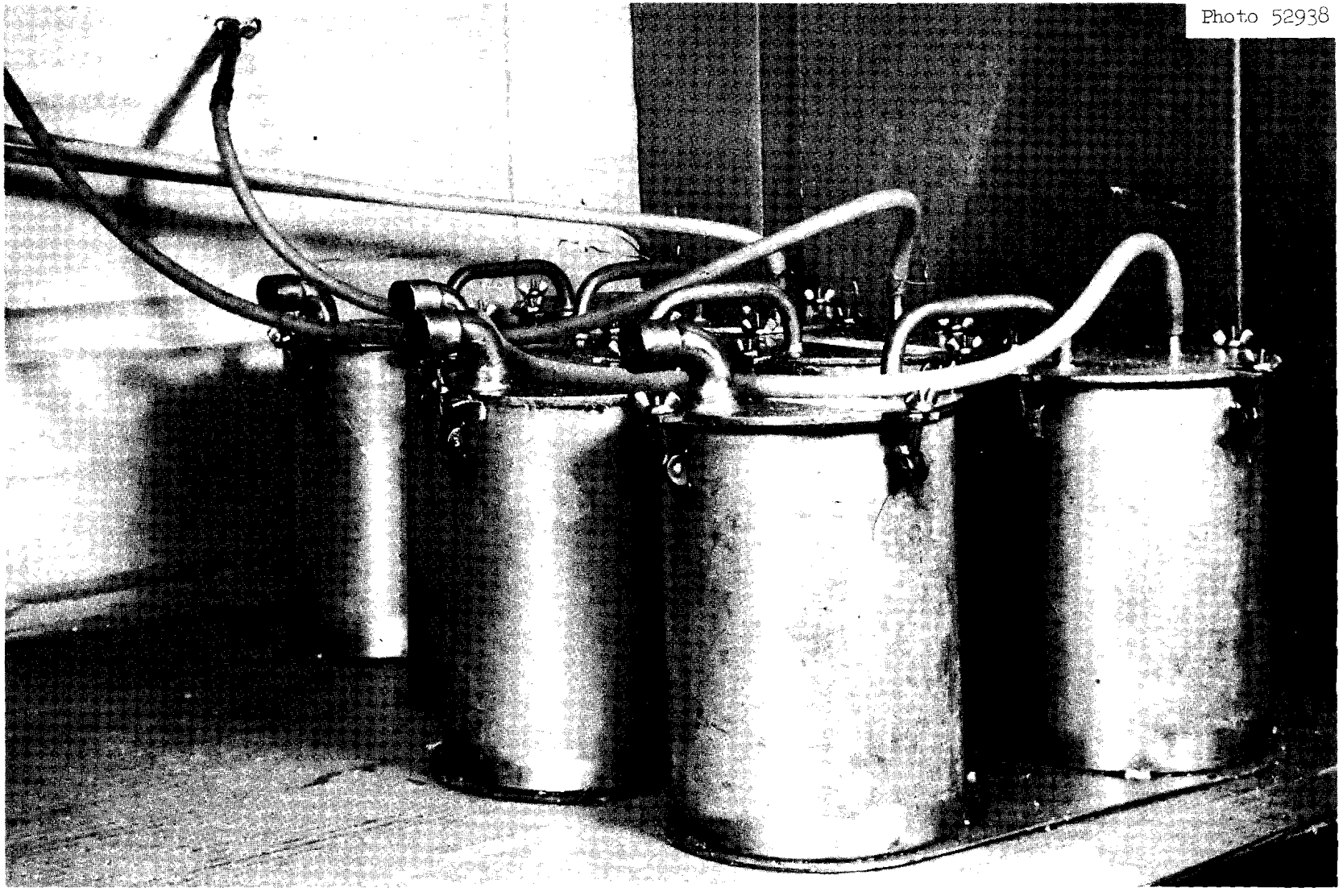

Fig. 8. Aerosol (Dioctylphthalate) Contaminant Containers.

3. Cooling air supply (1" plant air header), throttling valve, 1/2" copper tubing and cooling nozzle
4. Brown electronic recorder and thermocouples (Chromel-Alumel)

Test Procedures

A. Filter efficiency testing was accomplished by flowing instrument air (at approximately ambient temperature and atmospheric pressure) through the filter at a flowrate of approximately 530 lb/hr - which corresponds to a helium (314.4 psia, 600°F) flow rate of 1000 lb/hr on the basis of equivalent Reynolds numbers. Dioctylphthalate was then sprayed into the airstream upstream of the filter and contamination levels were measured upstream and downstream of the test unit. The stepwise procedure was as follows:

1. The filter was given a visual inspection and installed in the test facility as shown in Figures 9 and 10.
2. Air flow through the filter was gradually brought to the designed flow rate.
3. The air flow equipment was allowed to come to thermal equilibrium before final flow adjustments were made.
4. The filter efficiency measuring equipment was turned on and allowed to warm up.
5. Aerosol contaminant equipment was started.
6. Air flow data and filter efficiency data were taken.

B. Pressure drop testing was accomplished by flowing instrument air (at approximately ambient temperature and atmospheric pressure) through the filter over the flow rate range of 150 to 530 lb/hr - which corresponds, on a Reynolds number basis, to a helium (314.4 psia, 600°F) flow rate range of 280 to 1000 lb/hr; and by taking pressure drop measurements at finite flow rate range increments as follows:

1. Air flow through the filter was gradually brought to the desired flow rate.

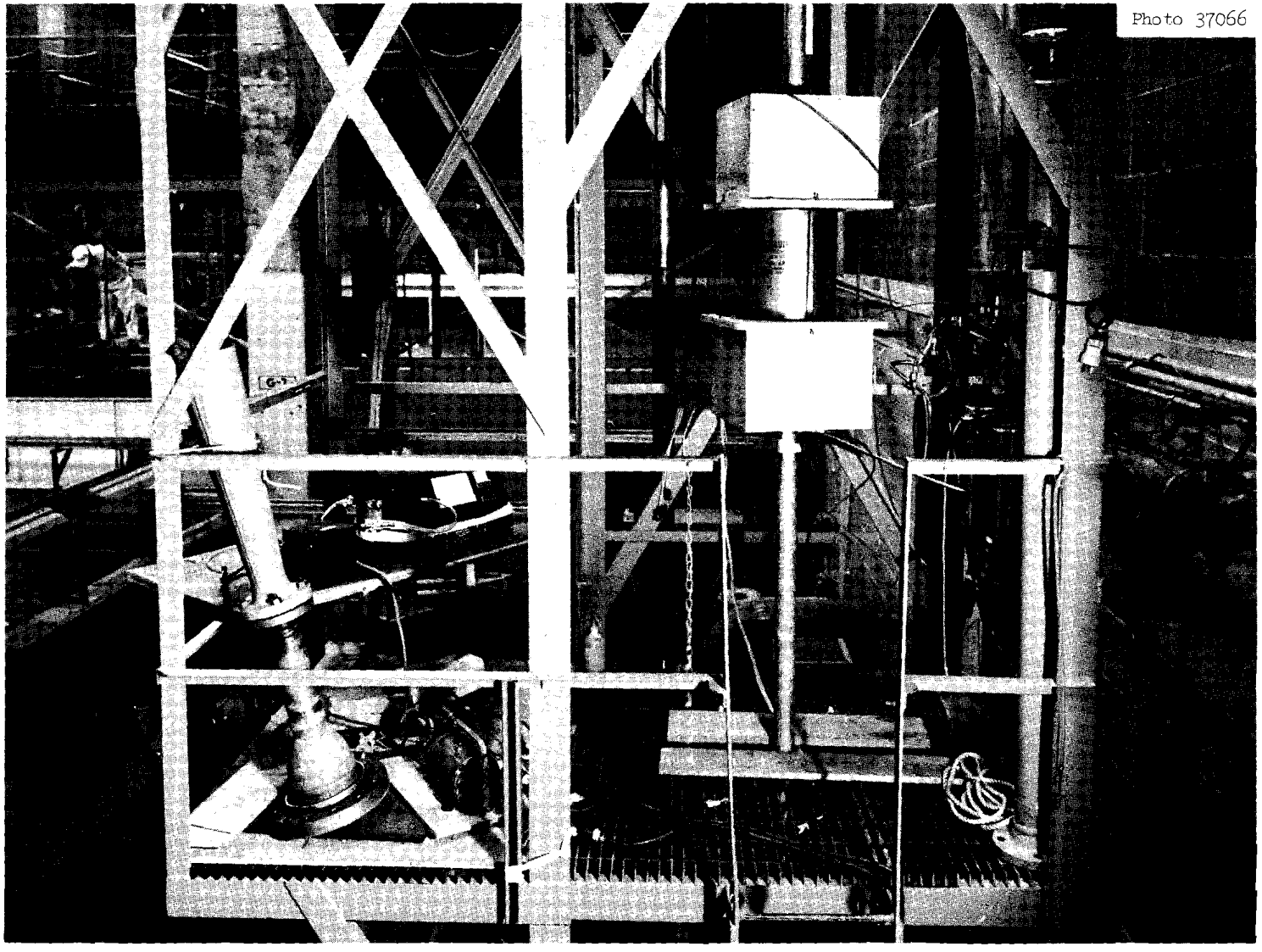

Fig. 9. "Uncanned" Filter in Test Rig.

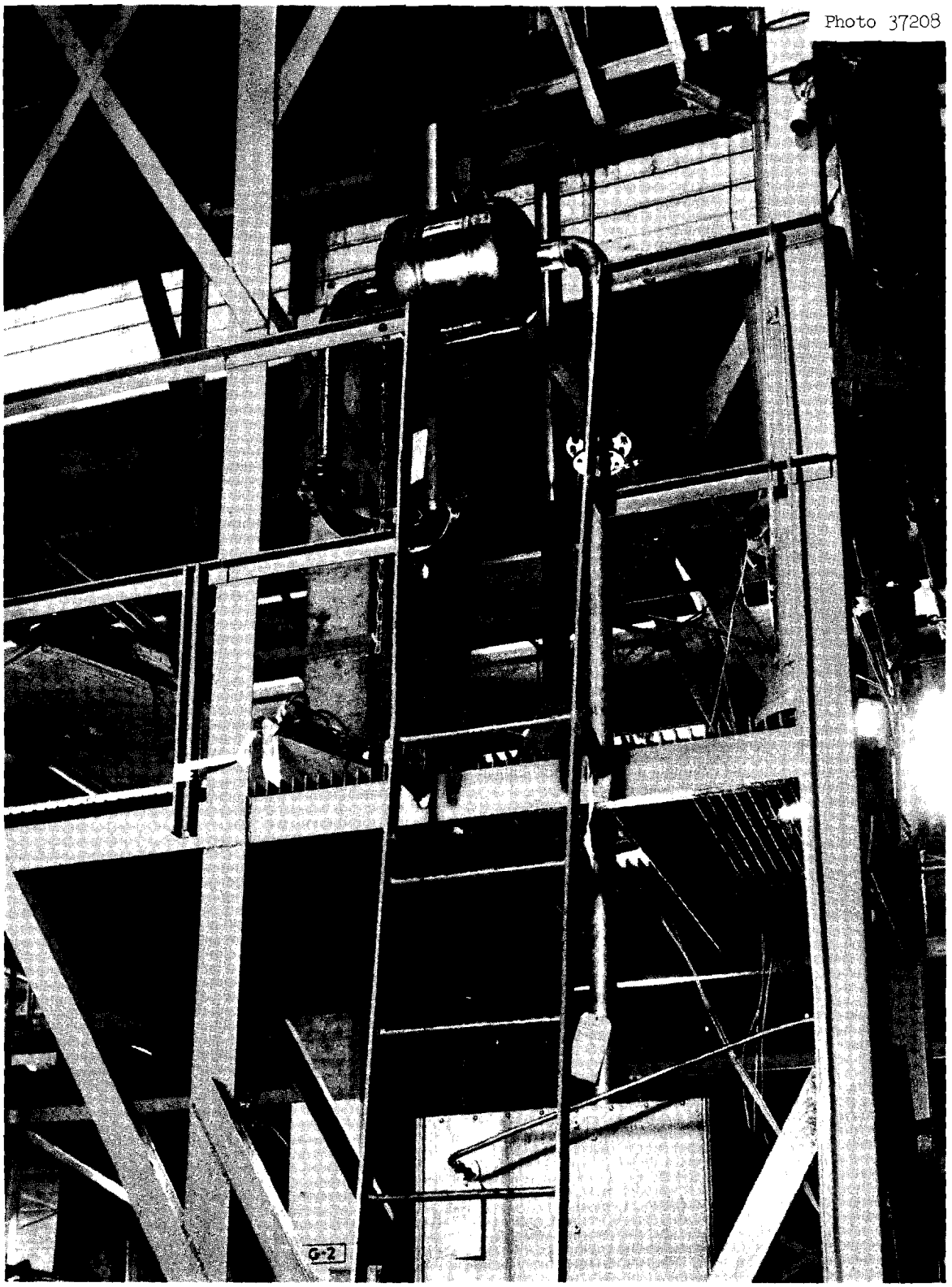

Fig. 10. "Canned" Filter Installed in Test Rig.

2. The air flow equipment was allowed to come to thermal equilibrium before final flow adjustments were made.
3. Air flow and pressure drop data were taken.

C. Thermal cycling was performed by alternately heating and cooling the evacuated filter in an electric furnace as follows:

1. The "canned" filter was placed in an electric furnace as shown in Figure 11.
2. Thermocouples were attached to the filter "can" as shown in Figure 4.
3. A vacuum pump and cold trap were connected to the filter outlet with 1/2 inch copper tubing, and a Hastings vacuum gauge was connected to the filter inlet with 1/4 inch copper tubing as shown in Figure 11.
4. The filter was heated to an average temperature of 750°F in three hours.
5. The filter was held at an average temperature of 750°F for 1/2 hour.
6. The filter was cooled to an average temperature of 150°F in three hours by turning off the power, removing the furnace top insulating cover at one end and properly adjusting the cooling air flow.
7. The above cycle was repeated three times for each filter.

D. The bake-out test was performed on Filter Unit I following post-thermal cycle efficiency testing as follows:

1. The filter was placed in the furnace as above.
2. The filter was heated to an average temperature of 750°F in three hours.
3. After the filter had been held at an average temperature of 750°F for twelve hours, the cold trap was changed.
4. After the filter had been held at an average temperature of 750°F for a total of 24 hours, the heat was turned off and the filter was allowed to cool slowly in the closed furnace.

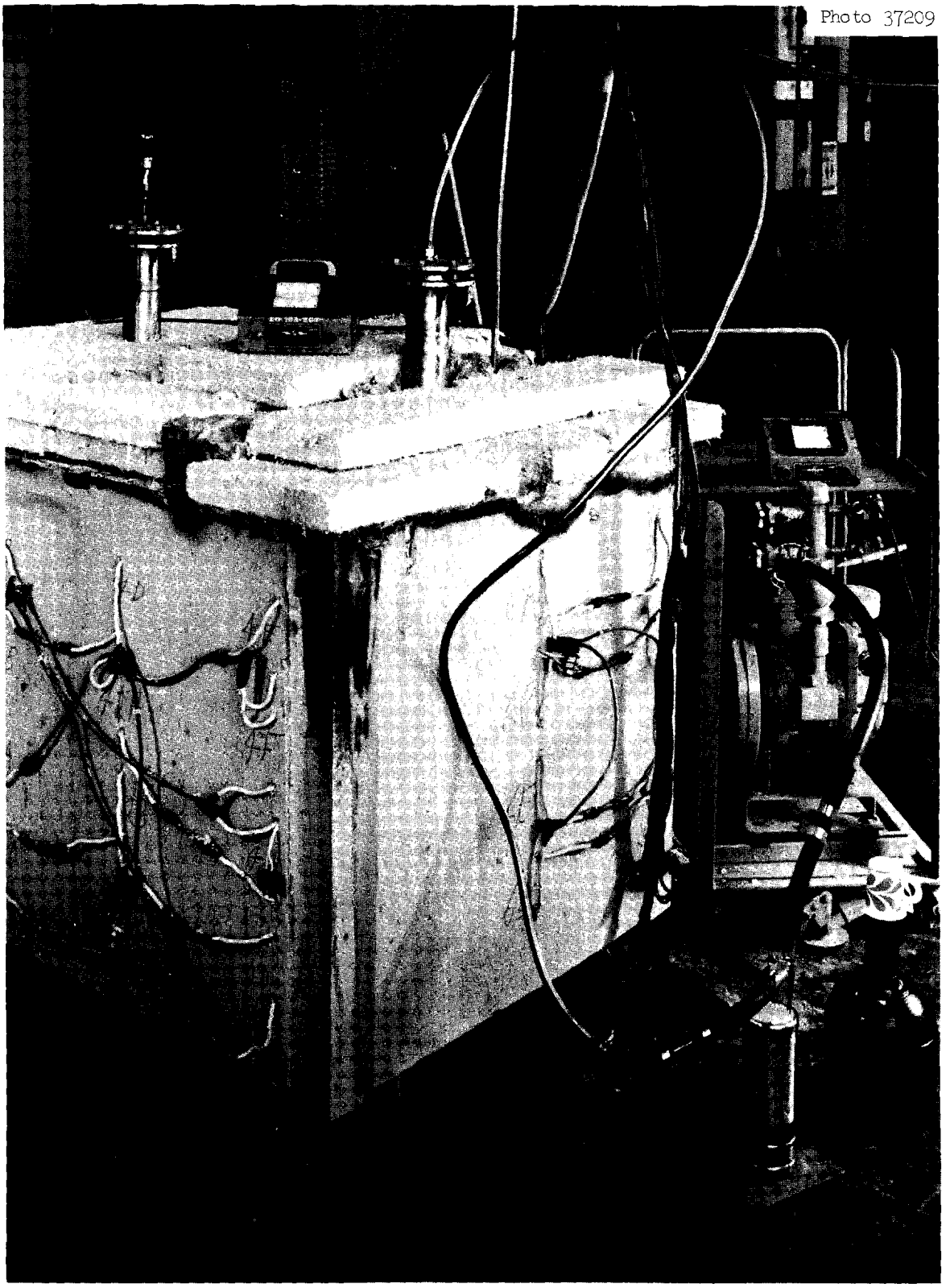

Fig. 11. "Canned" Filter Being Thermal Cycled.

Test Results

A. Visual Inspection

Visual inspection of the "as received" filters showed no holes in the folds of the filter paper or visible openings around the edge of the filter element. However, as can be seen in Figures 2 and 3, the fiber-glass seal material used around the periphery protruded from under the metal screen and covered part of the flow passages.

Inspection of the filters following the "as received" efficiency test showed no visible loss of the fiber-glass or plugging of the other flow passages.

B. The filter efficiency test results are given in Table I.

C. The pressure drop test results are given in Table II.

D. Thermal Cycling

Following thermal cycling, the filters were removed and visually inspected prior to post-thermal cycle efficiency testing. In both cases the portion of the filter inlet and outlet pipes which protruded out of the furnace were coated on the inside with a greenish-oily film. In addition, Filter Unit I had spots of greenish-black residue baked on the inside of the inlet and outlet pipes at the points where the pipes entered the furnace. Several cubic centimeters of greenish-yellow liquid were condensed in the cold trap in each case. The contents of the cold traps were analyzed spectrographically. The results of these analyses are given in Table III.

E. "Bake-Out" Operation

A small sample of light greenish-yellow liquid was condensed in the cold trap used during the first 12 hours of baking out. The spectrographic analysis of this sample is given in Table IV. There was no condensation in the cold trap used during the second 12 hours of baking out. No evidence of an oily film and/or residue was found on the inside of the filter inlet and outlet pipes after the test.

Table I. Results of D.O.P.* Efficiency Tests on Cambridge Absolute Filters

Unit Number	Condition During Test	Flow Rate lb/hr	Serial Number	Air Temperature °F	Air Pressure	Filter Efficiency** %
I	As received	520	681605	82	Atmospheric	99.926
II	As received	515	--	72	Atmospheric	99.540
I	"Canned" Pre-Thermal Cycle	526	--	83	Atmospheric	99.991
II	"Canned" Pre-Thermal Cycle	524	--	73	Atmospheric	99.930
I	"Canned" Post-Thermal Cycle	530	--	78	Atmospheric	99.964
II	"Canned" Post-Thermal Cycle	531	--	71	Atmospheric	99.885
I	"Canned" Post-Bake-Out to 705°F	540	--	89	Atmospheric	99.93
III	As received	527	681604	89	Atmospheric	99.850

* Particle size 0.3μ

** Average of two tests

Table II. Pressure Drop Across GCR-ORR Loop II "Canned" Filters

Flow Rate (lb/hr)	Pressure Drop (inches H_2O)
Filter Unit I	
167	0.34
217	0.52
319	0.96
397	1.38
463	1.79
540	2.41
Filter Unit II	
157	0.34
229	0.65
342	1.24
395	1.57
463	2.09
528	2.62

Table III. Spectrographic Analyses of Thermal Cycle Off-Gas Condensate

Unit I (g/ml)	Unit II (qualitative)
Al - 2	Al - trace
B - 2	B - trace
Ca - 4	Ca - trace
Cd - 20	Cu - trace
Cu - 1	Fe - trace
Fe - 0.4	K - trace
K - 2	Mg - trace
Li - .1	Na - trace
Mg - 100	Si - major
Na - 10	
Si - 40	
Zn - 100	

Table IV. Spectrographic Analyses of "Bake-Out" Off-Gas Condensate

Unit I (qualitative)
Al - minor
Ca - minor
Cu - major
Fe - trace
K - minor
Mg - minor
Na - minor
Pb - major
Si - major

Discussion

A. Filter Efficiency Tests

From Table I it can be seen that for both "canned" filters the "as received" efficiencies were lower than either the pre-thermal cycle or the post-thermal cycle efficiencies. The cause of this efficiency variation pattern was not determined.

B. Pressure Drop Test

In order to permit calculation of helium pressure drop (314.4 psia, 600°F) from the results of the air tests, the pressure drop across the filter was considered to be a friction loss which could be expressed by the D'arcy-Weisbach equation:

$$H_L = \frac{f_e L_e}{D_e} \frac{\bar{V}^2}{2g}$$

The filter was considered to be a straight pipe of equivalent length L_e, equivalent diameter D_e, and having an equivalent friction factor f_e. Since L_e, D_e, and f_e are constant for all fluids flowing through

the same geometry at the same Reynolds number, $\frac{f_e L_e}{D_e}$ may be expressed as C_L (dimensionless loss coefficient) and the D'arcy-Weishbach equation becomes:

$$H_L = C_L \frac{\bar{V}^2}{2g}$$

An expression for pressure drop was obtained by multiplying both sides of the D'arcy-Weisbach equation by the average specific weight of the flowing fluid.

$$\Delta P = H_L \bar{\gamma} = C_L \frac{\bar{V}^2 \bar{\gamma}}{2g}$$

From the continuity equation ($W = A\gamma\bar{V}$), $\bar{V}^2 = \frac{W^2}{A^2\gamma^2}$ was substituted into the above equation to give:

$$\Delta P = C_L \frac{W^2\bar{\gamma}}{2g\ A^2\gamma^2}$$

It follows that pressure drop data across a given configuration may be readily converted from one flow medium to another with the above equation through the loss coefficient term. Filter pressure drop data were investigated from both the incompressible and compressible standpoints.

1. Incompressible Flow

   The above equation was directly applied to the incompressible flow case and loss coefficient solved for

$$C_L = \frac{\Delta P\ 2g\ A^2\gamma}{W^2}$$

2. Compressible Flow

   An expression for head loss coefficient for the compressible flow case was developed from the general energy equation and the D'arcy-Weisbach equation as follows. The general energy equation was

written in the form[2]

$$U_1 + P_1v_1 + \frac{\bar{V}_1^2}{2g} = U_2 + P_2v_2 + \frac{\bar{V}_2^2}{2g} + H_L$$

$H_L = C_L \frac{\bar{V}_1^2}{2g}$ was substituted into

the general energy equation above and C_L solved for resulting in the following equation:

$$(1) \quad C_L = \frac{2g}{\bar{V}_1^2} \left[J(U_1 - U_2) + P_1v_1 - P_2v_2 + \frac{\bar{V}_1^2 - \bar{V}_2^2}{2g} \right]$$

$$U_1 - U_2 = C_v \ (T_1 - T_2)$$

$$C_v = \frac{R}{J(K-1)}$$

$$(2) \quad U_1 - U_2 = \frac{R}{J(K-1)} \ (T_1 - T_2)$$

Equation (2) was substituted into Equation (1) to give equation (3).

$$(3) \quad C_L = \frac{2g}{\bar{V}_1^2} \left[\frac{R}{K-1} \ (T_1 - T_2) + P_1v_1 - P_2v_2 + \frac{\bar{V}_1^2 - \bar{V}_2^2}{2g} \right]$$

To facilitate calculations, the pressure drop across the filter was assumed to be an isentropic expansion (adiabatic reversible) although the process was actually adiabatic irreversible.

Using the isentropic relation (Pv^k = constant), the perfect gas law ($Pv = RT$), and the continuity equation ($W = A\gamma\bar{V}$), the following expressions were developed:

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1} \right)^{\frac{K-1}{K}}$$

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[2] C. L. Beaudoin and R. M. Higgins, Pressure Drop Experiments on a Proposed Fuel Assembly for the EGCR, Allis-Chalmers Report No. RD 0007, Section I (January 1960), page 52.

$$\frac{\gamma_1}{\gamma_2} = \left(\frac{P_2}{P_1}\right)^{-\frac{1}{K}}$$

$$Pv = \frac{P}{\gamma}$$

$$\bar{V}_2^2 = \frac{\gamma_1^2 \bar{V}_1^2}{\gamma_2^2}$$

These expressions were substituted into equation (3), which was then arranged to give equation (4).

$$(4) \quad C_L = \frac{2gA_1^2 \gamma_1 P_1}{W^2} \left(\frac{K}{K-1}\right) \left[1 - \left(\frac{P_2}{P_1}\right)^{\frac{K-1}{K}}\right] + 1 - \left(\frac{P_2}{P_1}\right)^{-\frac{2}{K}}$$

Loss coefficients for the incompressible and the compressible flow cases for Filter Unit II are compared in Table V.

Table V. Loss Coefficients for Filter Unit II

Reynolds Number	Incompressible Flow	Compressible Flow
2.2×10^4	4.81	4.84
3.2×10^4	4.30	4.31
4.8×10^4	3.69	3.67
5.5×10^4	3.50	3.50
6.5×10^4	3.40	3.41
7.4×10^4	3.29	3.28

C. Thermal Cycling

It was noted that the cold trap content analyses were not identical for Filter Units I and II. The analysis for Filter Unit I showed three elements, Cd, Li, and Zn, which were not shown in the analysis for Filter Unit II. Also, the Mg content was proportionately larger

in the sample from Unit I. Considering that the filters were supposed to be identical and that they were identically tested, it would seem that the two analyses would have been identical. The fact that they were not could be accounted for by the difference in the type of analyses performed on each sample. The sample from Filter Unit I was analysed semiquantitatively, while the sample from Filter Unit II was analysed qualitatively.

D. Bake-Out Test

The bake-out test sample was so small that only a qualitative analysis could be performed. Nine elements were detected, eight of which had been detected previously in the thermal-cycle sample. The presence of Pb in this sample was not accounted for.

Conclusions

A. Filter Efficiency Test

From the results of the filter efficiency tests, it was concluded that the efficiency of the filters was not impaired by thermal cycling or handling when reasonable care was exercised. Also, it was concluded that the filters were adequate for their intended use, even though the desired efficiency rating of 99.97% following thermal cycling was not achieved on either of the filters tested.

B. Pressure Drop Test

Considering that the loss coefficients for the incompressible and the compressible flow cases were nearly equal and that some error was incurred by using the isentropic relationship in calculating the compressible flow loss coefficients, it was concluded that the incompressible flow loss coefficients could be used without incurring appreciable error at the flow rates considered. Curves of pressure drop versus Reynolds number (Figures 12 and 13) and pressure drop versus flow rate (Figures 14 and 15) were plotted for both air and helium using the incompressible flow loss coefficients.

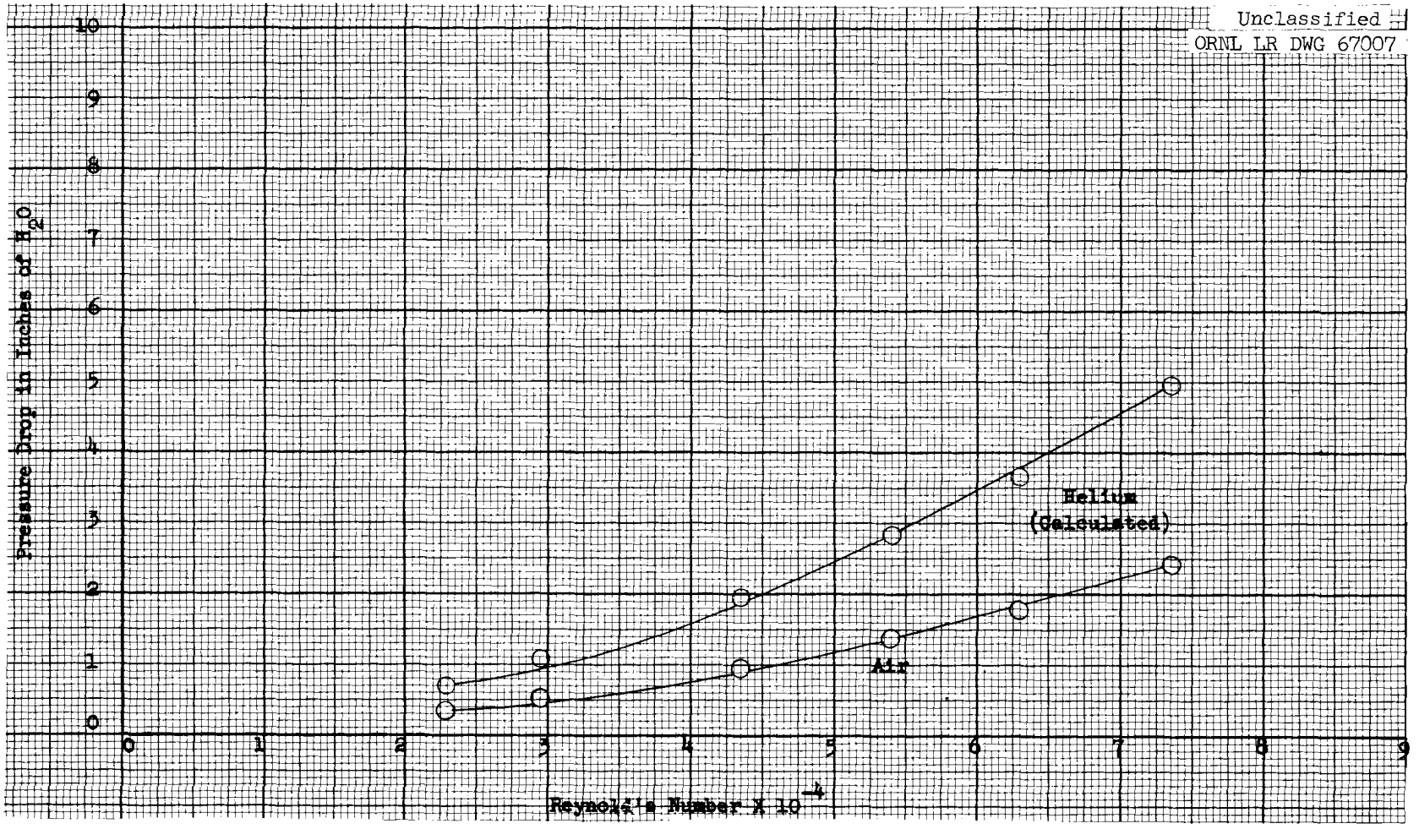

Fig. 12. Pressure Drop Versus Reynold's Number Across Filter (Unit I).

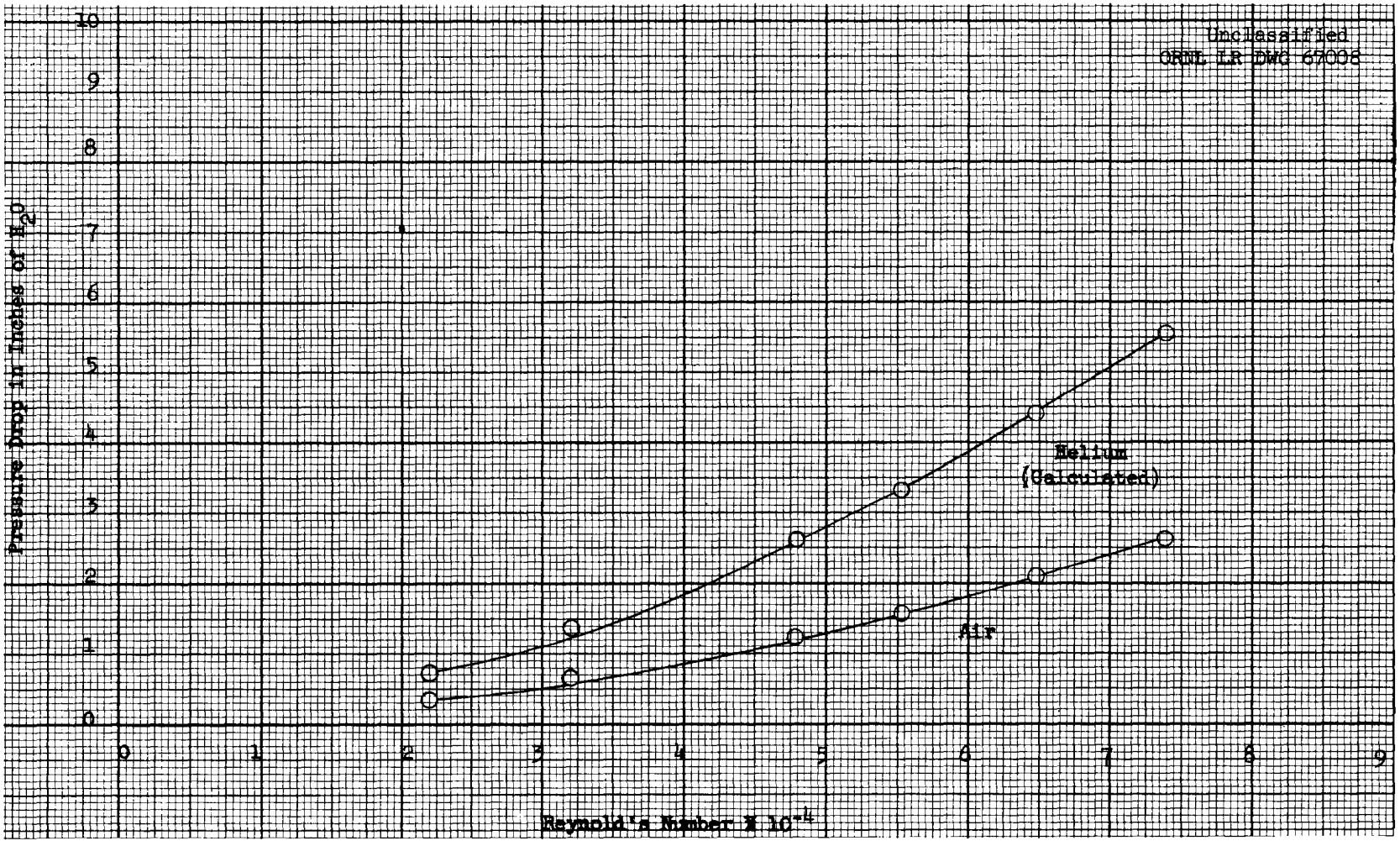

Fig. 13. Pressure Drop Versus Reynold's Number Across Filter (Unit II).

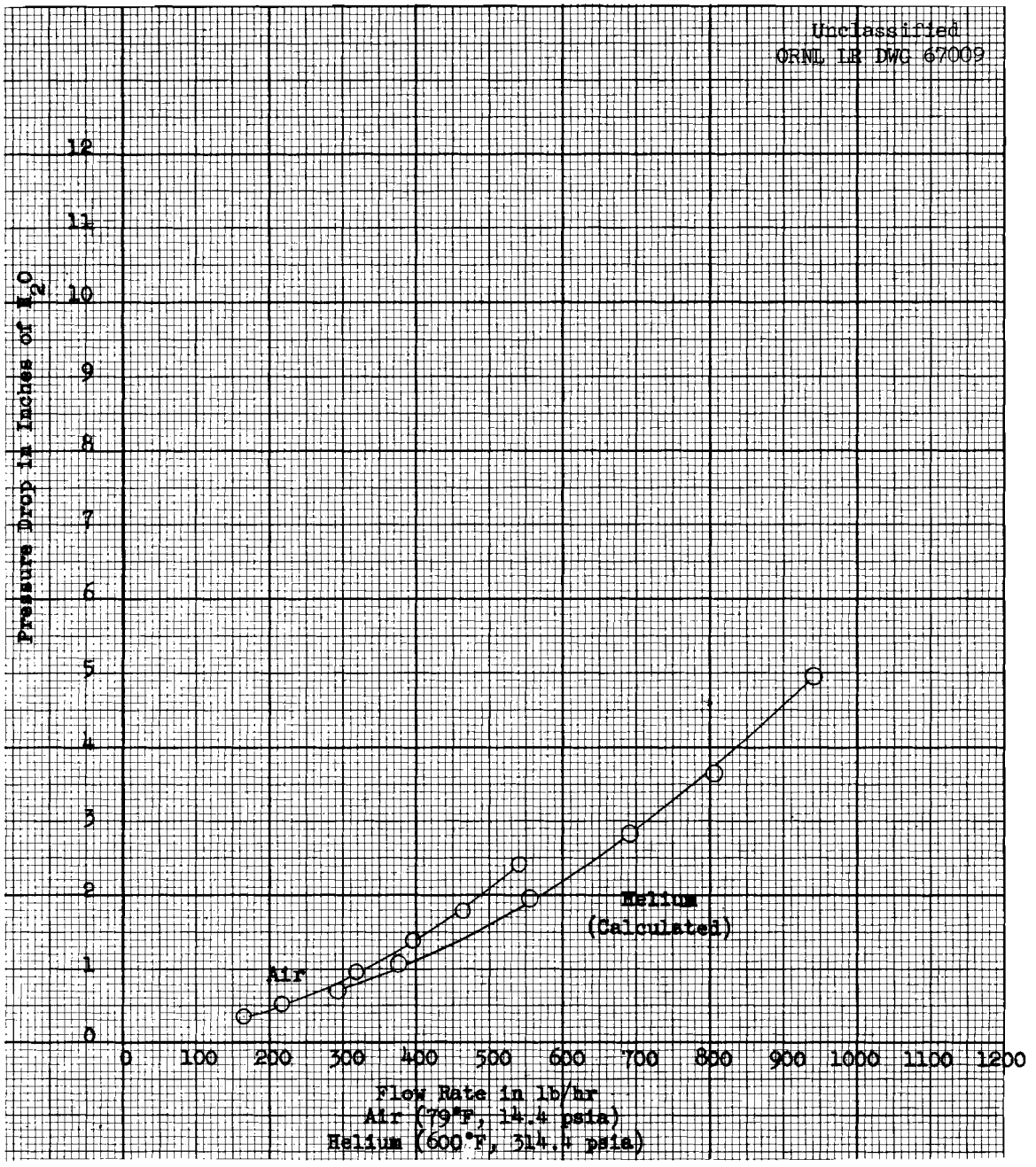

Fig. 14. Pressure Drop Versus Flow Rate Across Filter (Unit I).

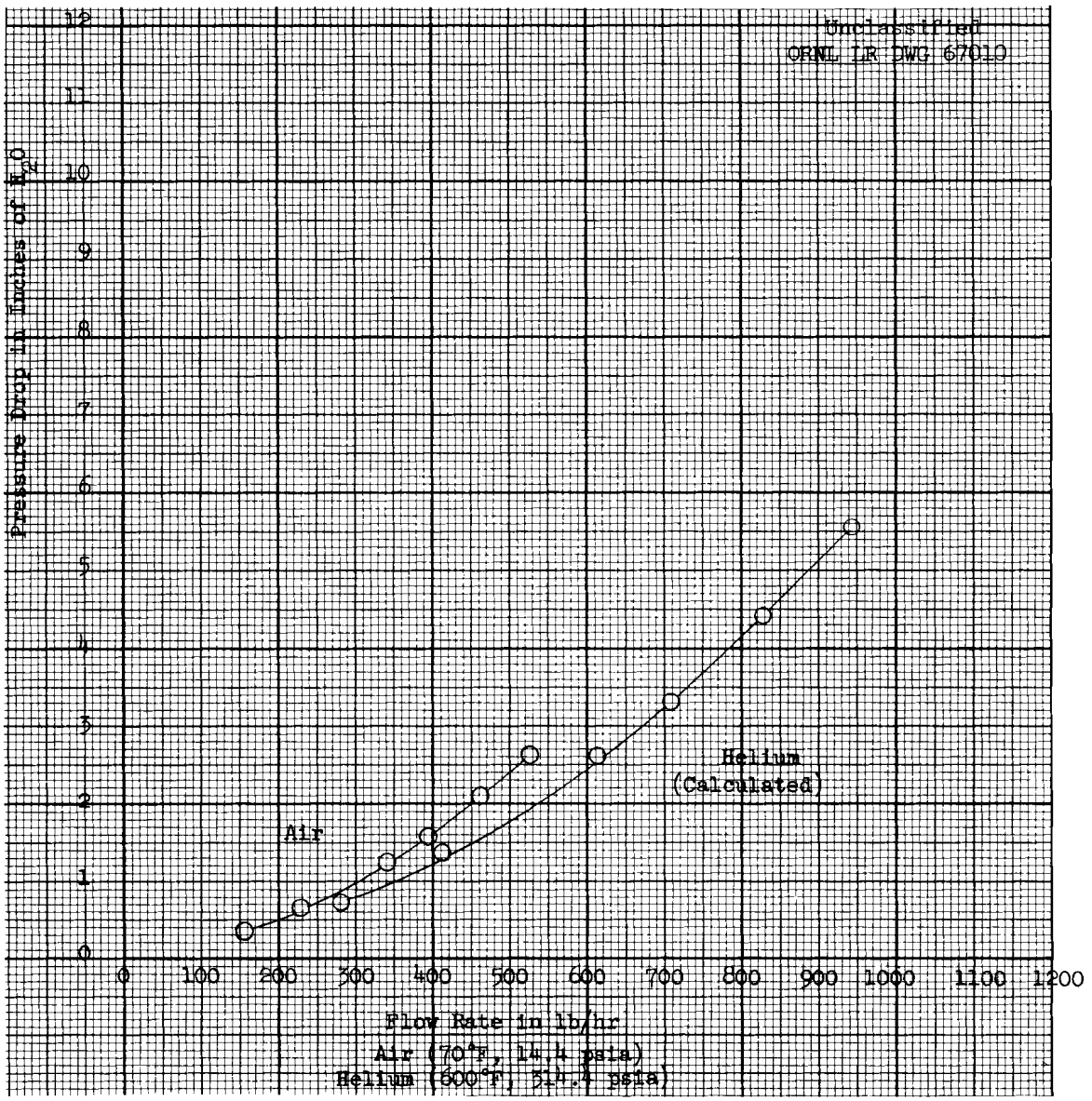

Fig. 15. Pressure Drop Versus Flow Rate Across Filter (Unit II).

C. Thermal Cycle and Bake-Out Tests

From the results of the thermal cycle and bake-out tests, it was concluded that off-gas products would be given off for a limited period of time when the filter was initially heated. The source of the off-gas products was not pinpointed. It could have been the filter paper, the fiber-glass sealant, or contaminants in the dioctylphthalate.

Appendix A

Definition of Terms:

H_L = Head Loss, ft.

f_e = Equivalent friction factor, dimensionless

L_e = Equivalent length, ft.

D_e = Equivalent diameter, ft.

g = Acceleration of gravity, 32.17 ft/sec^2

$\bar{V}$ = Average velocity of flow, ft/sec

C_L = Head loss coefficient, dimensionless

γ = Specific weight of coolant, lb/ft^3

A = Cross sectional area of coolant flow, ft^2

U = Internal energy of coolant, Btu/lb

P = Static Pressure, lb/ft^2

v = Specific volume of coolant, ft^3/lb

J = Joule's constant, 778 ft-lb/Btu

C_v = Specific heat of coolant at constant volume, Btu/lb-°F

R = Gas constant, ft/°F

C_p = Specific heat of coolant at constant pressure Btu/lb-°F

K = Ratio of specific heats $\frac{C_p}{C_v}$, dimensionless (taken as 1.4 for air, and as 1.667 for helium in these calculations)

T = Temperature of coolant, °R

W = Gas flow rate, lb/hr

ρ = Coolant mass density, lb-sec^2/ft^4

μ = Dynamic viscosity of coolant, lb-sec/ft^2

$\bar{\gamma}$ = Average specific weight of coolant, lb/ft^3

Internal Distribution

1. J. C. Amos
2. S. E. Beall
3. M. Bender
4. A. L. Benson
5. A. L. Boch
6. R. B. Briggs
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