APAE-Memo-108

COOLANT FLOW TAILORING PROGRAM OF THE APPR-1 CORE EMPLOYING A FULL SCALE MODEL OF THE REACTOR VESSEL

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Author: Salvatore M. Ingeneri

Alco Products, Inc.
Post Office Box 414
Schenectady, New York

DISCLAIMER

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NOMENCLATURES

Symbols

Q = volumetric flow rate

A = area

V = Control rod or fuel element coolant velocity

P = pressure drop

ρ = density

C = orifice coefficient

Vavg = average velocity through core

H = velocity head

Subscripts

RR = required control rod behavior

RP = Control Rod fuel plate section

CA = experimental core data

C = core

RA = experimental control rod data

RE = required fuel element behavior

FE = fuel element

W = water

A = Air

O = orifice

EA = Experimental fuel element data

1 = 1st Orifice Plate Data

2 = 2nd Orifice Plate Data

3 = 3rd Orifice Plate Data

INTRODUCTION

Control of fuel plate surface temperatures in the APPR-1 core is achieved by a non-uniform flow distribution through and between the 38 stationary fuel elements and seven control rods which comprise the whole core. The coolant enters the reactor through a single inlet duct, flows down and around a concentric annulus bounded by the core structure and reactor vessel, and into a plenum chamber located directly below the core. From the plenum chamber it enters the fuel elements and control rods as well as the network of passages between them - hereafter called the lattice.

In order to determine the flow distribution resulting from the approach and plenum chamber effects, it was necessary to build a model of the complete reactor to simulate these flow characteristics. The necessity of measuring these effects upon the flow in channels with actual widths of 0. 133 of an inch required making the model the same size as or larger than the real reactor, with the former being the final choice as shown in Figure 1. Dimensionally accurate simulating fuel elements and control rods were procured, with one of each kind containing accurately simulating parts. These comprised dummy fuel plates for the fuel element (Figure 2), and dummy absorber section, fuel plates, and cap and locking mechanism for the control rod (Figure 3). Figure 4 is a top view of the flow rig core showing the relative positions of the fuel elements and control rods with respect to the coolant inlet duct and control rod drive assemblies. An idea of how the fuel elements and control rods look when fitted into the reactor core is shown in Figure 5.

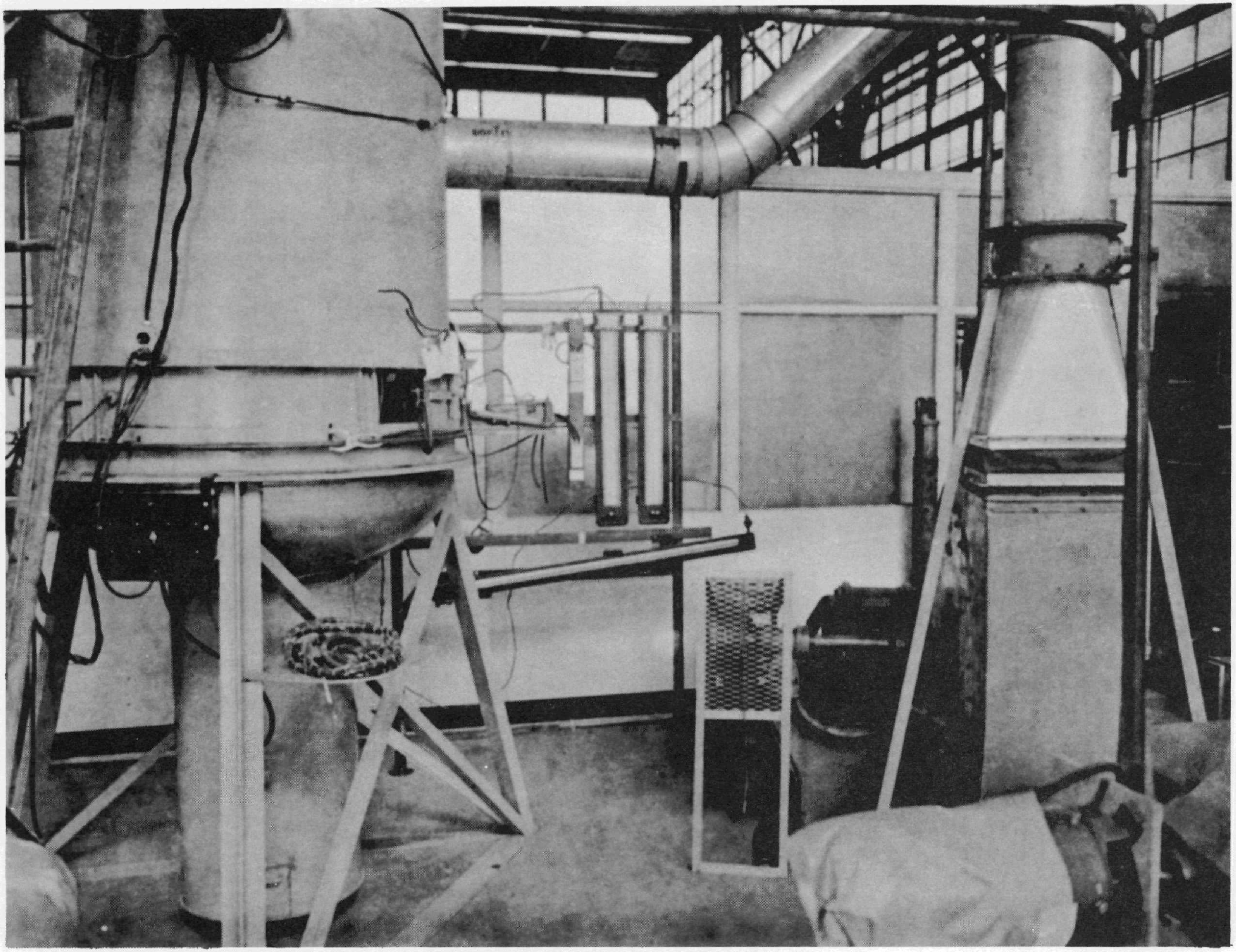


Fig. No. 1 View of the Simulating Reactor Vessel and Blower Used for the Air Flow Rig Tests

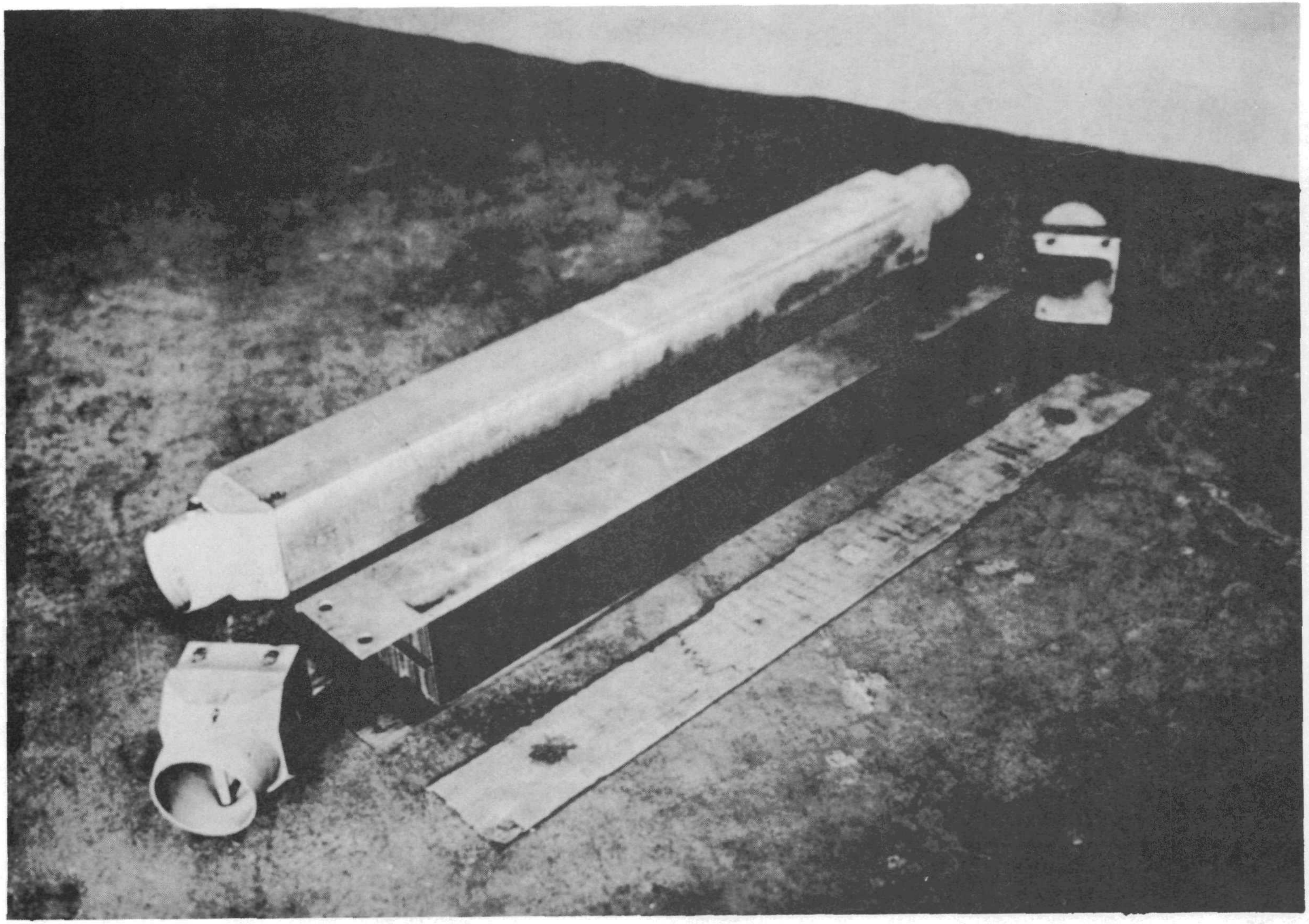


Fig. No. 2 The Simulating Fuel Element and Fuel Plates as Seen with the Plastic Side Plate and End Boxes Removed

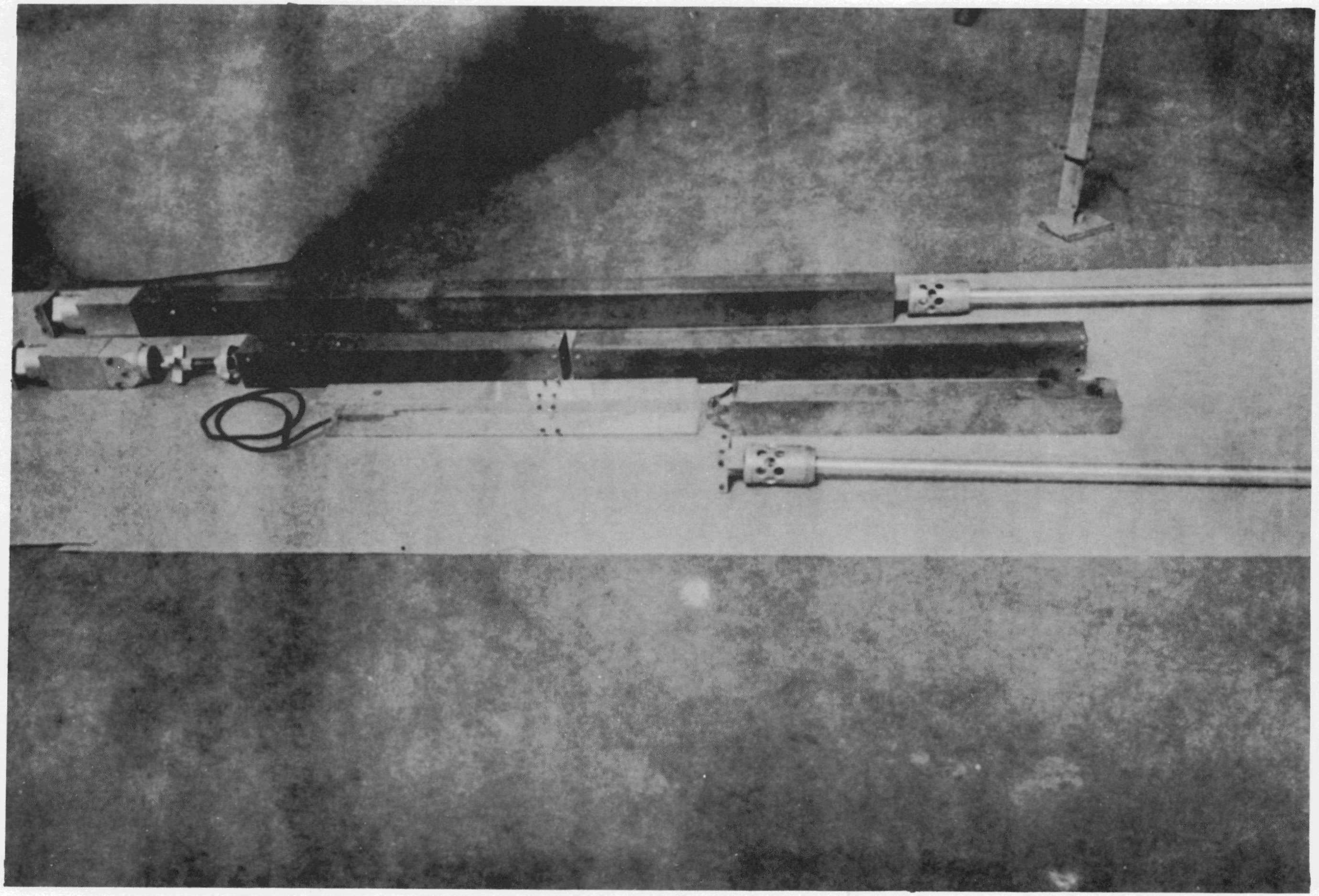
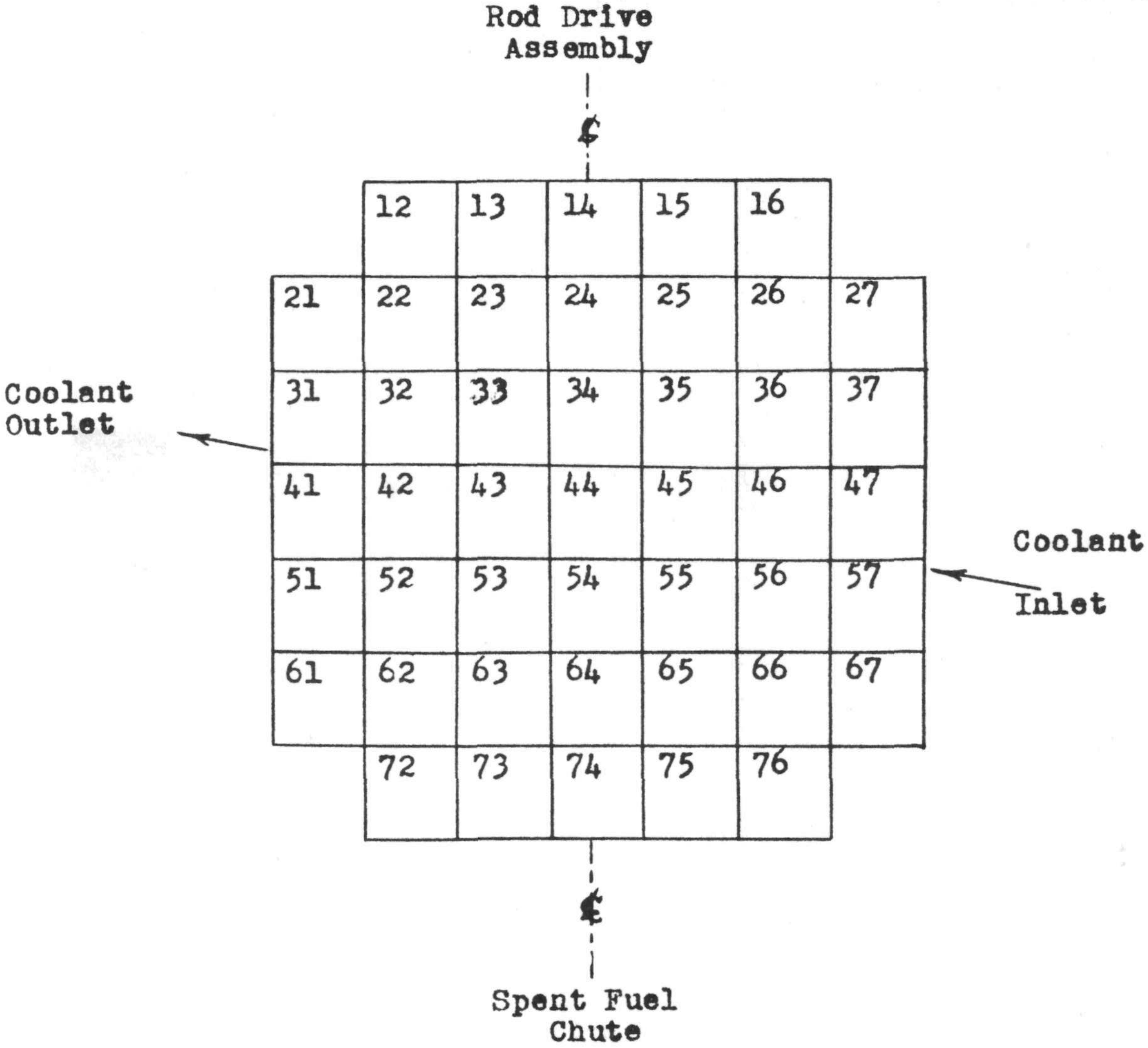


Fig. 3 The Simulating Control Rod With Its Components, With the Total Pressure Tube Installed



Position 44 - Control Rod C
42,24,46,64, - Shim Rods 1,2,3,4, respectively
55,33 - Safety Rods A & B respectively

Figure 4 Top View Of Flow Rig Core Showing Relative Positions of Fuel Elements and Control Rods and Also Method of Identification

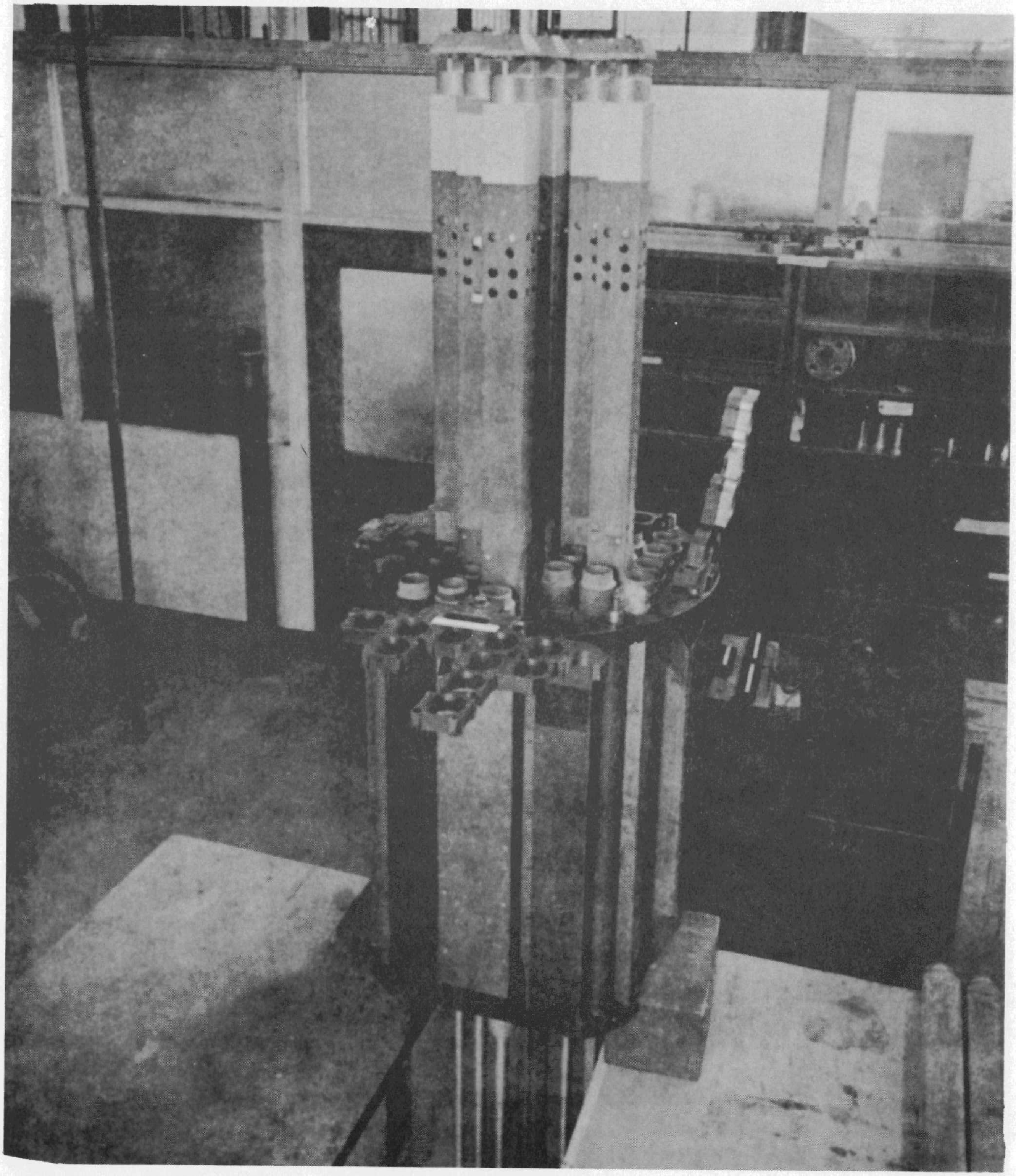


Fig. 5 View of Flow Rig Core Containing Stationary Fuel Elements and Control Rods

Although water is utilized as the coolant in the real reactor is was decided that the use of air as the test fluid in the rig would yield correct simulation and permit large savings in cost compared to handling large volumes of water. The air velocities used were far below the range at which compressibility becomes a factor.

Flux calculations and measurements have shown that a relatively greater portion of the coolant should flow through the central area of the core with the requirements decreasing for those elements and control rods located at increasing radii from the center.

To compensate for the random flow irregularities and to match the flow to the radial variation of heat flux in the core, orificing of the inlet of each of the fuel elements was undertaken. To do this a schedule of orifices was prepared which would directly regulate the flow through the fuel elements and lattice and indirectly control the coolant flow through the control rods.

OBJECT

1. To determine the existing flow distribution in the rig core without flow control devices.
2. To regulate by orificing in the test rig, the coolant flow pattern in the core with respect to fuel elements, control rods, and lattice flow to match the heat flux pattern anticipated in the core.
3. Upon obtaining satisfactory flow distribution within the flow rig, to prescribe the necessary orifice diameters for application in the APPR-1 reactor core.

PROCEDURE

Calibration

Before tests could be performed on the air flow rig it was necessary to calibrate the simulating control rod with regard to internal flow as a function of pressure drop. From this curve it was possible to select the diameter for internal orifices which were installed in each of the remaining six dummy control rods to give them the same flow resistance. A total pressure tube was installed in the simulating control rod in order to determine the total pressure drop for various internal flow rates. The calibration of this control rod was completed and the data employed to ascertain the flow through any control rod position within the core by simply interchanging the core positions of the instrumented control rod and a given dummy control rod. In like manner, since only one fuel element contained simulating fuel plates, it was necessary to determine the pressure drop through this fuel element and then proceed to install a flow resistant orifice in each of the remaining thirty-seven fuel elements which did not contain simulating fuel plates. The method and materials employed for calibrating the fuel elements and control rods are discussed in the appendix. The calibration data may also be found in the appendix along with the results and pertinent graphs.

Flow Measurement in Fuel Elements and Control Rods

In the reactor, two of the seven control rods are primarily to guarantee reactor shutdown when cold and five are for purposes of control. Zero power experiments indicated that the maximum insertion of the absorber sections required for criticality at any time during core life time would be 14 inches.

This position produces the severest axial peak of heat flux at the rated power of the reactor. Accordingly, the flow rig tests were carried out with the control rods in the aforementioned "fourteen-inch" position. During most of the testing the two safety rods were held in the "full-up" position, that is, the active fuel section in the safety rod at the same level as the active fuel section of the fixed fuel element since this was expected to be the normal position of the safety rods in the real reactor during operation.

After checking for leaks in the system, a probe was then taken of each fuel element in the core by measuring the velocity pressure with a pitot-static tube placed at the center of the outlet of the fuel element. A check of possible variations in velocity pressure across a given outlet diameter showed no measurable variation. Consequently, further measurements were taken only on the center-line of the outlet boxes. Upon completion of the fuel element probe, investigation of flow in the control rods was begun. Since only the complete simulating control rod contained a flow measuring device and was calibrated against pressure drop, it was necessary to move this calibrated control rod to each of the seven rod positions in order to determine the flow for every rod position. Upon completion of the initial investigation of flow in control rods and fuel elements, it was apparent that the anticipated orificing would have to accomplish substantial correction of the existing random distribution into the non-orificed core simultaneously with tailoring of the coolant flow to match the radial power distribution.

Orifice Design

The orifice plate is a thin plate cut to the same profile as and fastened to the lower side of the bottom support plate for the reactor core. It has rectangular clearance holes matching the outside cross-sectional dimensions of the seven rods, and sharp-edged round holes of varying diameters to regulate the flow into all the fuel elements and junction points of the lattice. No direct orifice regulation of the control rod flow by this plate was possible because the rods move up and down through the plate. The coolant is trapped within the rods before it reaches the plane of the plate, except for the two safety rods. Since the basic pressure drop was higher for the rods than for the fuel elements for any given flow, satisfactory coolant distribution in the core could be obtained by orificing only the stationary fuel elements and the lattice. Thus the holes in the orifice plate will vary in size in accordance with the experimental data acquired from the rig tests and also to match the required flow rates as calculated from a thermal analysis of the APPR-1 core.[1]

Orifice Development

The required flow rate through each unit of the flow rig is determined in terms of the ratio of the required coolant velocity through a given core position to the average coolant velocity through the core as obtained from the aforementioned thermal analysis. A schedule of the original and revised values of $^{V}/V_{avg}$ for fuel elements and control rods at various core radii is contained in Table I. The procedure for obtaining the final orifice diameter for an arbitrarily selected fuel element may be found under "Discussion". However, a brief preliminary explanation will perhaps be of some help. Following completion of the initial set of tests, hole diameters for the first trial orifice plate were computed and this plate was prepared and installed. Flow distribution was measured again, and a second schedule of hole sizes was calculated and machined. Similar tests were repeated with this second trial orifice, and

[1] APAE Memo No. 57 issued 8/17/56 C.H. Harvey.
APAE Memo No. 91 issued 4/1/57 C.H. Harvey.

TABLE I

Values of $^{V}/Vavg$ for APPR-1 Core

Core Radius (inches)	Member Fuel Elements And Control Rods Identification	*Initial Values of Required V/Vavg	**Revised Values of Required V/Vavg
0.00	44	1.48	1.362
2.95	34, 43, 45, 54	1.39	1.420
4.16	33, 35, 53, 55	1.33	1.347
5.90	24, 42, 46, 64	1.20	1.250
6.60	52, 32, 23, 25, 36, 56, 65, 63	1.25	1.214
8.32	62, 22, 26, 66	0.990	0.922
8.80	14, 74, 41, 47	0.938	0.789
9.30	73, 75, 51, 57, 31, 37, 13, 15	0.828	0.752
10.60	72, 76, 61, 67, 21, 27, 12, 16	0.660	0.607

* Employed for orifice plates numbers 1 and 2.

** Employed for orifice plate number 3 and final orifice dimensions.

the results of tests with both the first and second orifices were correlated in preparing the recommendations for the third orifice plate. This latter plate resulted in a satisfactory radial flow distribution except for the flow in the two safety rods which were much lower than their prescribed value.

At this time it was found that the entire simulating core structure of the rig had been installed 90^{o} out of phase from its proper relation to the inlet and outlet nozzles of the vessel. The core was then rotated to the correct position and the complete flow test was repeated using the third orifice plate. Here again the results indicated that the two safety rods were not receiving their required flow. At about this same time, nuclear considerations had indicated that these two rods should normally be positioned 1-1/2 inches below full up. Adopting this position moved the coolant entrance holes of the control rods below the bottom core support plate and into the lower plenum chamber, thus correcting the deficiency without further orificing work. The change in core and orifice plate position to correct the angular error changed the flow rate through some of the fuel elements, but only slightly. Therefore, only small modifications in those fuel element orifice dimensions were necessary. The final schedule of orifice diameters are contained in the section titled "Results".

Lattice Flow Measurements

Coolant flow in the lattice passages was measured by a variation of hot wire anemometry employing glass coated bead thermistors because of the limited area of the lattice passages and also because of the inherent sensitivity of thermistors. These are basically composed of semi-conducting material which has a large negative temperature coefficient of electrical conducitivity.

The principal advantage of thermistors is partly this large change in electrical resistance for a relatively small change in temperature and partly their inherently high resistance even at the upper end of the useful temperature range. With the proper electrical circuit, thermistors may be readily applied to anemometry as was done in these flow rig tests. Before introduction into the core, the thermistors were first calibrated at known flow rates and temperatures. The method employed for calibration is described in the appendix. Experimental data for thermistor behavior as shown on representative curves may also be found in the appendix.

The thermistors were installed on the outer "fuel" plate of the simulating fuel element, as shown in Figure A7. Flow measurements were taken in lattice passages flanking fuel plates rather than in those areas between non-fuel bearing side plates. The former, of course, were the only important channels from the point of view of adequacy of flow. Upon completion of the probe in a given fuel element position, the leads were disconnected and the fuel element with the thermistors was transferred to another core position. Due to time limitations, probes were not carried out for every lattice passage but rather only for a representative sampling of passages.

Flux Suppressors

During the orificing program, results obtained from Alco's Criticality Facility indicated a much higher neutron flux density between the fuel section and absorber section of the control rods than was anticipated. At rated power of the APPR-1 this condition if uncorrected might well have lead to temperatures sufficient to cause boiling. In order to reduce the flux density at this location, flux suppressors (neutron absorbers) were introduced into the gap. The effect of the suppressors on the overall pressure drop through the control rod was measured in the flow rig and found negligible. This work substantiated theoretical calculations which were performed concurrently.

DISCUSSION

As described previously in the section titled Procedure, flow regulation into the fuel elements and lattice is achieved by an orifice program. Before actual orificing was initiated it was necessary to determine the existing flow pattern in the unorificed flow rig core.

The results of this investigation are shown in Table II. The total flow through the fuel elements and control rods was approximately 4200 ft^3/min at a pressure drop across the core of 3.12 inches of water. It will be noted that the center control rod has a coolant velocity of 1431 ft/min or 54.6 ft^3/min. From the experimental data obtained for control rods and fuel elements as tabulated in the appendix, it is apparent that for a given flow rate a control rod has greater head loss than a fuel element. Consequently, since the center rod requires the greatest coolant flow, it will govern the pressure drop across the core. Thus, determining the pressure drop through the center control rod for its required flow will also yield the pressure drop across each of the fuel elements and control rods since they are all operating in parallel with the center control rod.

TABLE II

Initial Pitot-Static Traverse of Flow Rig Core Without Fuel Element Orificing

Core Position	H (inches H_2O)	Flow Velocity (ft/min)	Core Position	H (inches H_2O)	Flow Vel. (ft/min)
72	1.28	4560	31	1.30	4610
73	1.38	4730	32	1.03	4100
74	1.37	4720	33	1.02	4090
75	1.33	4650	34	1.05	4140
76	1.33	4650	35	Safety Rod	
61	1.06	4140	36	1.31	4630
62	1.21	4440	37	1.37	4730
63	1.45	4880	21	1.07	4170
64	Shim Rod		22	1.24	4490
65	1.25	4500	23	1.31	4630
66	1.29	4570	24	Shim Rod	
67	1.38	4740	25	1.25	4500
51	1.28	4560	26	1.27	4550
52	1.14	4310	27	1.41	4800
53	Safety Rod		12	1.21	4440
54	0.91	3890	13	1.30	4610
55	1.07	4170	14	1.34	4670
56	1.21	4440	15	1.28	4560
57	1.38	4740	16	1.24	4490
41	1.50	4970			
42	Shim Rod				
43	1.29	4570			
44	Center Control Rod				
45	1.25	4500			
46	Shim Rod				
47	1.38	4740			

P across Core = 3.12" H_2O

Static Pressure Upper Plenum Chamber = 4.15" H_2O

TABLE II (Con't.)

Control Rod Position	Total Pressure ("H_2O)	H ("H_2O)	*Flow Velocity (ft/min)
64	5.05	0.90	1731
53	4.67	0.62	1352
42	4.85	0.70	1462
44	4.82	0.67	1431
46	4.92	0.77	1559
35	5.08	0.93	1780
24	5.02	0.87	1700

*Reference calibration curves for control rods - Fig. A6

Total Volumetric Flow through Fuel Elements and Control Rods = 4200 ft^3/min

NOTES:

1. Flow Rig Core 90^o out of phase which in essence will change control rod position from 35 and 53 as above to 55 and 33 respectively.

2. Pressure drop measurements taken at exit of fuel elements, area of which = 0.0218 ft^2.

Development of 1st Orifice Plate Schedule

Based on the above total flow, the required flow in the center control rod is:

$$Q_{RR} = A_{RP} \text{ x } V$$

$$= A_{RP} \text{ x } V_{avg} \text{ x } 1.48$$

$$= A_{RP} \text{ x } \frac{Q_{CA}}{A_C} \text{ x } 1.48$$

$$= 119 \text{ ft}^3/\text{min}$$

where: $A_{RP} = 0.03815 \text{ ft}^2$
$Q_{CA} = 4200 \text{ ft}^3/\text{min}$
$A_C = 1.998 \text{ ft}^2$
$V = 1.48 \text{ Vavg}$

and the corresponding pressure drop

$$P_{RR} = P_{CA} \text{ x } \frac{Q_{RR}^2}{Q_{RA}^2}$$

$$= 14.75 \text{ "}H_2O$$

where: $P_{CA} = 3.12\text{" } H_2O$
$Q_{RR} = 119 \text{ ft}^3/\text{min}$
$Q_{RA} = 54.6 \text{ ft}^3/\text{min}$

The required flow rate for fuel element 72 is

$$Q_{RE} = A_{FE} \text{ x } V$$

$$= A_{FE} \text{ x } V_{avg} \text{ x } 0.66$$

$$= A_{FE} \text{ x } \frac{Q_{CA}}{A_C} \text{ x } 0.66$$

$$= 63.4 \text{ ft}^3/\text{min}$$

where: $A_{FE} = 0.0456 \text{ ft}^2$
$Q_{CA} = 4200 \text{ ft}^3/\text{min}$
$A_C = 1.998 \text{ ft}^2$
$V = 0.66 \text{ Vavg}$

The pressure drop across the fuel element at the required flow rate of 63.4 ft^3/min may be obtained by the relation:

$$P_{RE} = P_{CA} \text{ x } \frac{Q_{RE}^2}{Q_{EA}^2}$$

$$= 1.24\text{" } H_2O$$

where: $P_{CA} = 3.12\text{" } H_2O$
$Q_{RE} = 63.4 \text{ ft}^3/\text{min}$
$Q_{EA} = 99.5 \text{ ft}^3/\text{min}$

The orifice must then account for the remainder of the pressure drop, or specifically 14.75 - 1.24 = 13.51" H_2O. The diameter of the orifice may then be calculated as follows assuming a constant orifice coefficient of 0.62.

$$Q_{RE} = CA \times 60 \sqrt{2gP_A}$$

$$A = \frac{Q_{RE}}{60C\sqrt{2gP_A}} = \frac{Q_{RE}}{60C\sqrt{2g \times \frac{P_W}{12} \times \frac{\rho_W}{\rho_A}}}$$

$$D = \frac{0.275\ Q_{RE}}{\sqrt[4]{P_W}}$$

$$= 1.12 \text{ inches}$$

Where:

Q_{RE} = 61.6 ft^3/min

P_W = 13.51"H_2O

ρ_W = 62.3 lb/ft^3

ρ_A = 0.075 lb/ft^3

g = 32.2 ft/sec^2

c = 0.62

A schedule of orifice diameters derived by the above procedure is shown in Table III.

TABLE III

ORIFICE DIAMETER SCHEDULE OF 1st ORIFICE PLATE

Fuel Element Position	Orifice Diameter (inches)	Fuel Element Position	Orifice Diameter (inches)	Fuel Element Position	Orifice Diameter (inches)
72	1.12	54	1.89	37	1.26
73	1.26	55	1.76	21	1.12
74	1.36	56	1.66	22	1.41
75	1.26	57	1.26	23	1.67
76	1.12	41	1.35	25	1.65
61	1.12	43	1.77	26	1.41
62	1.41	45	1.79	27	1.11
63	1.62	47	1.35	12	1.11
65	1.61	31	1.26	13	1.26
66	1.44	32	1.69	14	1.36
67	1.11	33	1.77	15	1.27
51	1.27	34	1.87	16	1.11
52	1.66	36	1.67		

Development of 2nd Orifice Plate Schedule

Experimental data obtained from the flow rig with the first orifice plate installed is shown in Table IV. Generally, the flow through the fuel elements and control rods did not satisfactorily follow the required flow pattern except for a few isolated cases. Instead of assuming a constant orifice coefficient for each fuel element, a coefficient was calculated for each fuel element position from the experimental data acquired with the 1st orifice plate on the core.

A description of the mechanics involved for determining an experimental orifice coefficient follows using as before fuel element 72 as an example. The flow rate through fuel element 72 is 39.2 ft^3/min (ref. Table IV) at a pressure drop across the core of 5.45 inches of water. From calibration data obtained on fuel elements, Figure A3, it may be seen that at a flow rate of 39.2 ft^3/min or 0.654 $ft^3/sec.$, the fuel element has a pressure drop of 0.67 inches of water. Of the 0.67 inches, 85.5% was found by analysis to take place after the entrance.

The pressure drop of the orifice alone is:

$$P_O = P_{CA} - (0.855)(P_{EA})$$

$$= 4.88'' H_2O$$

$$= 3.56 \text{ ft. of air}$$

where: $P_{CA} = 5.45'' H_2O$

$P_{EA} = 0.67'' H_2O$

then the orifice coefficient is:

$$C = \frac{Q_{EA}/60}{A_O/144 \sqrt{2gP_O}}$$

$$= \frac{0.298 \; Q_{EA}}{A_O \sqrt{P_O}}$$

$$= 0.643$$

where: $Q_{EA} = 39.2 \; ft^3/min$

$A_O = 0.968 \; in^2$

$P_O = 356$ ft. air

$g = 32.2 \; ft/sec^2$

TABLE IV

PITOT STATIC TRAVERSE OF FLOW RIG CORE WITH 1st ORIFICE PLATE INSTALLED

Core Position	H (inches H_2O)	Flow Velocity (ft/min)	Core Position	H (inches H_2O)	Flow Vel. (ft/min)
72	0.21	1800	31	0.46	2740
73	0.53	2940	32	1.11	4250
74	0.53	2940	33	1.36	4700
75	0.38	2470	34	1.49	4930
76	0.20	1770	35	Safety Rod	
61	0.26	2050	36	1.16	4340
62	0.63	3210	37	0.42	2610
63	1.07	4160	21	0.24	1960
64	Shim Rod		22	0.59	3100
65	1.03	4100	23	1.17	4360
66	0.68	3340	24	Shim Rod	
67	0.25	2000	25	1.13	4280
51	0.49	2810	26	0.62	3170
52	1.08	4180	27	0.26	2050
53	Safety Rod		12	0.21	1800
54	1.60	5100	13	0.36	2410
55	1.44	4850	14	0.52	2910
56	1.19	4400	15	0.39	2520
57	0.38	2480	16	0.23	1940
41	0.65	3260			
42	Shim Rod				
43	1.50	4940			
44	Center Control Rod				
45	1.49	4930			
46	Shim Rod				
47	0.53	2940			

P across Core = 5.45" H_2O

Static Pressure Upper Plenum = 4.01" H_2O

TABLE IV (Cont'd)

Control Rod Position	Total Pressure ("H_2O)	H ("H_2O)	*Flow Velocity (ft/min)
64	5.90	1.89	2720
53	5.43	1.42	2300
42	5.93	1.92	2740
44	6.01	2.00	2830
46	5.83	1.82	2680
35	5.48	1.47	2360
24	5.91	1.90	2720

* From calibration curves for control rods - Fig. A6

Total volumetric flow through fuel elements and control rods = 3420 ft^3/min

NOTES:

1. Flow rig core 90° out of phase which in essence will change safety control rod position from 35 and 53 as above to 55 and 33 respectively.
2. Pressure drop measurements taken at exit of fuel elements, area of which = 0.0218 ft^2.

With the orifice coefficients evaluated in Table V, a similar process as described for the first orifice plate is followed for determining a new schedule of orifice diameters which are recorded in Table VI.

Development of 3rd Orifice Plate Schedule

The results of installing the 2nd orifice plate on the flow rig core are shown in Table VII. Here again the flow pattern was not satisfactory in that those fuel elements which were located at greater core radii were receiving much more than their prescribed share. This in turn caused a deficiency of coolant flow to those fuel elements more centrally located as well as all of the control rods. Calculation of orifice coefficients from the new data indicated a significant deviation from those values which were determined from experimental data with the first orifice plate on the core. This disagreement may be partially explained from the changes in the inlet orifice diameters of the fuel elements. These changes cause a variation in the crossflow pattern within the lower plenum chamber resulting in a variation of orifice entrance characteristics.

The third orifice dimensions were obtained by first calculating the product of the orifice coefficient and orifice area for the experimental data of the first and second orifice plates. These products were arithmetically averaged and in turn utilized for interpolation with the experimental data to obtain a new orifice plate schedule.

A brief description of the method employed for determining the 3rd orifice plate schedule follows. The orifice coefficient for core position 72 was calculated from the second orifice plate data and was found to equal 0.799. At this point a change in the schedule of the optimum V/Vavg ratios

TABLE V

ORIFICE COEFFICIENTS EVALUATED FROM DATA OBTAINED WITH THE 1st ORIFICE PLATE

Fuel Element Position	Orifice Coefficient	Fuel Element Position	Orifice Coefficient	Fuel Element Position	Orifice Coefficient
72	0.64	54	0.84	37	0.76
73	0.87	55	0.89	21	0.70
74	0.75	56	0.86	22	0.74
75	0.71	57	0.72	23	0.87
76	0.63	41	0.86	25	0.83
61	0.73	43	0.90	26	0.76
62	0.77	45	0.89	27	0.74
63	0.83	47	0.75	12	0.64
65	0.78	31	0.80	13	0.69
66	0.77	32	0.78	14	0.74
67	0.72	33	0.84	15	0.71
51	0.82	34	0.82	16	0.70
52	0.79	36	0.87		

TABLE VI

ORIFICE DIAMETERS SCHEDULE OF 2nd ORIFICE PLATE

Fuel Element Position	Orifice Diameter (inches)	Fuel Element Position	Orifice Diameter (inches)	Fuel Element Position	Orifice Diameter (inches)
72	1.382	54	2.057	37	1.463
73	1.370	55	1.957	21	1.326
74	1.594	56	1.863	22	1.666
75	1.511	57	1.504	23	1.858
76	1.394	41	1.488	25	1.901
61	1.297	43	2.035	26	1.644
62	1.635	45	2.049	27	1.292
63	1.903	47	1.592	12	1.382
65	1.960	31	1.419	13	1.530
66	1.635	32	1.959	14	1.606
67	1.345	33	2.022	15	1.507
51	1.403	34	2.137	16	1.328
52	1.942	36	1.860		

TABLE VII

PITOT-STATIC TRAVERSE OF FLOW RIG CORE WITH 2nd ORIFICE PLATE INSTALLED

Core Position	H (inches H_2O)	Flow Velocity (ft/min)	Core Position	H (inches H_2O)	Flow Vel. (ft/min)
72	0.47	2760	31	0.70	3370
73	0.52	2900	32	1.44	4810
74	0.79	3570	33	1.63	5130
75	0.59	3090	34	1.81	5400
76	0.49	2820	35	Safety Rod	
61	0.39	2510	36	1.31	4590
62	0.90	3820	37	0.67	3300
63	1.39	4730	21	0.42	2600
64	Shim Rod		22	0.92	3860
65	1.44	4810	23	1.40	4750
66	0.93	3870	24	Shim Rod	
67	0.45	2700	25	1.42	4770
51	0.64	3220	26	0.88	3780
52	1.45	4830	27	0.42	2600
53	Safety Rod		12	0.50	2840
54	1.62	5100	13	0.71	3390
55	1.51	4930	14	0.87	3700
56	1.42	4790	15	0.74	3460
57	0.60	3120	16	0.41	2570
41	0.87	3770			
42	Shim Rod				
43	1.81	5400			
44	Center Control Rod				
45	1.72	5260			
46	Shim Rod				
47	0.82	3650			

P across Core = 4.24" H_2O

Static Pressure Upper Plenum = 4.17" H_2O

TABLE VII (Cont'd)

Control Rod Position	Total Pressure ("H_2O)	H "H_2O	*Flow Velocity (ft/min)
64	5.68	1.51	2380
53	5.19	1.02	1873
42	5.58	1.41	2320
44	5.63	1.46	2340
46	5.78	1.61	2490
35	5.30	1.13	2000
24	5.62	1.45	2330

* Reference calibration curves for control rods - Fig. A6

NOTES:

1. Flow Rig Core 90° out of phase which in essence will change safety control positions from 35 and 53 to 55 and 33 respectively.
2. Pressure drop measurements taken of exit of fuel elements, area of which = 0.0218 ft^2.

Total Volumetric Flow through fuel elements and Control Rods ≃ 3800 ft^3/min for the APPR-1 core was published. The new values are contained in Table I. From results obtained with the previous orifice plates, a total flow of 3590 ft^3/min through the fuel elements and control rods was anticipated with a pressure drop across the core of 4.87" H_2O. The required flow through fuel element 72 could then be determined as before by:

$$Q_{RE} = A_{FE} \times V$$
$$= A_{FE} \times Vavg \times 0.607$$
$$= A_{FE} \times \frac{Q_C}{A_C} \times 0.607$$
$$= 49.6\ ft^3/min$$

where: $A_{FE} = 0.0456\ ft^2$

$Q_C = 3590\ ft^3/min$ (anticipated flow rate)

$A_C = 1.998\ ft^2$

$V = 0.607\ Vavg.$

Reference to fuel element calibration curves indicated that at a flow rate of 49.6 ft^3/min or 0.83 ft^3/sec, the fuel element would have a pressure drop of 0.94 inches of water. As shown previously 85.5% of this pressure drop takes place after the entrance. Thus the pressure drop which could be attributed to the orifice was:

$$P_O = P_{RR} - (0.855)(P_{EA})$$
$$= 4.07''H_2O$$

where: $P_{RR} = 4.87''H_2O$

$P_{EA} = 0.94''H_2O$

By simple ratios of the existing data it was possible to determine the product of the orifice coefficient and orifice area for the third orifice plate in relation to experimental data obtained for each of the other two orifice plates tested. An example follows:

$$C_3A_3 = \frac{Q_3}{Q_1}\ C_1A_1 \sqrt{\frac{P_{o1}}{P_{o3}}}$$
$$= 0.861$$

where:

P_{o1} = 4.88"H_2O

P_{o3} = 4.07"H_2O

Q_3 = 4.96 ft^3/min

Q_1 = 39.2 ft^3/min

C_1 = 0.643

A_1 = 0.968 in^2

From experimental data obtained with the second orifice plate on the core

$C_3A_3 = 0.875$

The values were then arithmetically averaged to obtain

$C_3A_3 = 0.868$

The diameter of element 72 in the third orifice plate was then interpolated as shown:

$$D_3 = \frac{1}{\pi/4} \sqrt{A_1 + \frac{C_3A_3 - C_1A_1}{C_2A_2 - C_1A_1} (A_2 - A_1)}$$

= 1.234 inches

where:

$C_1A_1 = 0.622$

$C_2A_2 = 1.199$

$C_3A_3 = 0.868$

$A_1 = 0.968$ in^2

$A_2 = 1.50$ in^2

A similar procedure was employed for each of the fuel element orifices. The schedule of orifice diameters for the third orifice plate is shown in Table VIII.

The results obtained with the new orifice schedule on the flow rig core are shown in Table IX. The flow distribution obtained is generally satisfactory with one exception - - that being the flow through each of the safety rods. The measured flow through these rods was much lower than the prescribed flow rate.

At this phase of the orificing program the flow rig core was found to be incorrectly oriented with respect to coolant inlet and control rod drive mechanism. The situation was promptly corrected by rotating the core 90 degrees. The flow rig core is schematically shown in Figure 6, before and after the correction. In the new core position, the orifice plate was inverted about the axis of the coolant inlet in order to obtain similar fuel element orificing relative to the coolant inlet geometry. The experimental results are shown in Table X. The reorientation of the core introduced small variations in the flow rate of some of the fuel elements. The coolant flow through each of the safety rods was again lower than the prescribed value. This condition was alleviated as described previously by lowering the two safety rods one and a half inches, the results of which are contained in Table XI. With the control rods in their new position, a probe of nearby elements indicated (Table XI) a slight change in their coolant flow which was readily corrected by a slight change in the particular orifice diameter.

TABLE VIII

ORIFICE DIAMETERS SCHEDULE OF 3rd ORIFICE PLATE

Fuel Element Position	Orifice Diameter (inches)	Fuel Element Position	Orifice Diameter (inches)	Fuel Element Position	Orifice Diameter (inches)
72	1.234	54	2.015	37	1.322
73	1.276	55	1.824	21	1.209
74	1.396	56	1.726	22	1.509
75	1.382	57	1.368	23	1.717
76	1.236	41	1.339	25	1.746
61	1.200	43	1.898	26	1.495
62	1.493	45	1.942	27	1.184
63	1.755	47	1.391	12	1.227
65	1.788	31	1.296	13	1.364
66	1.496	32	1.792	14	1.398
67	1.184	33	1.931	15	1.345
51	1.294	34	1.994	16	1.213
52	1.773	36	1.745		

TABLE IX

PITOT STATIC TRAVERSE OF FLOW RIG CORE WITH 3rd ORIFICE PLATE INSTALLED

Core Position	H (inches H_2O)	Flow Velocity (ft/min)	Core Position	H (inches H_2O)	Flow Vel. (ft/min)
72	0.33	2280	31	0.55	2960
73	0.47	2730	32	1.28	4520
74	0.53	2910	33	1.68	5190
75	0.53	2910	34	1.77	5330
76	0.34	2310	35	Safety Rod	
61	0.36	2380	36	1.30	4560
62	0.76	3500	37	0.58	3050
63	1.31	4570	21	0.34	2310
64	Shim Rod		22	0.73	3430
65	1.34	4630	23	1.26	4480
66	0.79	3560	24	Shim Rod	
67	0.33	2280	25	1.30	4560
51	0.55	2960	26	0.78	3540
52	1.32	4590	27	0.33	2280
53	Safety Rod		12	0.38	2450
54	1.79	5350	13	0.51	2770
55	1.55	4990	14	0.58	3050
56	1.27	4500	15	0.52	2880
57	0.46	2700	16	0.34	2320
41	0.63	3170			
42	Shim Rod				
43	1.80	5370			
44	Center Control Rod				
45	1.77	5330			
46	Shim Rod				
47	0.60	3100			

P across Core = 5.04"H_2O

Static Pressure Upper Plenum = 4.32"H_2O

TABLE IX (Cont'd.)

Control Rod Position	Total Pressure "H_2O	H ("H_2O)	*Flow Velocity (ft/min)
64	6.10	1.78	2630
53	5.57	1.25	2140
42	6.04	1.72	2570
44	6.05	1.73	2580
46	6.12	1.80	2660
35	5.62	1.30	2190
24	6.02	1.70	2550

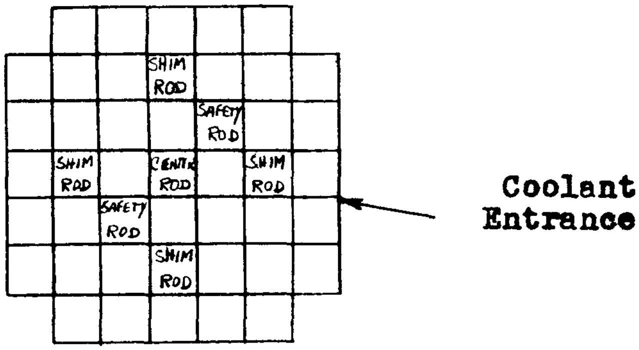
* Reference calibration curves for control rods - Fig. A6

NOTES:

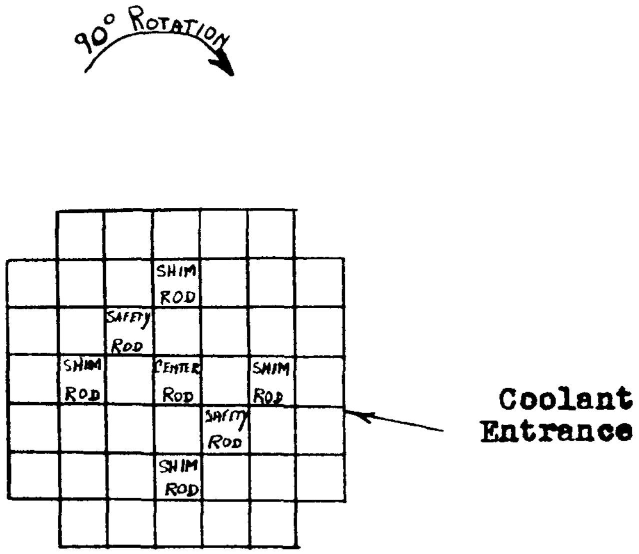
1. Flow rig core 90^{o} out of phase which in essence will change safety control rod positions from 35 and 53 as above to 55 and 33 respectively.

2. Pressure drop measurements taken at exit of fuel elements, area of which = 0.0218 ft^2.

Total Volumetric flow through fuel elements and control rods = 3640 ft^3/min



Original Core Position
(Top view)



Corrected Core Position
(Top view)

FIGURE 6 - Flow Rig Core Orientations During Orificing Program

TABLE X

PITOT STATIC PROBE OF THE REORIENTATED FLOW RIG CORE WITH THE 3rd ORIFICE PLATE INSTALLED

Core Position	H (inches H_2O)	Flow Velocity (ft/min)	Core Position	H (inches H_2O)	Flow Vel. (ft/min)
72	0.34	2350	31	0.53	2960
73	0.54	2970	32	1.27	4560
74	0.57	3070	33	Safety Rod	
75	0.51	2900	34	1.81	5470
76	0.35	2400	35	1.52	5020
61	0.34	2350	36	1.20	4450
62	0.71	3440	37	0.55	3020
63	1.25	4550	21	0.33	2330
64	Shim Rod		22	0.75	3504
65	1.29	4620	23	1.22	4480
66	0.72	3460	24	Shim Rod	
67	0.31	2250	25	1.39	4780
51	0.52	2930	26	0.74	3500
52	1.23	4500	27	0.32	2280
53	1.62	5185	12	0.33	2330
54	1.63	5200	13	0.41	2590
55	Safety Rod		14	0.56	3040
56	1.24	4520	15	0.55	3020
57	0.49	2850	16	0.36	2430
41	0.63	3240			
42	Shim Rod				
43	1.77	5420			
44	Center Control Rod				
45	1.81	5470			
46	Shim Rod				
47	0.54	2970			

P across Core = 5.09"H_2O

Static Pressure Upper Plenum = 3.98"H_2O

TABLE X (Cont'd)

Control Rod Position	Total Pressure ("H_2O)	H "H_2O	*Flow Velocity (ft/min)
64	5.91	1.93	2760
55	5.28	1.30	2200
42	5.88	1.90	2710
44	5.90	1.92	2760
46	5.92	1.94	2770
33	5.15	1.17	2050
24	5.90	1.92	2770

* Reference calibration curves for control rods Fig. A6

NOTES:

1. Pressure drop measurements taken at exit of fuel elements, area of which = 0.0218 ft^2.

Total volumetric flow through fuel elements and control rods = 3670 ft^3/min

TABLE XI

A. CHECK OF FLOW THROUGH VARIOUS FUEL ELEMENTS WITH WITH SAFETY CONTROL RODS 33 AND 55 LOWERED 1-1/2"

Core Position	H (inches H_2O)	Flow Velocity (ft/min)	Original Flow Velocity (ft/min)
22	0.74	3490	3430
23	1.24	4500	4480
32	1.26	4510	4520
43	1.74	5340	5370
45	1.78	5340	5330
54	1.60	5110	5350
56	1.26	4500	4500
65	1.29	4590	4630
66	0.72	3410	3560
16	0.36	2410	2320

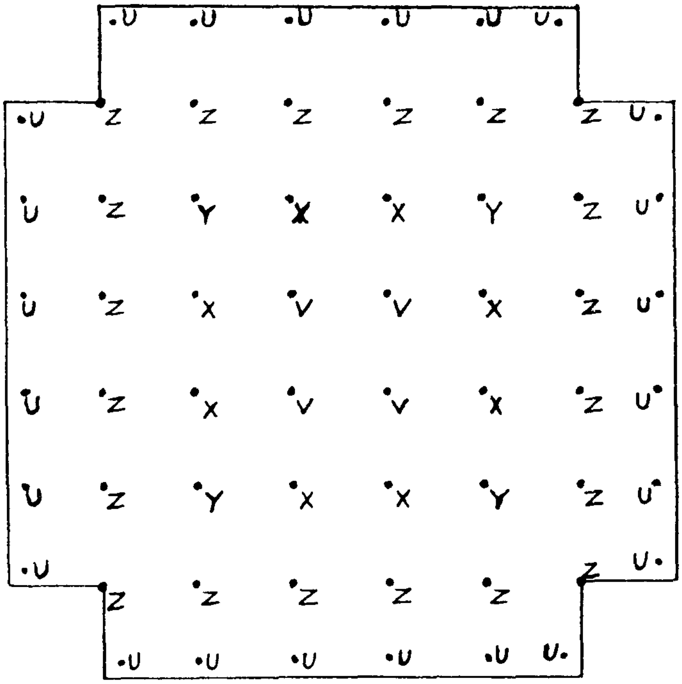
B. FLOW THROUGH LOWERED (1-1/2") SAFETY RODS

Control Rod Position	Total Pressure ("H_2O)	P ("H_2O)	Flow Velocity (ft/min)	Original Flow Velocity (ft/min)
33	6.00	1.71	2580	2050
55	6.07	1.74	2600	2200

The final schedule of orifice diameters was determined by weighting the experimental data obtained with each of the orifice plates, greater significance being given to the results of the last orificing schedule.

Lattice

Initially, the various lattice orifice diameters based on an early estimate of requirements were 1/4", 1/2", 3/4", 1", and 1-1/4" respectively, with the larger diameters nearer the core center as shown in Figure 7. Flow tests with thermistors indicated a flow velocity ranging from 53 ft/sec to greater than 60 ft/sec based upon the center thermistor readings. Since these velocities were far greater than required as shown in Table XII, the lattice orifice diameters were then reduced to 1/8", 1/4", 3/8", 1/2" and 1/2" respectively. It was at this point that the flow rig core was physically rotated 90° as explained previously. Also, the two safety rods were lowered 1-1/2" to increase their flow rates. A probe of similar lattice positions was then repeated. The results of the tests are shown in Table XII. It may be noted that the measured flow rates as compared to the required values indicate further orificing was needed. However, reference to the curve of thermistor behavior (Fig. A9), shows that a slight variation in potential would show a relatively greater change in velocity. This behavior in conjunction with erratic calibration data obtained for the thermistors led to a conservative approach to the problem of lattice orificing. The lattice orifice diameters were therefore increased to a value which would allow a lattice flow of approximately 1.75 times the average core velocity. The final dimensions of the lattice orifice diameter are contained in Table XIII.



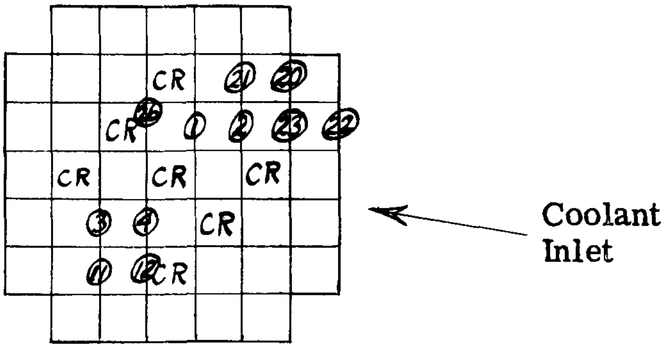
ORIFICE SYMBOL	INITIAL DIAMETER
U	1/4"
V	1-1/4"
X	1"
Y	3/4"
Z	1/2"

FIGURE 7 - Lattice Orifice Locations, Dimensions, and Identification

TABLE XII

(1)LATTICE FLOW MEASUREMENTS AS COMPARED TO REQUIRED FLOW VELOCITIES

Lattice Position Designation	Required Lattice Velocity (ft/sec)	Lattice Velocity(2) with initial orifice diameters (ft/sec)	Lattice Velocities(3) with reduction in orifice diameters (ft/sec)	(4) Lattice Velocity w/red. in orif. dia. and safety rods lowered 1-1/2" (ft/sec)
1	41.5	>60 (~90)	41.5	51.1
2	39.0	58.5	25.0	30.0
3	39.0	>60 (75-90)	46.3	43.7
4	41.5	>60 (75-90)	46.2	38
11	32	>60	28.3	
12	36.9	>60	54.4	
20	24			20.4
21	32			27.3
22	18.2			23.9
23	30.5			28.2
26	41.5			45.2



NOTES:
(1) Lattice flow measurements based on center thermistor data
(2) Initial position of core
(3) Core rotated 90° to correct position
(4) Core rotated 90° to correct position

TABLE XIII

SCHEDULES OF LATTICE ORIFICE DIAMETERS

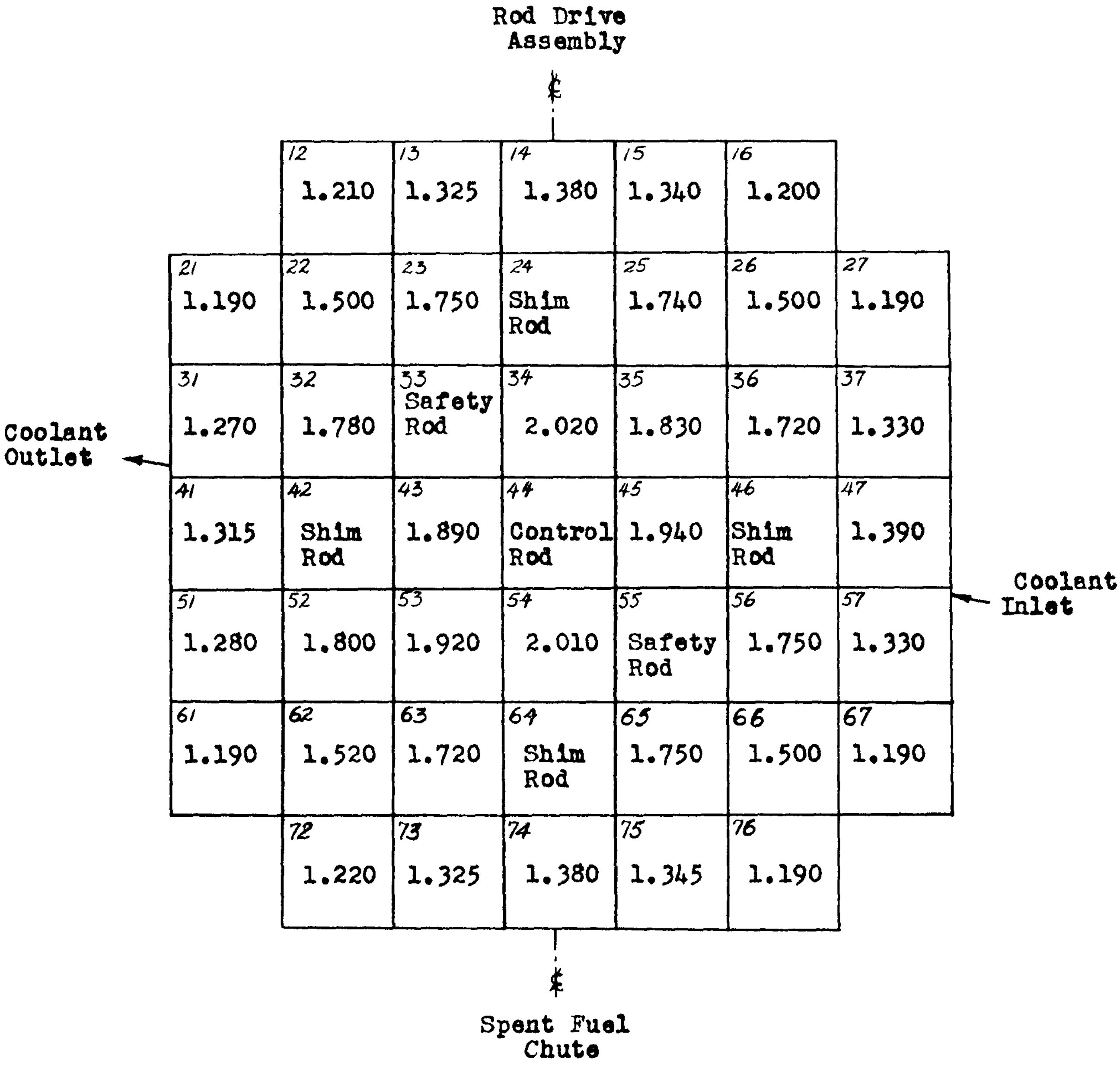
Letter Designation	Initial Diameter (inches)	Intermediate Diameter (inches)	Final Diameter (inches)
U	1/4"	1/8"	3/16"
V	1-1/4"	1/2"	7/8"
X	1"	1/2"	3/4"
Y	3/4"	3/8"	9/16"
Z	1/2"	1/4"	3/8"

RESULTS

Experimental data obtained from the simulating air flow rig indicated that though the fluid entering the fuel elements and control rods from the plenum chamber follows a rather random behavior, there is however, a fairly consistent distributional pattern. Thus, fuel elements located equidistant from the core center may require different orifice diameters to meet a given flow requirement. This, in fact is apparant from the final orifice diameter schedule which was recommended as shown in Figure 8.

Control of flow into the control rods was accomplished by restricting the flow into the fuel elements, thus allowing more fluid to enter the rods. Orificing or other direct forms of flow regulation were not used on the control rods since their geometry was not conductive to installation of control means, and also because of the satisfactory results obtained without resort to flow control devices.

The effect of the orifice schedule on the coolant flow distribution in the core is shown in Figure 9. These curves are based on the average of V/Vavg values determined from experimental data for families of fuel elements and control rods located at specific core radii. It should be noted that the final recommended orifice schedule is an attempt to further refine the nearly satisfactory flow distribution obtained with the 3rd orifice plate.

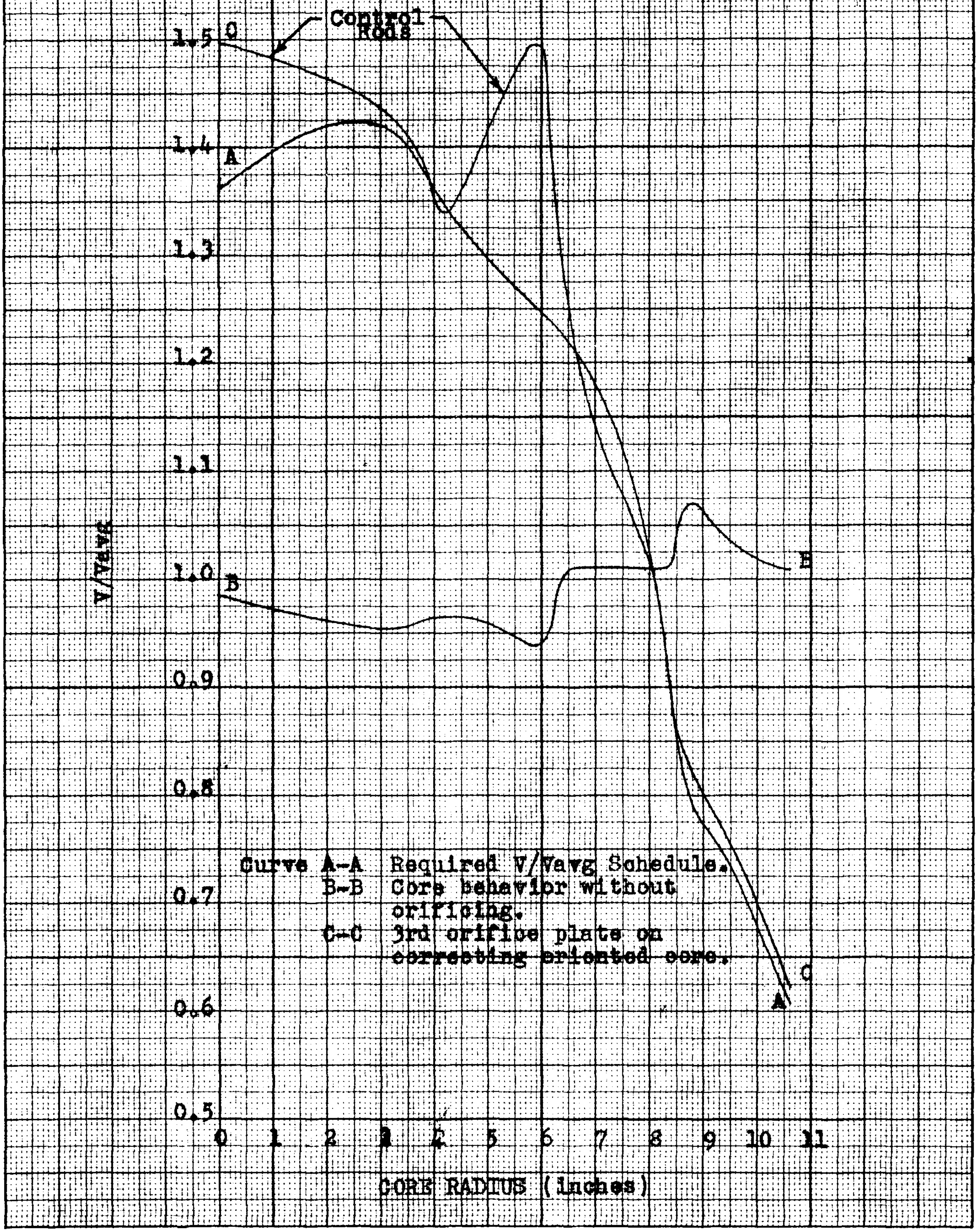


	12 1.210	13 1.325	14 1.380	15 1.340	16 1.200	
21 1.190	22 1.500	23 1.750	24 Shim Rod	25 1.740	26 1.500	27 1.190
31 1.270	32 1.780	33 Safety Rod	34 2.020	35 1.830	36 1.720	37 1.330
41 1.315	42 Shim Rod	43 1.890	44 Control Rod	45 1.940	46 Shim Rod	47 1.390
51 1.280	52 1.800	53 1.920	54 2.010	55 Safety Rod	56 1.750	57 1.330
61 1.190	62 1.520	63 1.720	64 Shim Rod	65 1.750	66 1.500	67 1.190
	72 1.220	73 1.325	74 1.380	75 1.345	76 1.190	

(All dimensions in inches)

FIGURE 8 - Recommended Orifice Diameters for APPR-1 Orifice Plate.

FIGURE 9 - EFFECT OF TAILORING IN THE APPR-1 FLOW RIG MODEL



Anticipated Maximum Fuel Plate Surface Temperature in Real Reactor Based on Final Orifice Plate Schedule and Actual Overall Flow Rate

The actual flow through the reactor in the completed plant has been established at 3810 GPM using the No. 1 pump (in the short leg of the primary loop), and 3960 GPM using the No. 2 pump. The lower, and therefore the more critical of these figures gives 0.965 as the ratio of actual to planned flow rate to be applied to all velocities predicted for the individual channels. The schedule of hole diameters adopted for the final orifice plate actually used in the reactor, which is given in Figure 8, is expected to yield maximum possible fuel plate surface temperatures as listed below, based on:

a. The flow results obtained on the final rig test.

b. The slight modifications to the schedule of orifice diameters tested which were made in preparing the recommendations for the reactor.

c. The correlation between hole size and flow rate developed by this testing.

d. The correlation between flow rate and temperature established analytically in APAE Memo No. 91.

e. Average coolant flow rate through the lattice equal to 1.75 times its pro-rata share because of the poor control over the distribution of this flow. This results in passing only 77.7% of the total flow through the fully confined or internal channels, which represent 85.5% of the total flow area, resulting in an average velocity for these passages amounting to 90.6% of the average for the whole core. Together with the previous 0. 965 factor this yields a ratio of actual internal flow to ideal flow of 0. 875.

f. Ratio of mean peak flux to peak centerline flux for the various element positions as shown in the following tabulation. This factor takes into account the difference in peak flux levels between the centerline of a particular element and its fuel plate nearest the center of the core.

Element Number	Ratio
14	1. 20
15	1. 24
16	1. 41
25	1. 06
26	1. 14
34	1. 05
35	1. 06
44	1. 00

The anticipated maximum fuel plate surface temperatures are as follows:

Fuel Element Number	Ts (max.) (^{O}F)
43	520
34	520
45	520
54	523
53	521
35	523
52	524

Fuel Element Number	Ts (max.) (^{o}F)
32	523
23	524
25	522
36	525
56	524
65	522
63	523
62	531
22	530
26	530
66	531
74	535
41	528
14	535
47	537
73	540
51	540
31	541
13	541
15	539
37	538
57	540
75	539
72	551
61	551
21	551

Fuel Element Number	Ts(Max.) (°F)
12	555
16	552
27	556
67	552
76	555

Control Rod Numbers	Temperature at end of fuel plate (°F)	Temperature at normal flux crest (°F)
44	554	509
55	---	519
33	---	520
64, 42, 24, 46	554	509

APPENDIX

Fuel Elements

As described previously, one fuel element was constructed as an exact duplicate of its real counterpart. The other thirty-seven fuel elements consisted only of the outer shell. Thus, it was necessary to orifice each of these thirty-seven fuel elements internally in order to provide the same pressure drop behavior as the complete fuel element. The first step was to determine experimentally the pressure drop characteristics of the simulating fuel elements. Upon completion of this phase of the work,orifices were then made for each of the dummy fuel elements.

The test set up employed for these tests is shown in Figure A1. A 3-1/2 I. D. adapter precedes the fuel element to approximate the conditions of the coolant in the lower plenum when entering the inlet box of a fuel element.

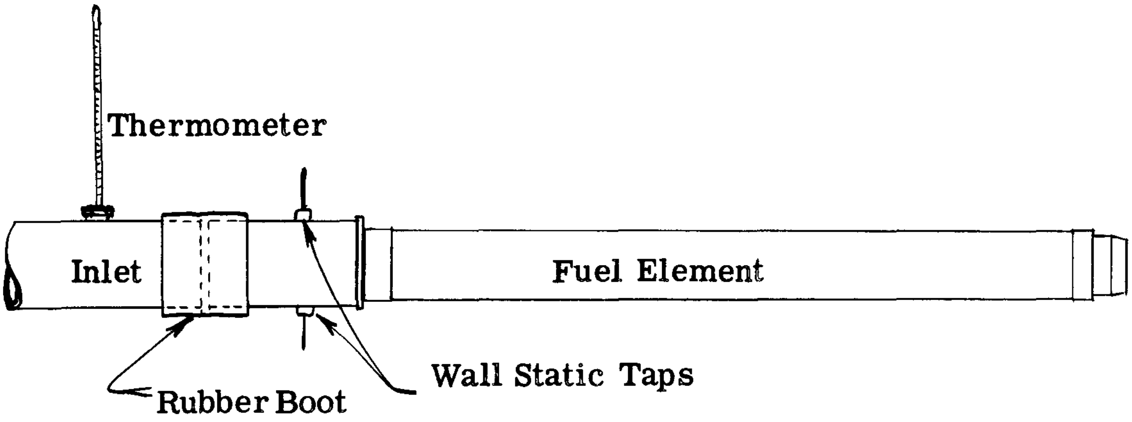


Fig. A1 Set-Up For Fuel Element Tests

The overall pressure drop of the fuel element including entrance effects is obtained by adding the average of the static pressure measurements in the adapter to the average velocity head, as measured by a pitot static probe upstream of the adapter, corrected to the cross-sectional area in the plane of the wall taps. The results are shown in Table A1.

TABLE A1 FLOW-PRESSURE DROP BEHAVIOR OF THE SIMULATING FUEL ELEMENT

Flow Rate (ft^3/sec)	P Static inches H_2O	Average Velocity Head (inches H_2O)	Total P (inches H_2O)
1.98	3.52	0.17	3.69
2.21	4.30	0.22	4.52
2.42	5.17	0.26	5.43
2.60	6.06	0.30	6.36

A similar procedure was employed for determing the pressure drop across a dummy fuel element.

Several orifices were subsequently made and tested in a dummy fuel element. By interpolating the experimental results a satisfactory orifice diameter was found to be 2.062 inches. The pressure drop characteristics for the dummy fuel elements with a 2.062 inch diameter internal orifice are shown in Table AII.

TABLE AII FLOW-PRESSURE DROP BEHAVIOR OF AN INTERNALLY ORIFICED FUEL ELEMENT

Flow Rate (ft^3/sec)	P Static (inches H_2O)	Average Velocity Head (inches H_2O)	Total P (inches H_2O)
1.98	3.52	0.17	3.69
2.21	4.37	0.22	4.59
2.42	5.30	0.26	5.56
2.60	6.25	0.30	6.55

Since the orifice plate thickness is only 3/32 of an inch, it was fastened to a wooden block having a much larger hole diameter, to provide a means of installation in the dummy fuel elements.

Figure A2 gives the pertinent dimensions of the orifice plates and wood backing and also their location within the dummy fuel element.

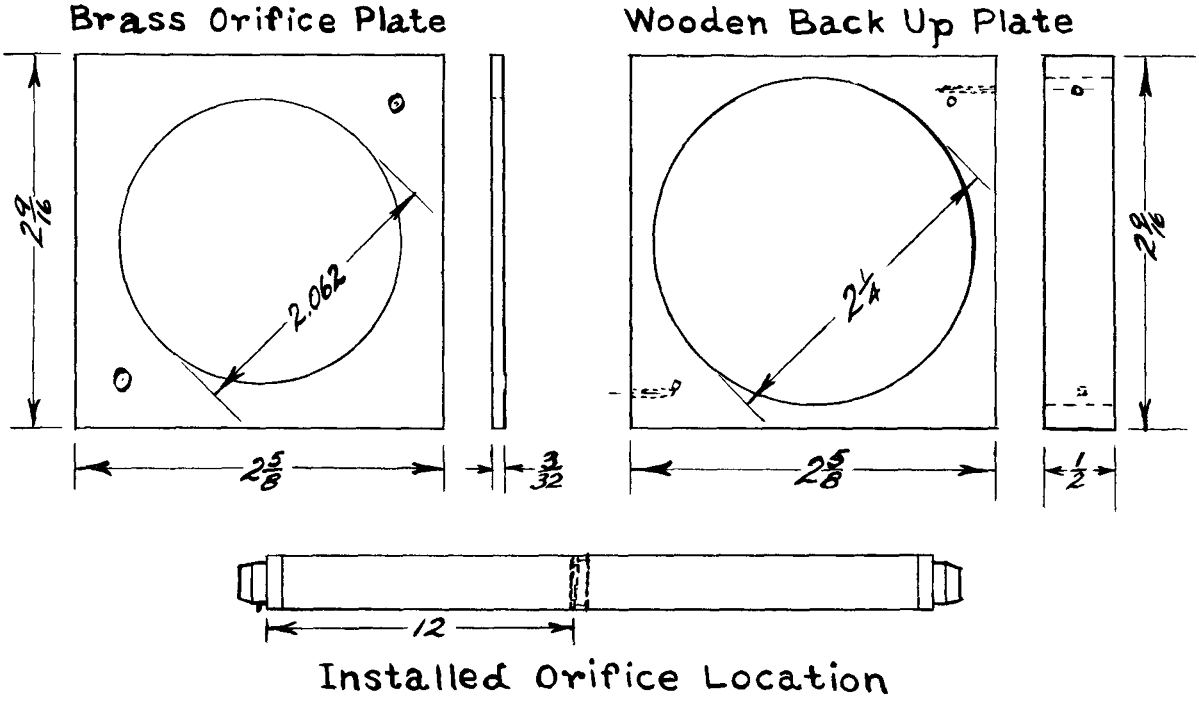


FIGURE A2 Fuel Element Orifice and Back Up Plate

Figures A3 and A4 contain respectively the calibration data for a dummy fuel element with and without internal orificing and for the simulating fuel element. Additional tests were made on approximately 50% of the orificed dummy fuel elements to determine whether their performance was sufficiently uniform. The data were satisfactorily uniform, substantiating results previously obtained with the initial orificed dummy fuel element.

Control Rod

The test set-up employed for calibrating the instrumented control rod is shown in Figure A5. This set-up was also used for determining the internal orifice diameter for each of the remaining dummy control rods. The entrance condition to the control rod in the APPR-1 is essentially a plenum chamber. A 55 gallon drum was utilized to simulate this with the rod entrance inserted into the drum.

A pitot static tube in the inlet pipe was used to measure the flow rate entering the system. Pressure drop across the control rod was obtained from the average of two wall static probes on the drum measured against the atmospheric pressure.

Of the seven control rods in the air flow rig only one rod exactly simulates its real counterpart except for materials of construction. The six other rods contain neither the fuel section nor the absorber section. Since the control rod construction does not lend itself to measuring coolant flow as in the fuel elements, a total pressure tube was installed

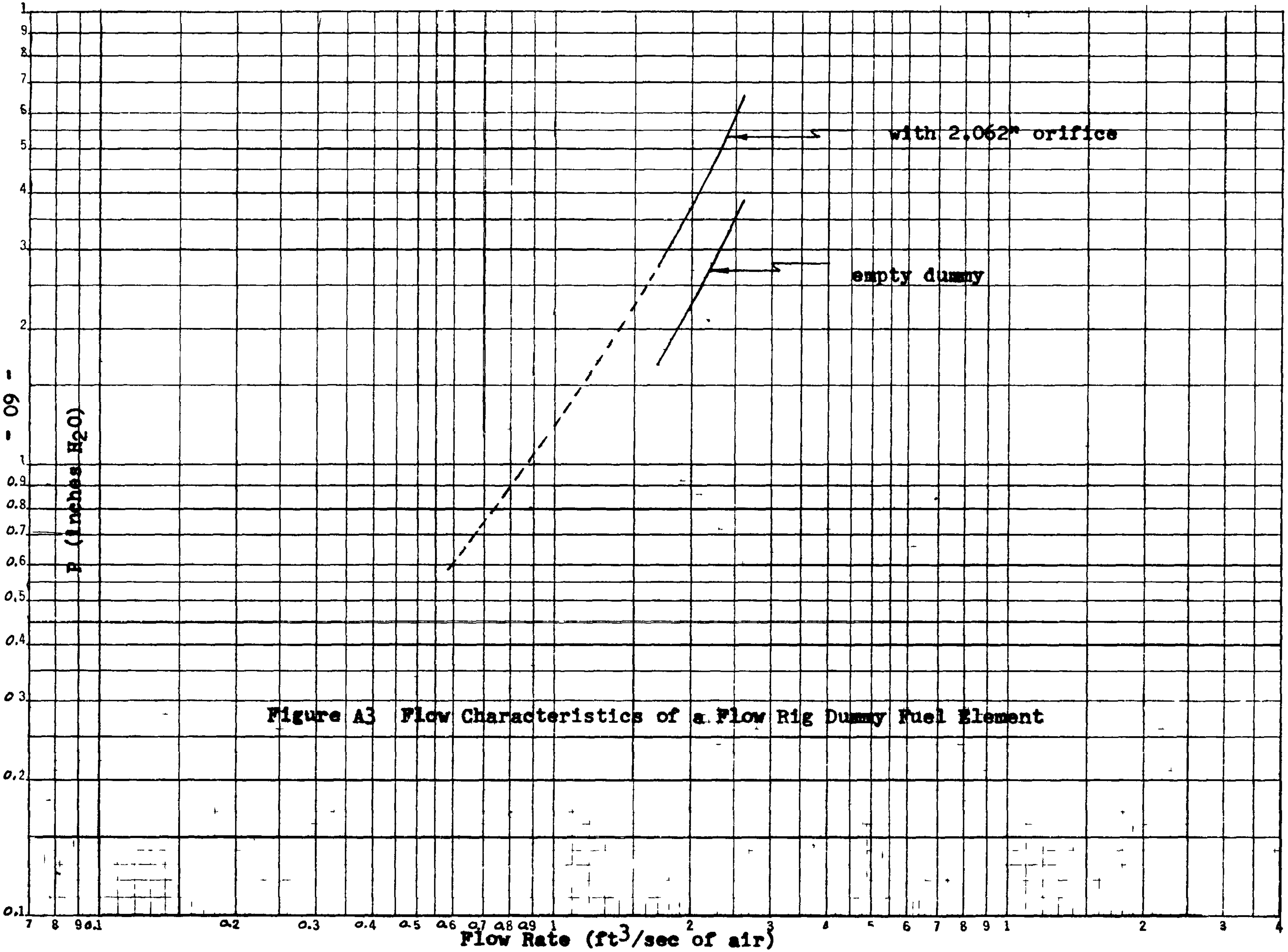


Figure A3 Flow Characteristics of a Flow Rig Dummy Fuel Element

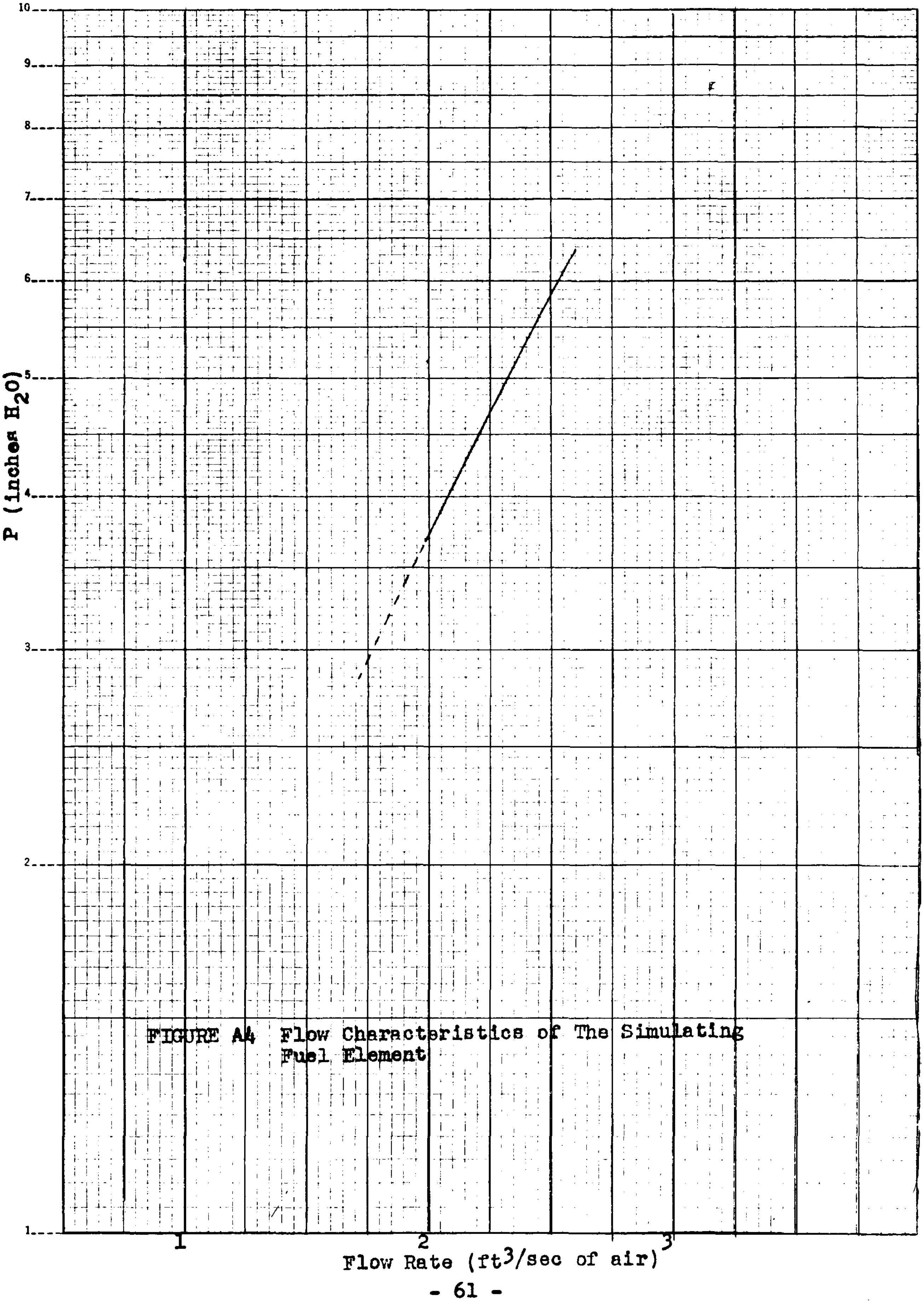


FIGURE A4 Flow Characteristics of The Simulating Fuel Element

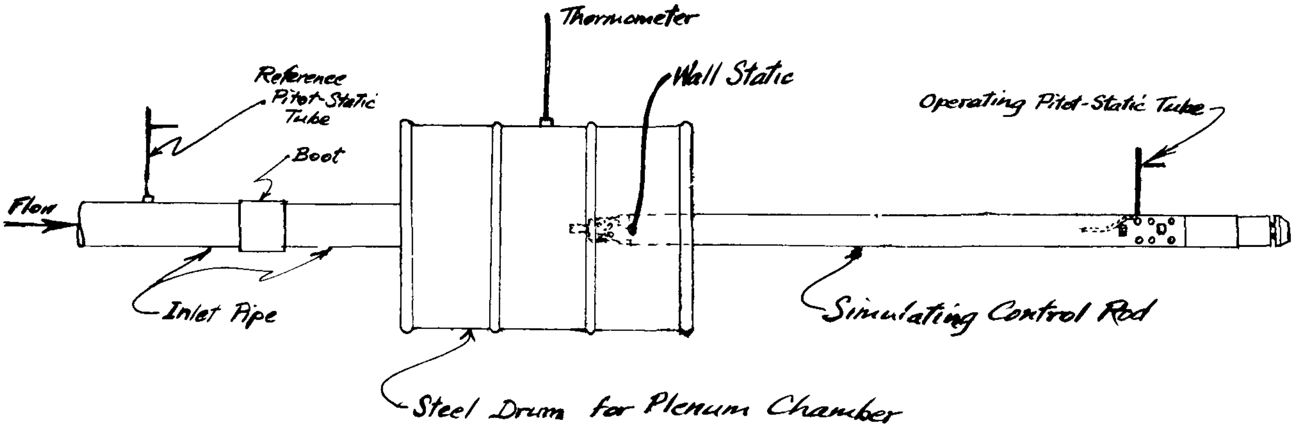


Figure A5 Set-Up For Control Rod Tests

in the simulating control rod. The instrumented control rod was then calibrated for pressure drop at various flow rates. The results of the calibration are shown in Fig. A6.

Following the calibration of the instrumented control rod, work was initiated to orifice internally each of the six dummy control rods.

The orifices are designed to yield the same pressure drop characteristics as the real control rod. Final orifice diameters are based on the criterion that the end-to-end static pressure drop would be 6.80 inches of water at a flow rate of 2.00 cubic feet per second. The results of testing each of the dummy control rods with the final orifice plate installed is tabulated in Table AIII.

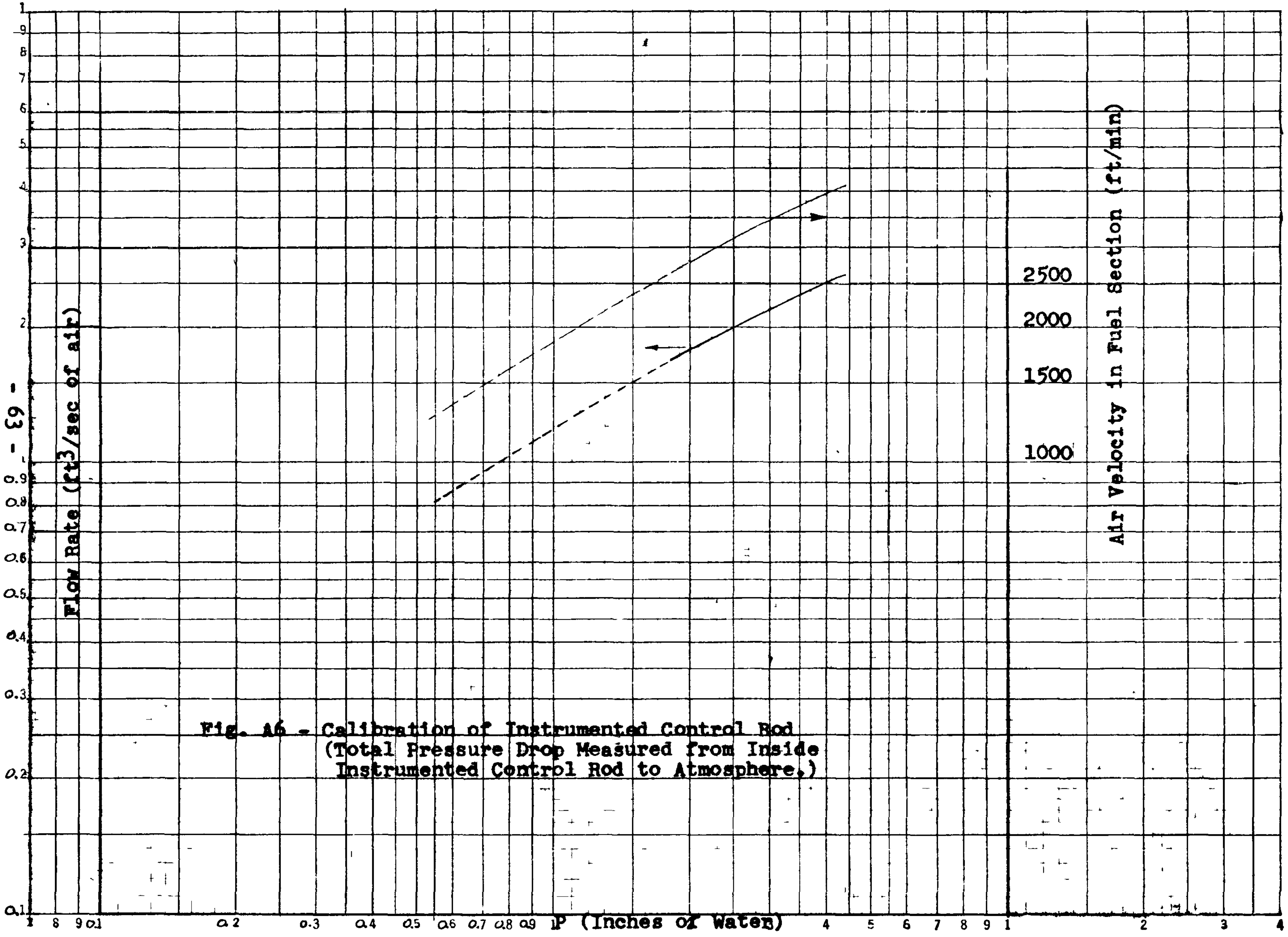


Fig. A6 - Calibration of Instrumented Control Rod (Total Pressure Drop Measured from Inside Instrumented Control Rod to Atmosphere.)

TABLE AIII - FLOW BEHAVIOR OF THE INTERNALLY ORIFICED CONTROL RODS

Rod Mo.	Flow (cfs)	P ("H_2O)
1	2.00	6.77
2	2.00	6.76
3	2.00	6.60
4	2.00	6.66
5	2.00	6.97
6	2.00	7.05

Thermistors

The thermistors employed for air flow measurements consisted of glass coated semi-conducting beads with fine platinum alloy leads. The thermistors are soldered to wire posts attached to plastic simulating fuel plates as shown in Figure A7. The plastic fuel plates have three pairs of inlaid copper strips which act as leads from the thermistors for connecting to leads which originate from a specially constructed wheatstore bridge. The plastic fuel plate with three thermistors attached to it was then fitted into a three sided trough which together formed a single flow passage identical in width and height to a single flow passage of a fuel element. This assembly was then attached to a 1-1/2" I. D. pipe. The pipe contained a sharp edged orifice plate, laboratory thermometer, a pressure control valve, and a flow regulating valve. The air passing through the pipe could be heated as desired by resistance coils which were connected to a rheostat. A schematic diagram of the set-up employed for the calibration tests is shown in Figure A8.

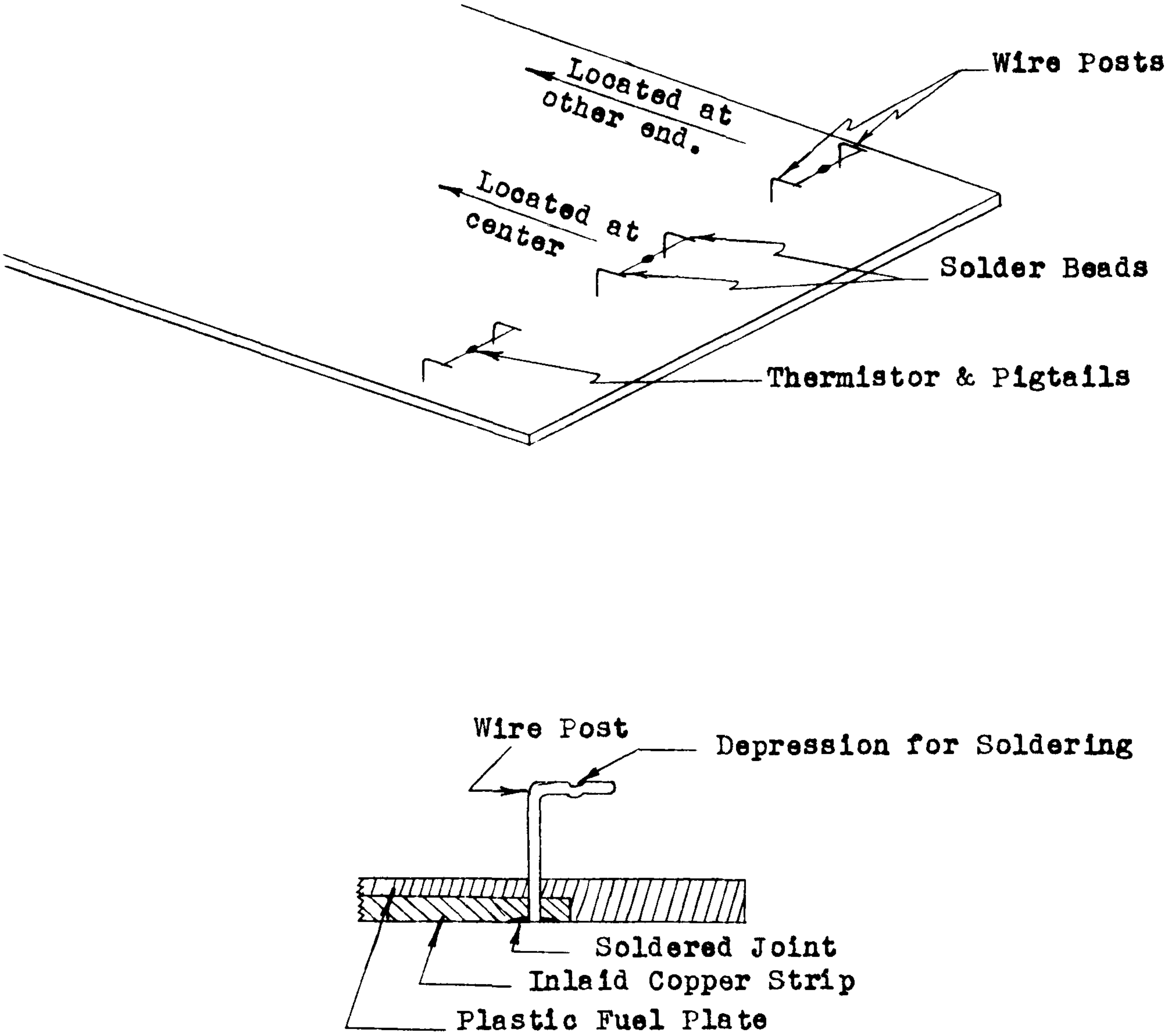


FIGURE A7 - Installation of Thermistors on Plastic Simulating Fuel Plate.

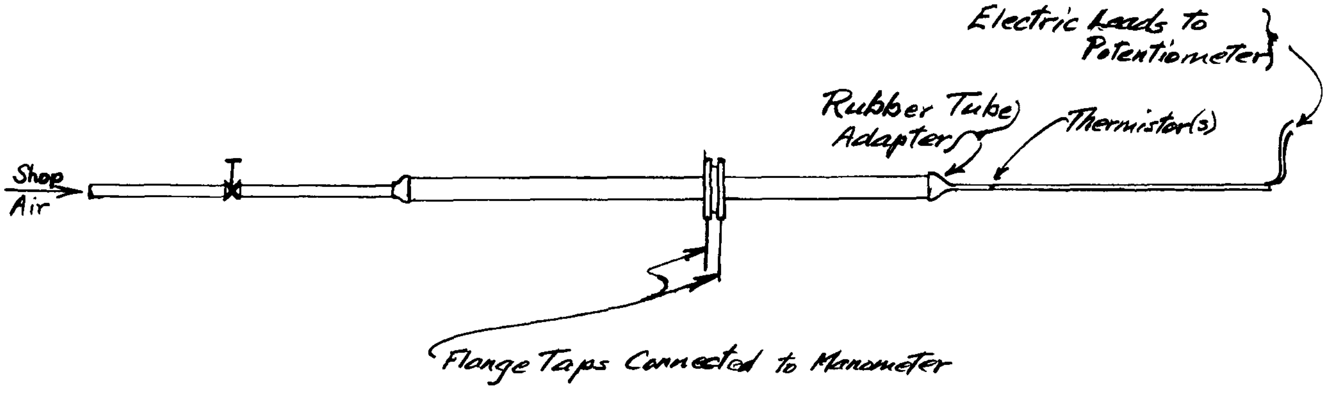


Figure A8 - Set-up for Thermistor Calibration Tests

The behavior of a typical thermistor as a function of flow rate and temperature is shown in Figure A9. The circuit employed for thermistor air velocity measurements is shown in Figure A10.

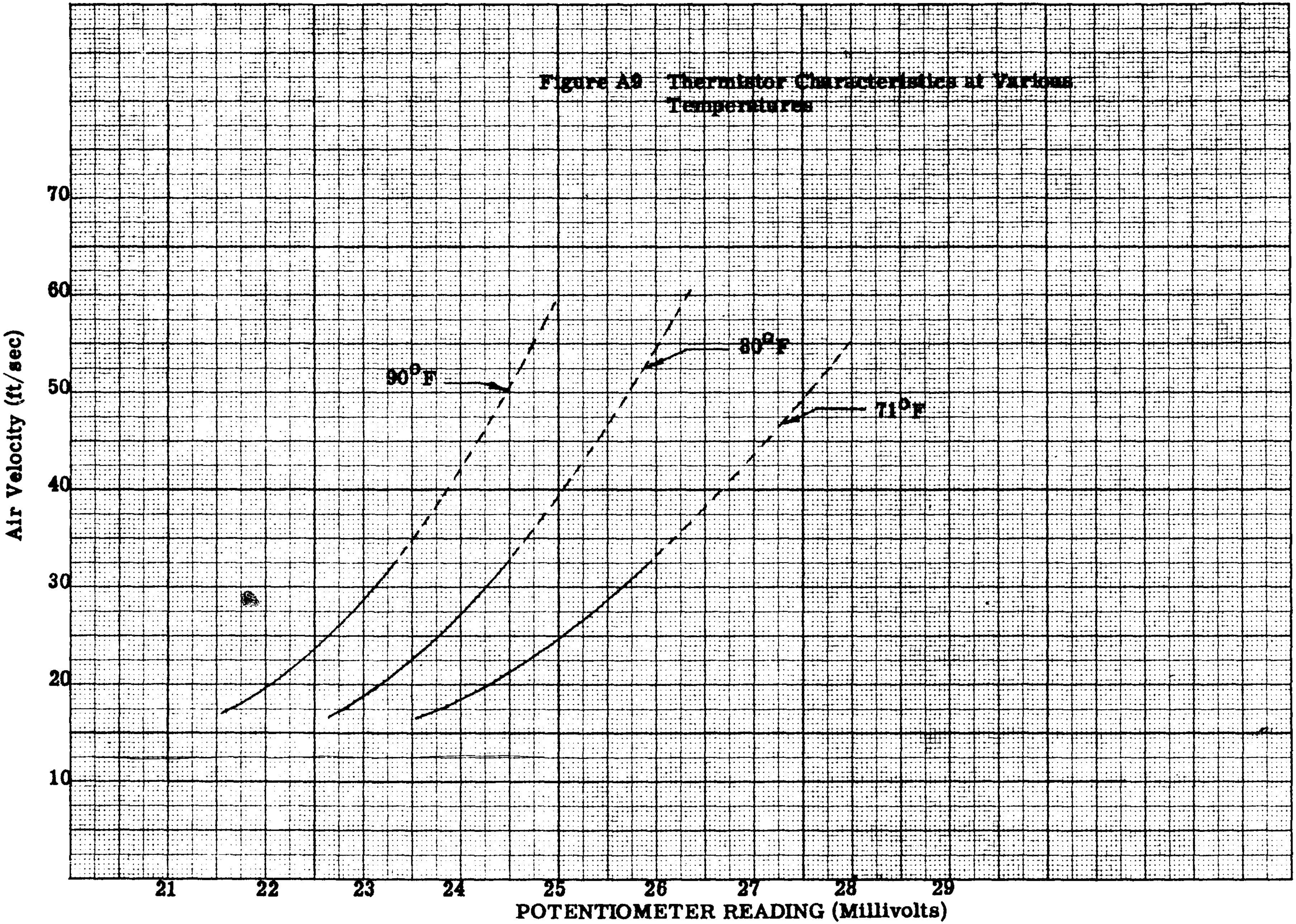
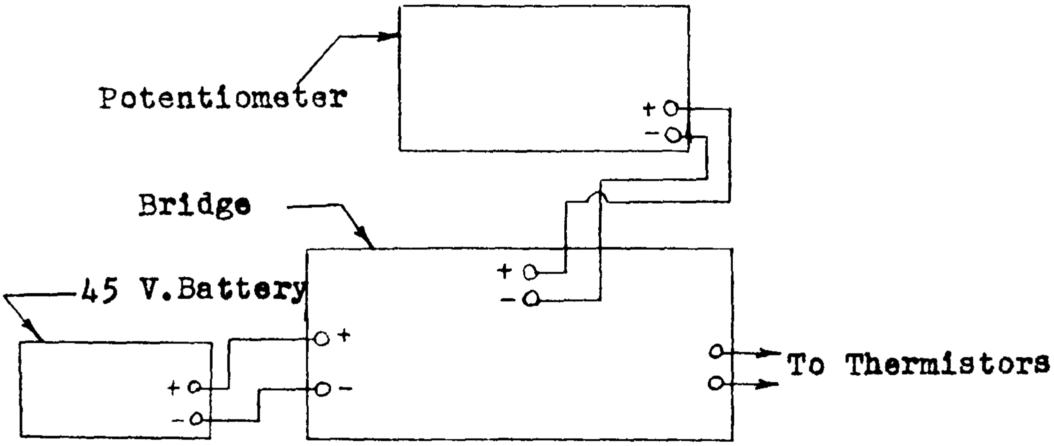
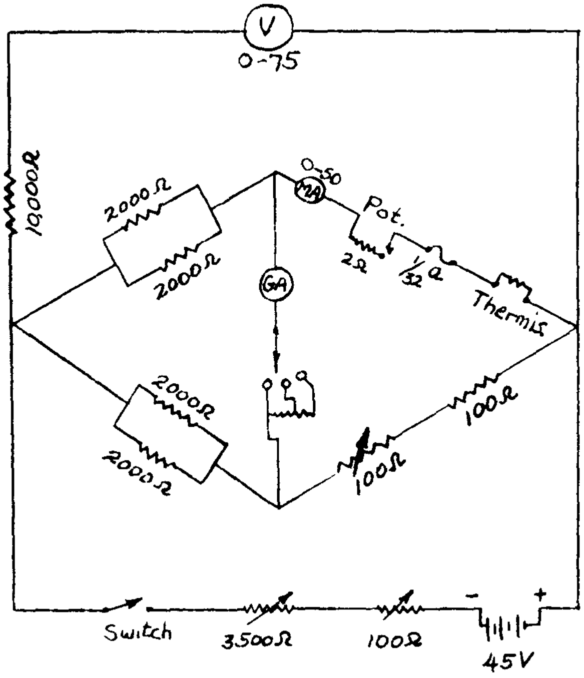


Figure A9 Thermistor Characteristics at Various Temperatures



Wiring Diagram for Thermistor Air Velocity Measurements



Special Bridge Circuit

FIGURE A10 - Electrical Circuits Employed for Thermistor Calibration