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PRESSURE DROP TESTS ON TWISTED RIBBON CORE ASSEMBLIES

by

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3

TABLE OF CONTENTS

4

LIST OF TABLES

5

LIST OF FIGURES

6

PRESSURE DROP TESTS ON TWISTED RIBBON CORE ASSEMBLIES

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ABSTRACT

Twisted ribbon fuel elements are a completely new concept for reactor core construction. Advantages of this construction are outlined briefly, together with a list of ribbon sizes and core designs now under consideration. A test program was conducted to determine pressure drop through core assemblies of various geometries. Cold water and water-air mixtures were used to simulate two-phase flow conditions. The results are presented in tabular and graphical form. Attempts were made to correlate experimentally determined pressure drops with theoretical data. The pressure drop through twisted ribbon cores appears to be much less than originally anticipated and the empirical data presented permits reasonably accurate calculations of any proposed design.

I. INTRODUCTION

Twisted flat wire fuel elements appear to have several good features for reactor core construction. They can be built into a core assembly which is structurally self-supporting, except for thin shells to contain the wires and thin-walled tubes to separate them from the control rods. The water passages can be accurately controlled dimensionally, and warping or swelling of the wires cannot change appreciably the size of the passages. Good mixing of the bulk flow of the coolant minimizes local hot zones, and uniform local mixing may break up laminar flow and permit some relaxation of hot channel factors. Point contact between adjacent wires is not considered critical from the standpoint of cooling. Almost any metal to water ratio can be obtained by proper selection of wire thickness and width. In particular, the larger ratios of metal to water can be obtained with a supporting structure that does not interfere with the water flow. By rolling to an elliptical shape, a tight mechanical bond can be assured.

The range of wire sizes being considered at present are 0.039 in. x 0.148 in; 0.250 in. x 0.700 in; and 7/16 in. x 15/16 in. The configurations include closely-packed cores with tubular passages for control rods; bundles of wires encased in thin-walled tubes arranged in a geometric lattice; and bundles of wires encased in closely-packed hexagonal tubes with central control rod spaces.

II. PURPOSE

7

A co-ordinated mechanical test program was conducted to determine the pressure drop through core assemblies composed of twisted wires with variation of flow rate, metal to water ratio, pitch, and change of water density (by introducing air).

III. TEST APPARATUS AND PROCEDURE

The test assembly consists of a cluster of twisted ribbons 48 in. long retained in a 3-in. (across flats) hexagonal channel formed by a Lucite tube, as shown in Figs. 1 to 5. The ribbons are twisted from commercially available, cold-rolled, round edge, flat steel wire and welded at one end to 5/8 in. wide steel plates which, in turn, are positioned in slots in the end of the Lucite tube (Fig. 6). A detailed description of the manufacture of twisted ribbons is given in Appendix C.

The specimens tested are listed in Table I.

Table I

DESCRIPTION OF TWISTED RIBBON
TEST SPECIMENS

Wire Size, in.	Pitch of Twist, in.
3/8 x 1/16	6; 12; 24
3/8 x 1/8	6; 24
3/8 x 3/16	6; 24
5/8 x 0.109	12; 24

Tests were made on the 6-in. pitch, to determine the extreme tight twist limit, and on the 24-in. pitch, the flattest pitch of any possible interest. The metal to water ratios varied from 1:4 to 1:1 (Figs. 7 and 8).

The assembly is inserted in a loop (Figs. 9 and 10) through which water can be circulated up to 200 gpm at room temperature. Valves are provided to control the rate of flow and the pressure in the test section. To enable studies of two-phase flow, air can be injected to lower the density to 0.1 with velocities of the water and air mixture up to 25 fps. Mercury manometers are provided to show pressure drop and flowmeters to show water and air flow. A pressure gauge at the center of the test section is used to

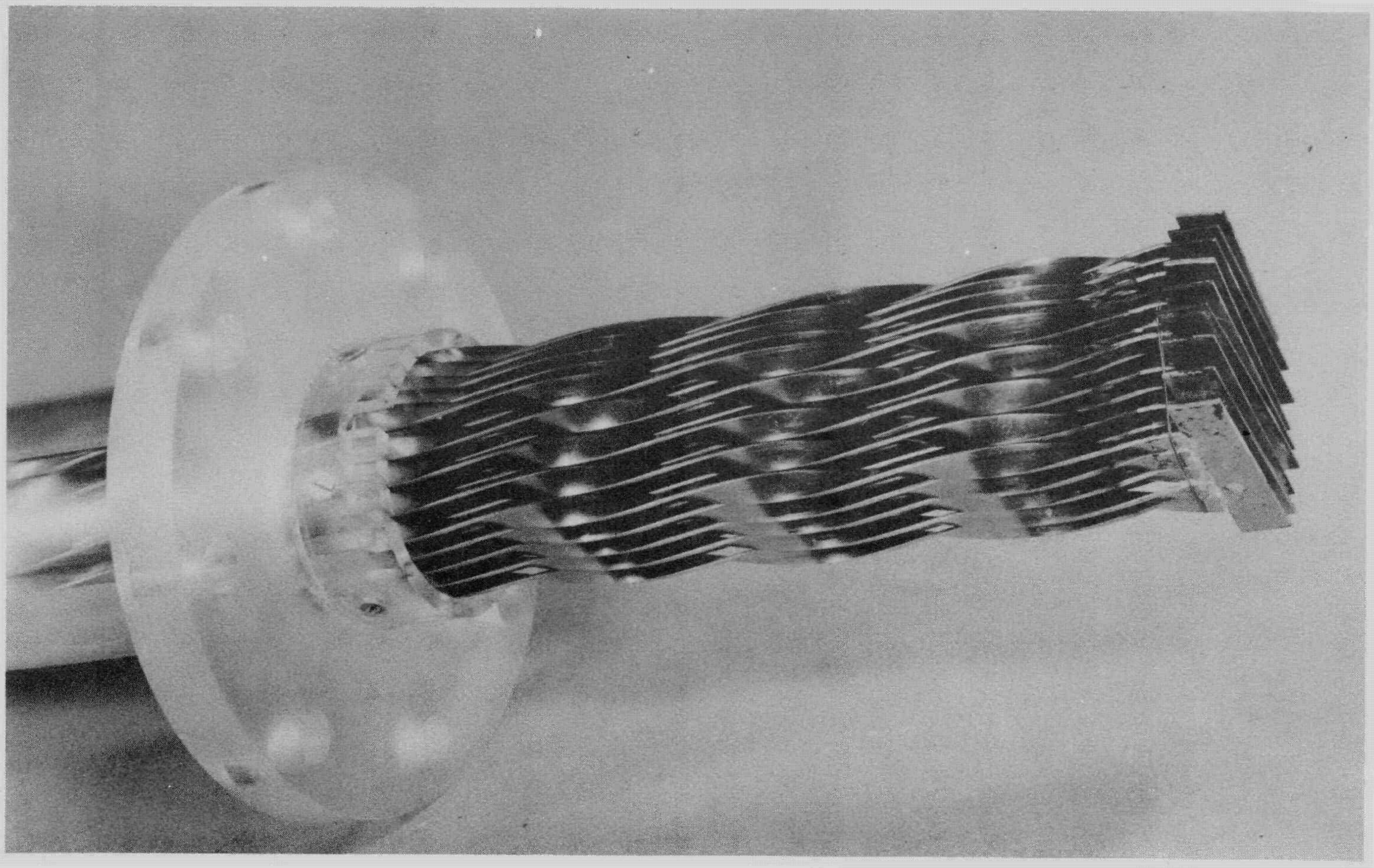

FIG. 1
TWISTED WIRE CORE ASSEMBLY

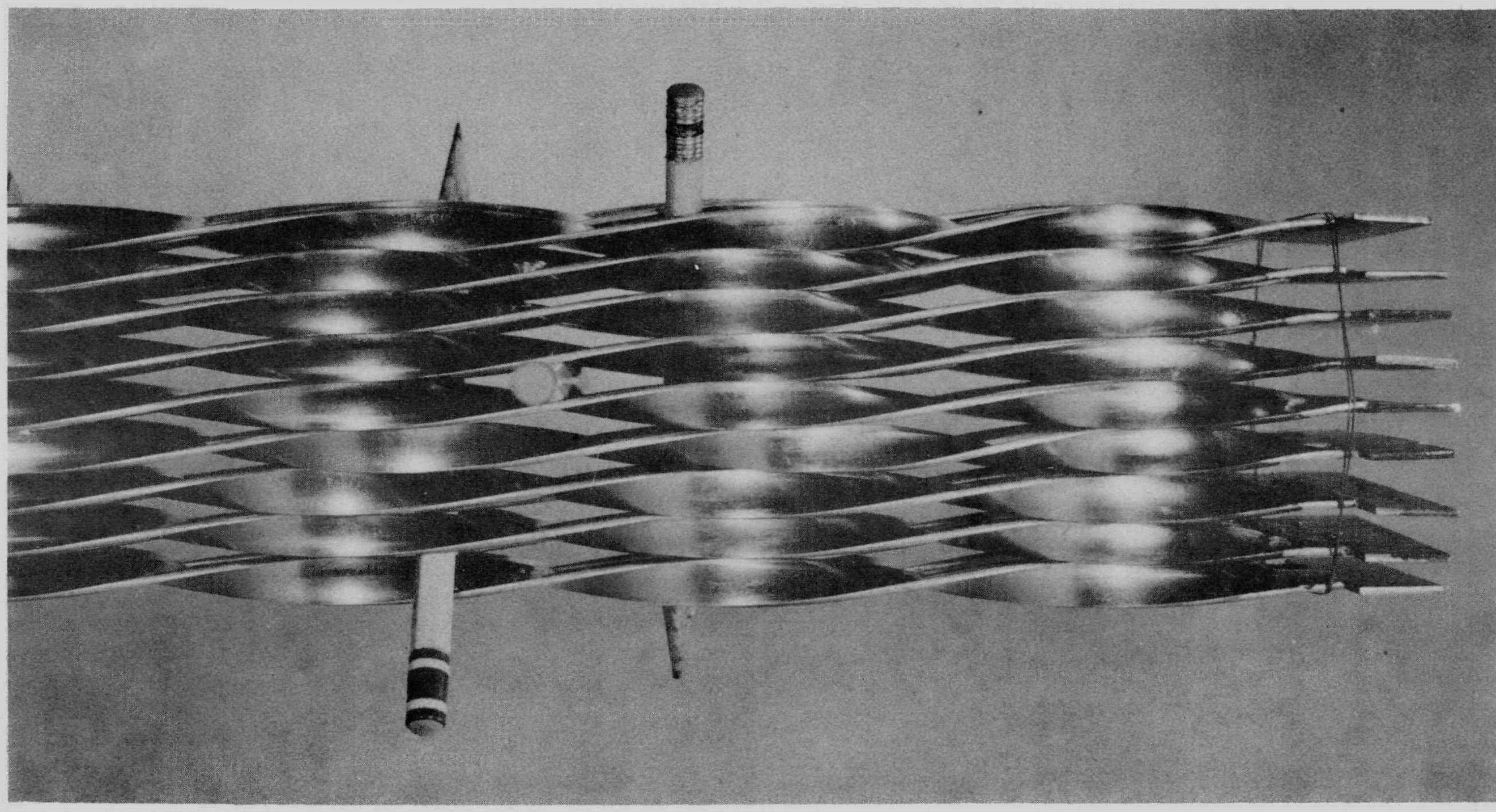

FIG. 2

TWISTED WIRE ASSEMBLY (6-INCH PITCH)
PENCILS INDICATE LINES OF SUPPORT

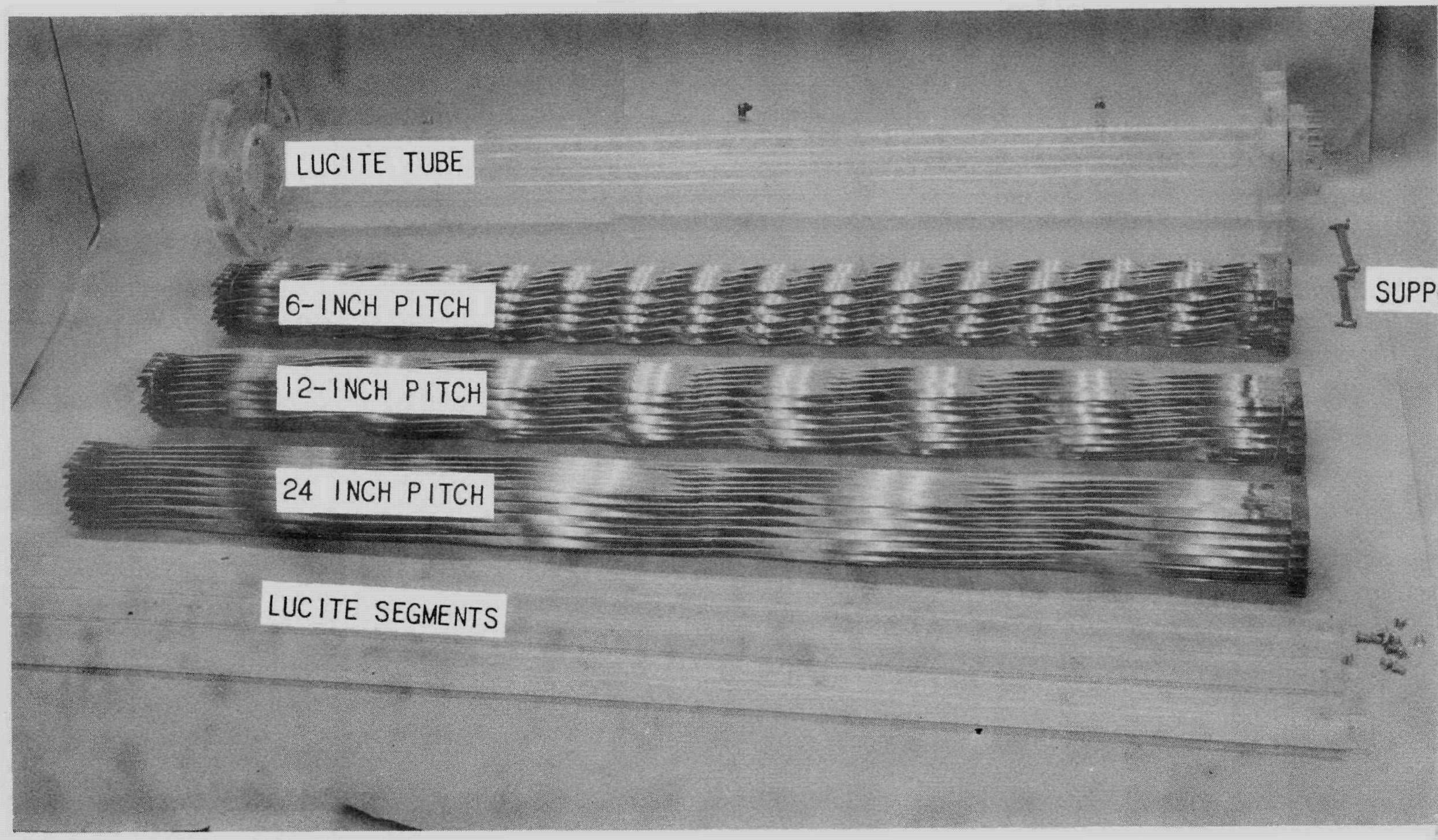

FIG. 3

DISASSEMBLED TEST SECTION AND 3/8 X 1/16 IN. WIRE SPECIMENS

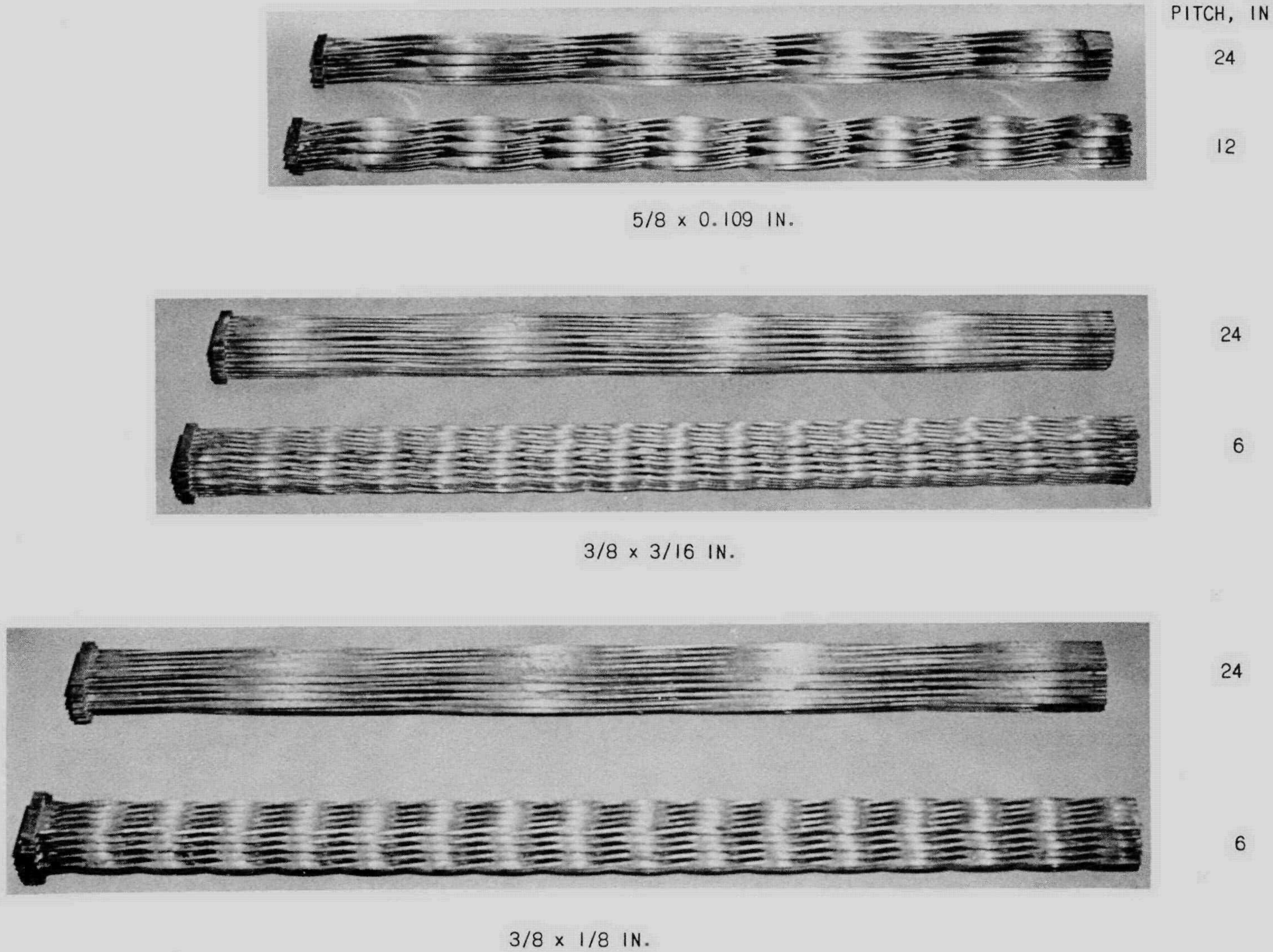

FIG. 4
TEST ASSEMBLIES

12

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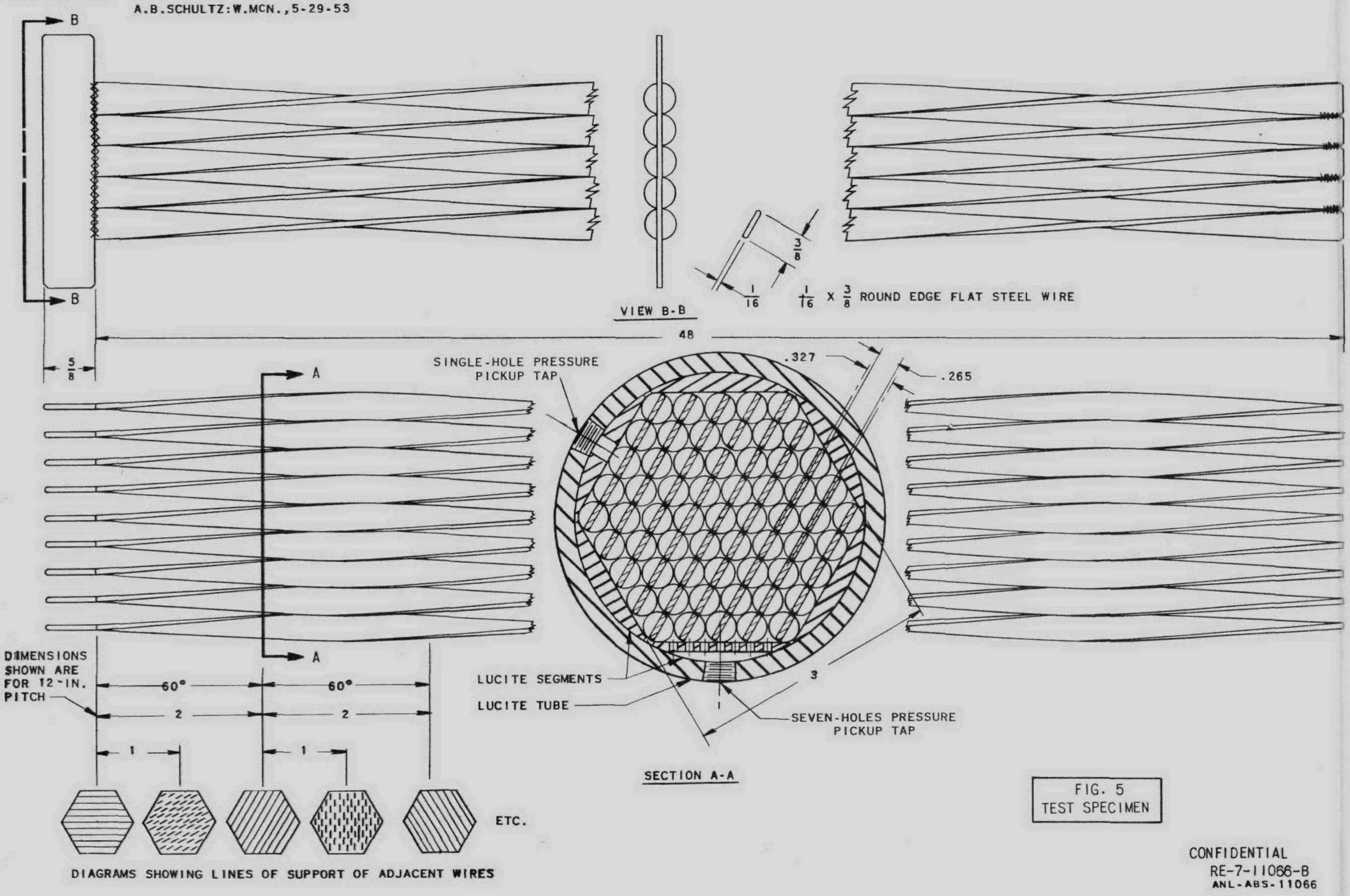

FIG. 5
TEST SPECIMEN

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ANL-ABS-11066

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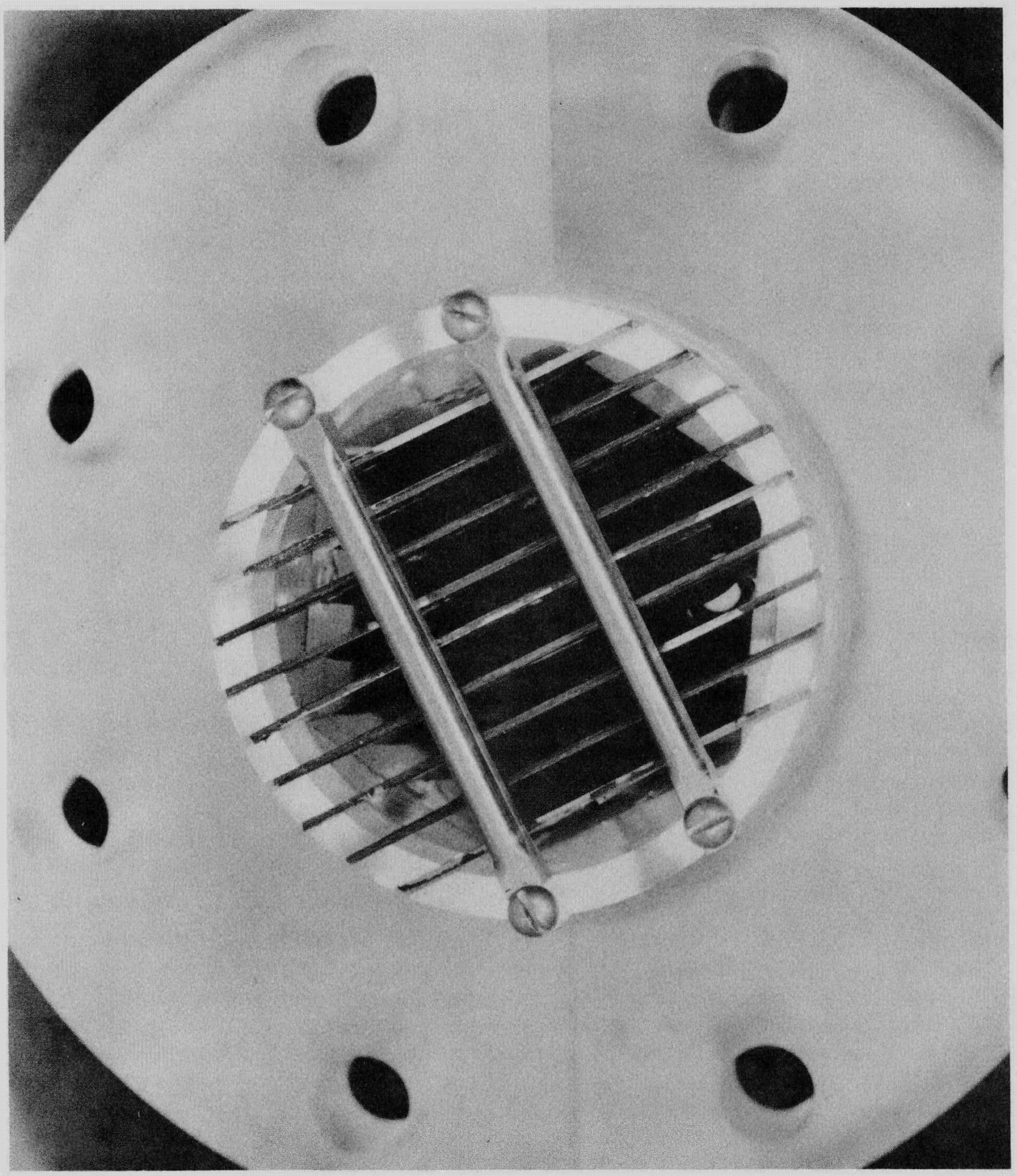

FIG. 6
END VIEW OF ASSEMBLED TEST SPECIMEN

14

RE-7-11516-A

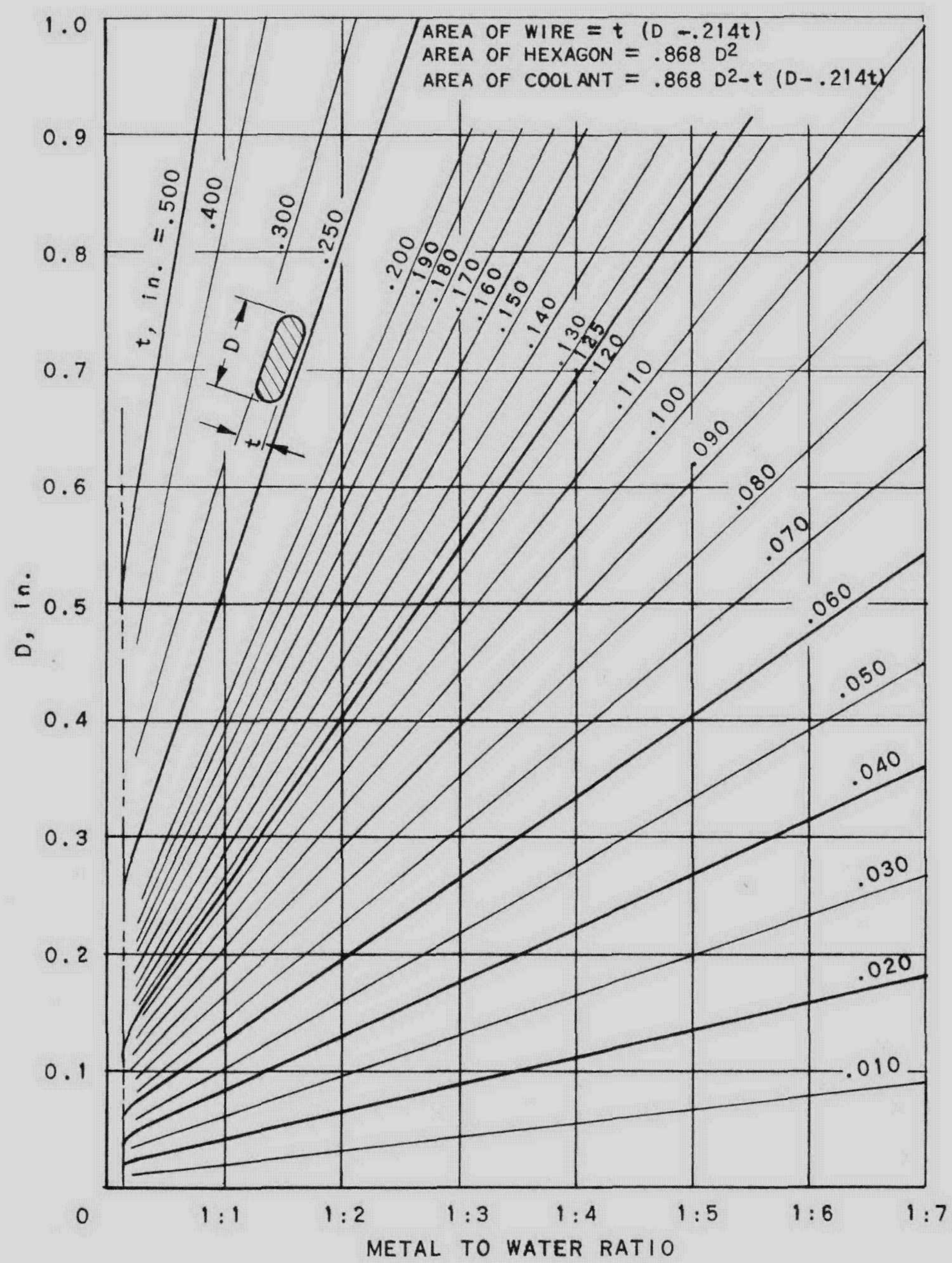

FIG. 7
METAL TO WATER RATIOS FOR TWISTED ROUND EDGE FLAT WIRES

A. B. SCHULTZ: E. A. K., 8-21-53

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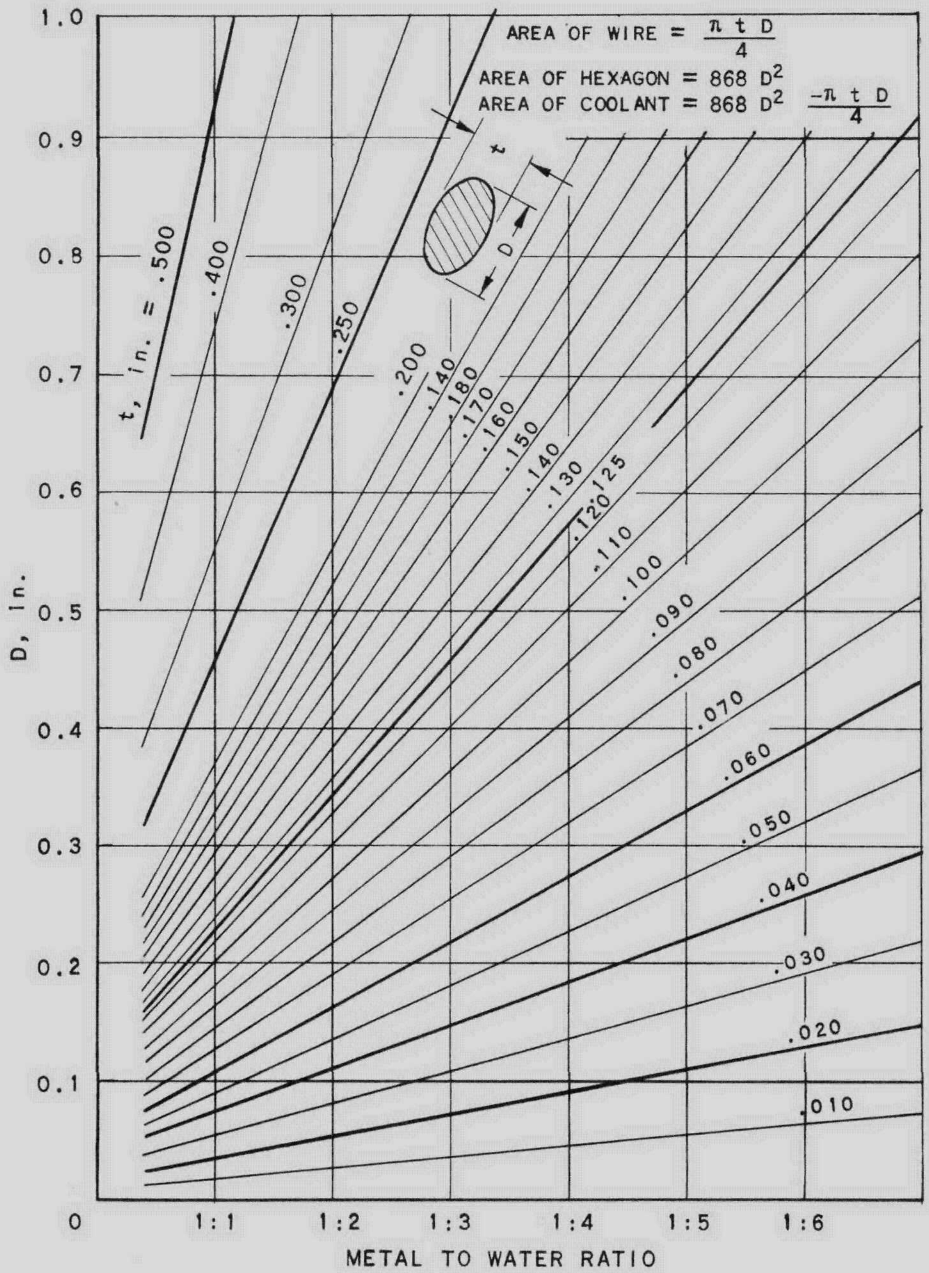

FIG. 8
METAL TO WATER RATIOS
FOR ELLIPTICAL WIRES

RE-7-11531-A

A.B.SCHULTZ:E.A.K.,8-21-53

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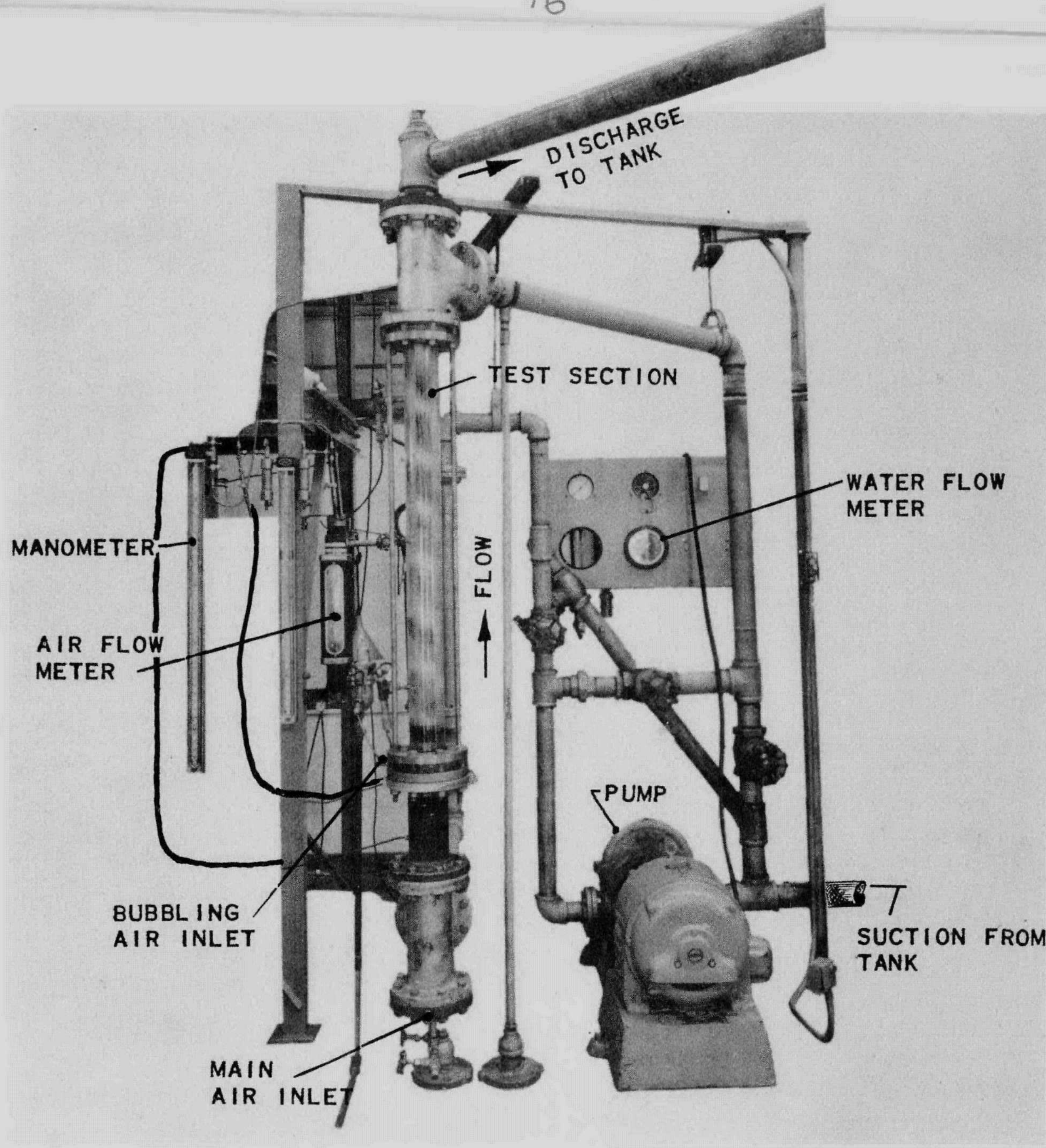

FIG. 9
PRESSURE DROP TEST FACILITY

A.B.SCHULTZ:G.D.,5-29-53

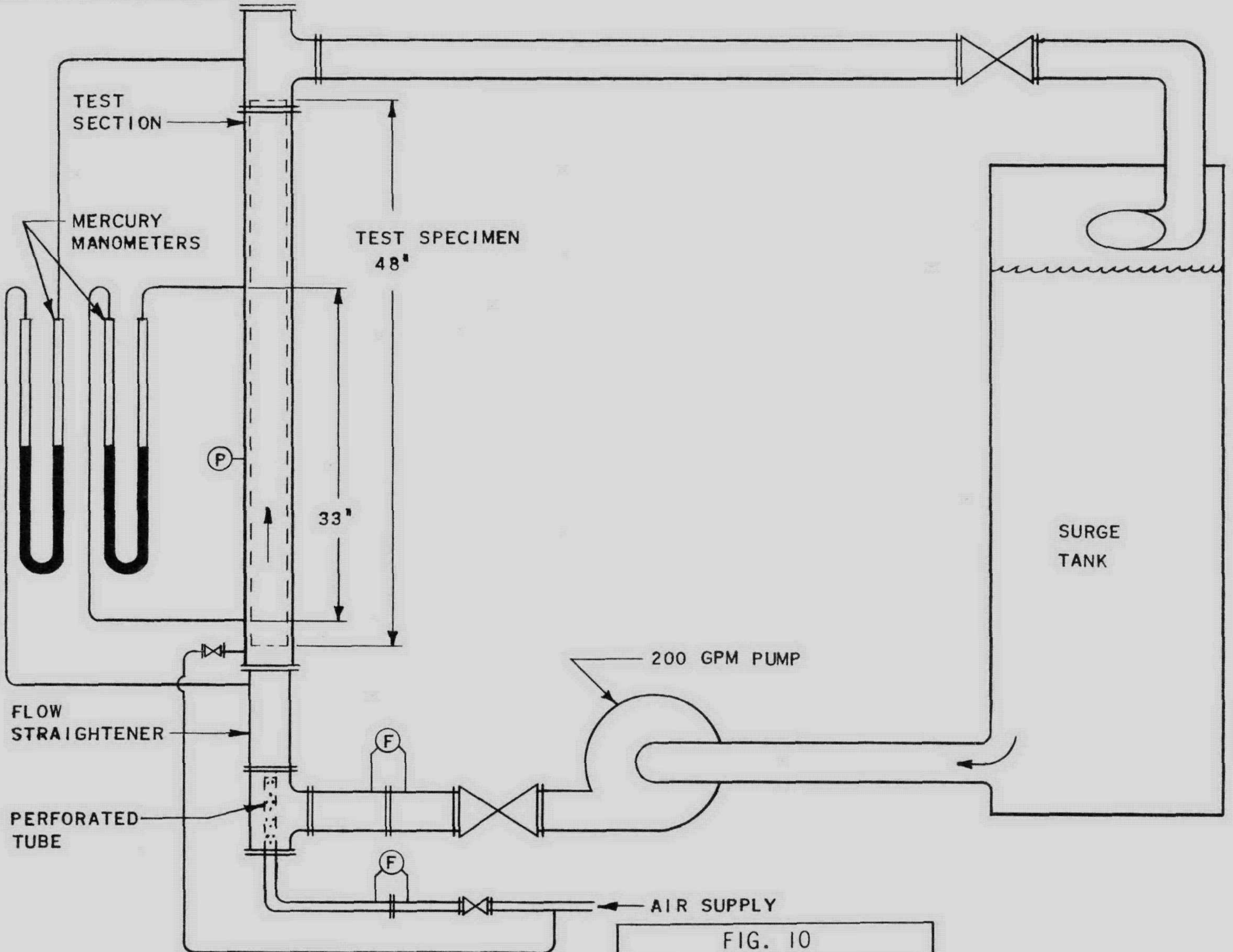

FIG. 10
SCHEMATIC OF PRESSURE DROP TEST FACILITY

RE-7-11048-A

determine average air density through the test section. A small air line into the side of the test section at the bottom is used for bubbling tests. The water is treated with sodium dichromate to prevent corrosion of the mild steel parts.

Calibration runs were first made to compare the pressure drop over the 48 in. section, including entry and exit losses, with the pressure drop between taps spaced 33 in. apart over the middle of the test section. Accumulated air was carefully vented from vital points; due allowance was made for the relative densities of the water in the manometer leads and in the test section, and also for the weight of the water over the mercury column differential.

The pressure pickup taps for the 3/8 in. x 1/16 in. ribbons were 5/16-in. holes at the center of the side of the hex. The taps for the 5/8 in. x 0.109 in. ribbons were rows of seven 1/8 in.-holes across one side of the hex. On the 3/8 in. x 1/8 in. and 3/8 in. x 3/16 in. ribbons, both types of pickup taps were used. The results are considered as accurate as the calibration and reliability of the instrumentation will permit.

Tests were run at water flows from 25 gpm up to 200 gpm in increments of 25 gpm. Air and water mixtures were run at densities of 1.0, 0.8, 0.6, 0.4, 0.2 and 0.1 to obtain data which proved useful for two-phase flow studies for boiling-type reactors. Bubbling tests were made to determine the rate of mixing and to observe the degree of spread at the top of the test section. Slow motion movies (1000 frames/sec) and high-speed snapshots were made to aid in studying the flow characteristics of the water and air mixtures.

IV. RESULTS

The test results for the pressure drop between 33-in. taps are shown graphically in Figs. 11 to 20. For convenience, all pressures are given in terms of direct manometer reading - water over mercury (in. Hg-H_2O). To convert to psi, the results must be multiplied by a factor of 0.455; to psi per foot of length by a factor of 0.165.

Figure 11 shows the comparative pressure drop for solid water for all the cores tested. It is to be noted that the increase of pressure drop due to the tighter pitch is not great. In the case of the 3/8 in. x 1/16 in. ribbons the added resistance of the 12 in. versus the 24 in. pitch (nearly parallel) is negligible.

Figures 12 to 20 show, through each test specimen, the pressure drop with varying density. Again, with the 3/8 in. x 1/16 in. ribbons, the difference between the 12-in. and 24-in. pitch is not significant; and the pressure drop of the 6-in. pitch over the others is of a small order of magnitude.

19

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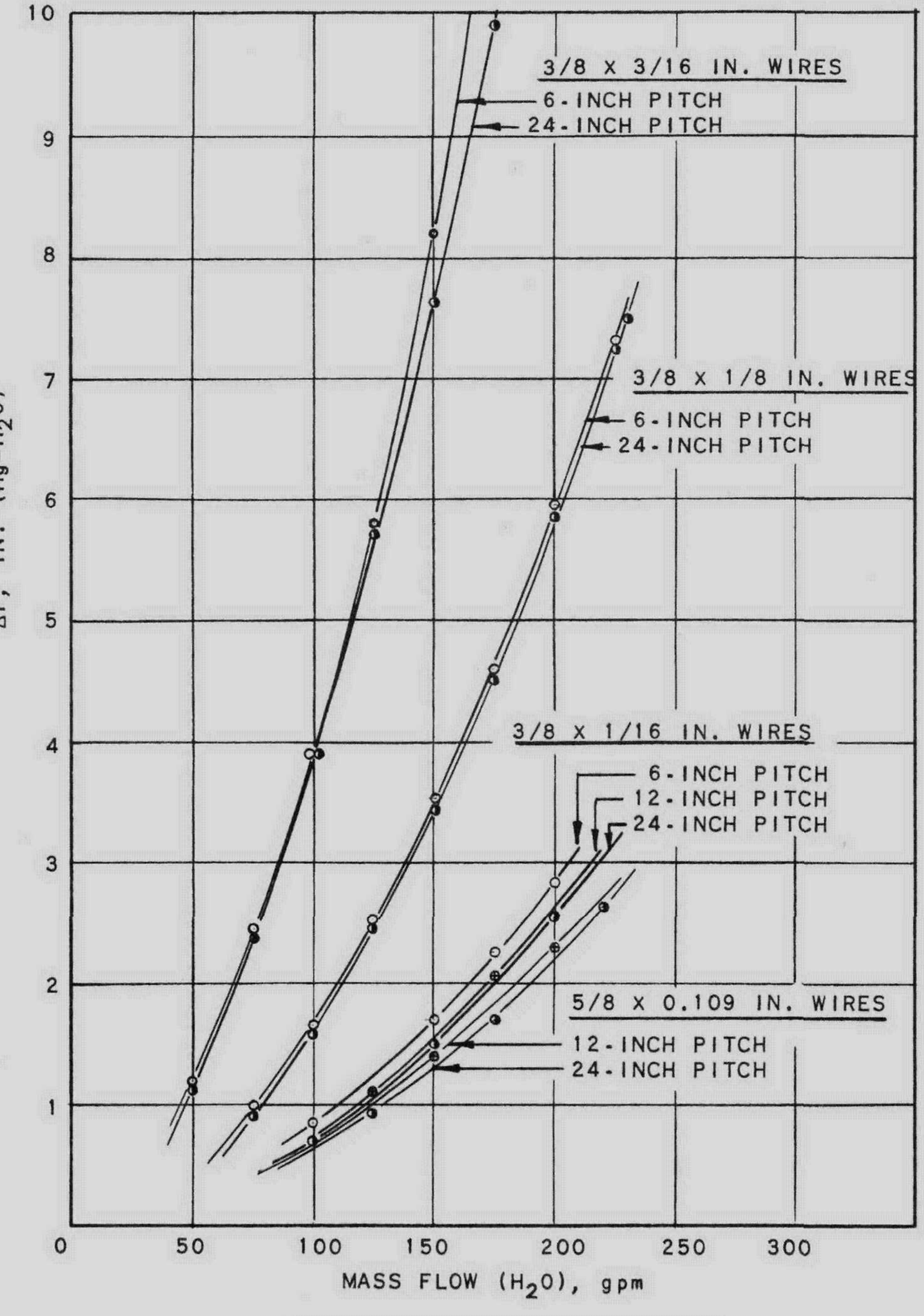

FIG. II
MASS FLOW VS PRESSURE DROP
AND CHANGE OF PITCH.
SOLID WATER

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A.B.SCHULTZ:V.H.,12-29-53

RE-7-11500-A

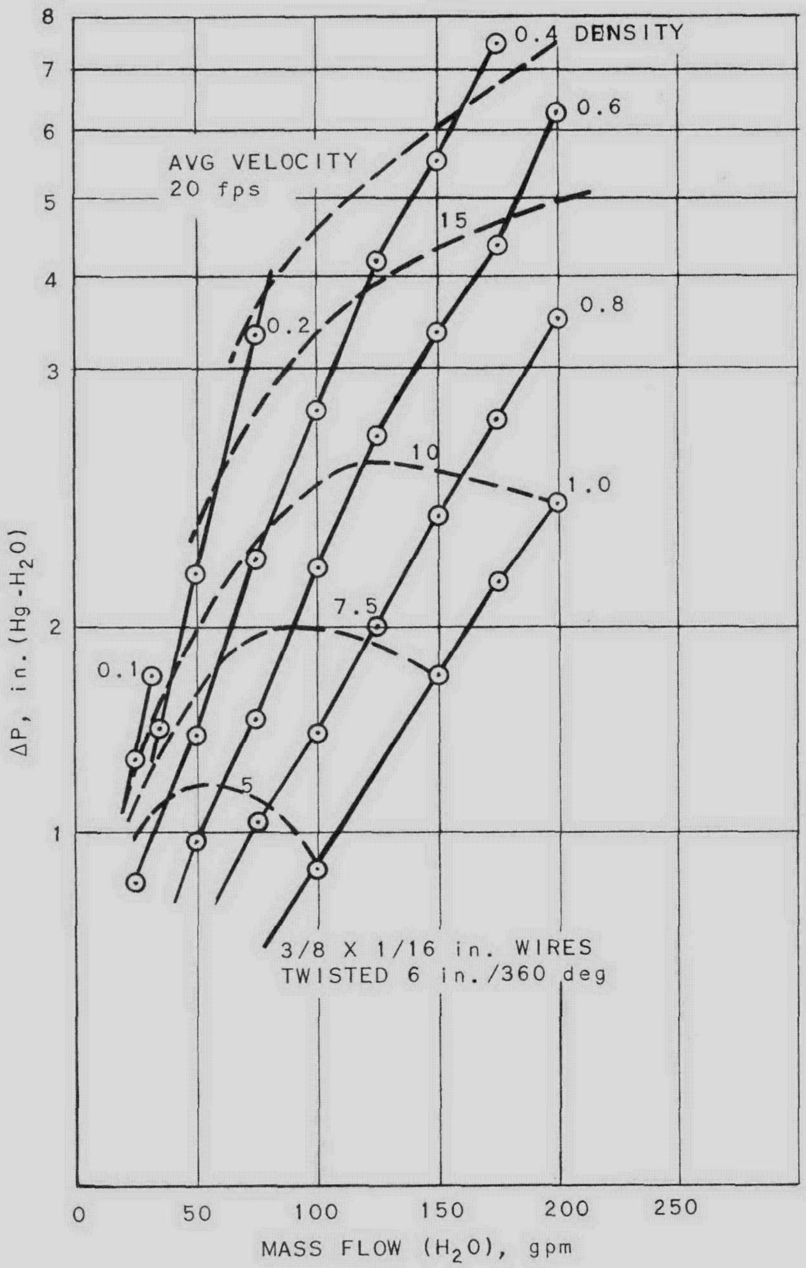


FIG. 12
MASS FLOW VS PRESSURE DROP.
WATER AND AIR MIXTURES

A.B.SCHULTZ & C.K.SOPPET:E.F.,8-19-53

643-19

RE-7-11499-A

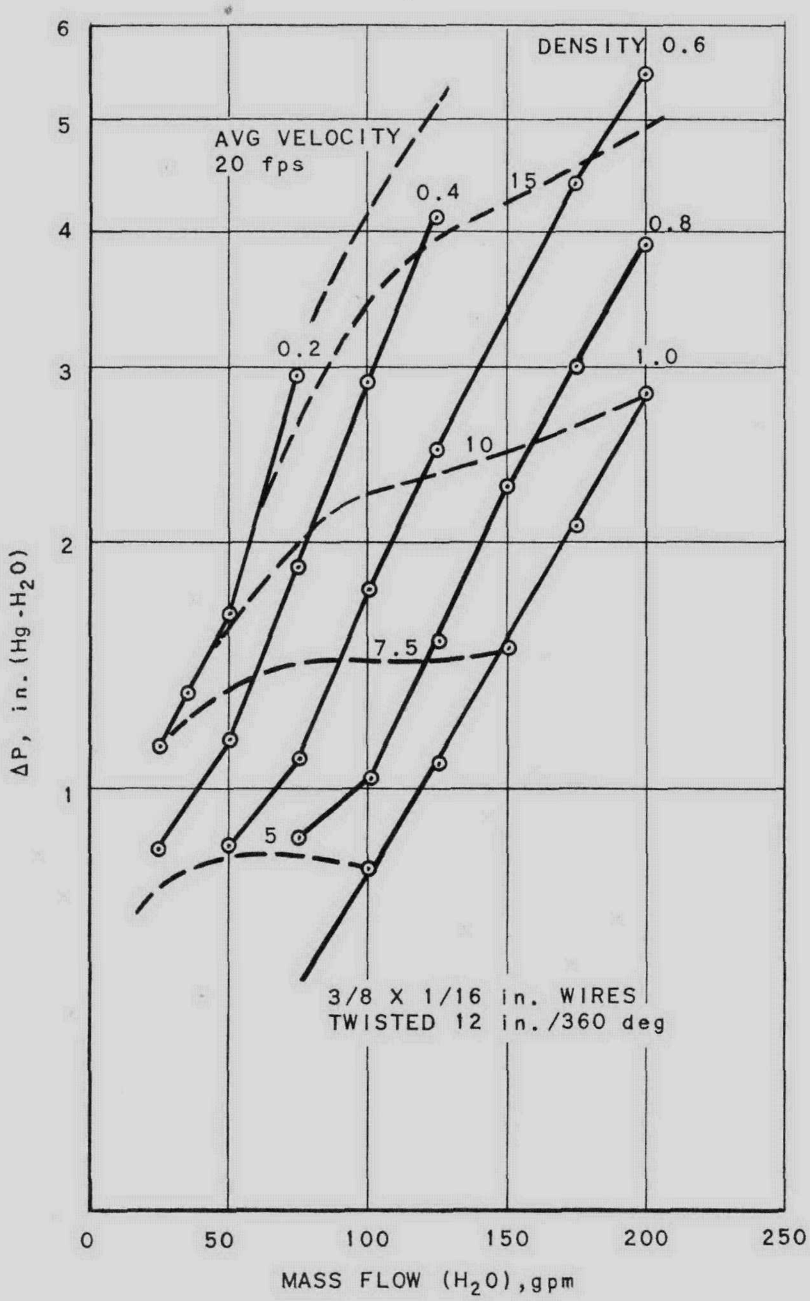


FIG. 13
MASS FLOW VS PRESSURE DROP.
WATER AND AIR MIXTURES

A.B.SCHULTZ:E.F.,8-18-53

020

RE-7-11510-A

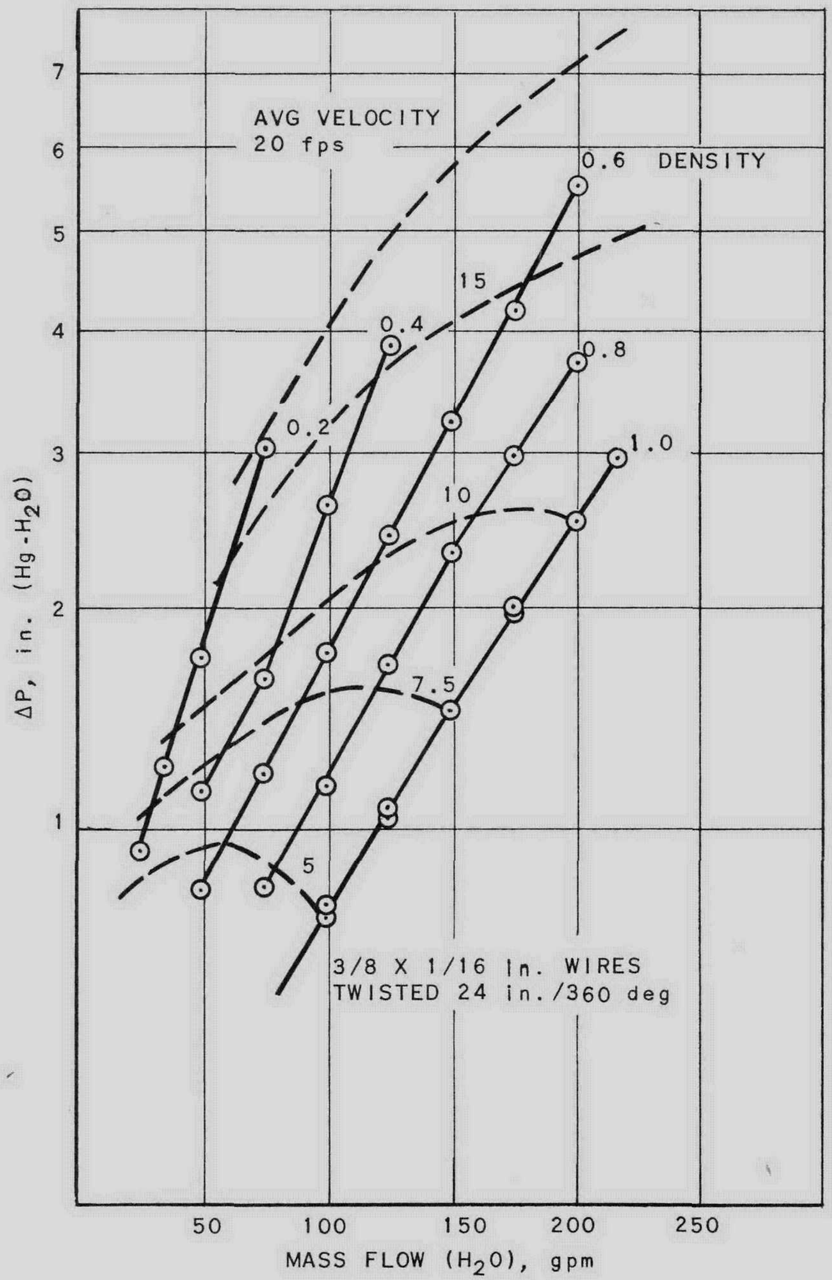


FIG. 14
MASS FLOW VS PRESSURE DROP.
WATER AND AIR MIXTURES

A.B.SCHULTZ & C.K.SOPPET:E.F., 8-19-53

RE-7-12117-A

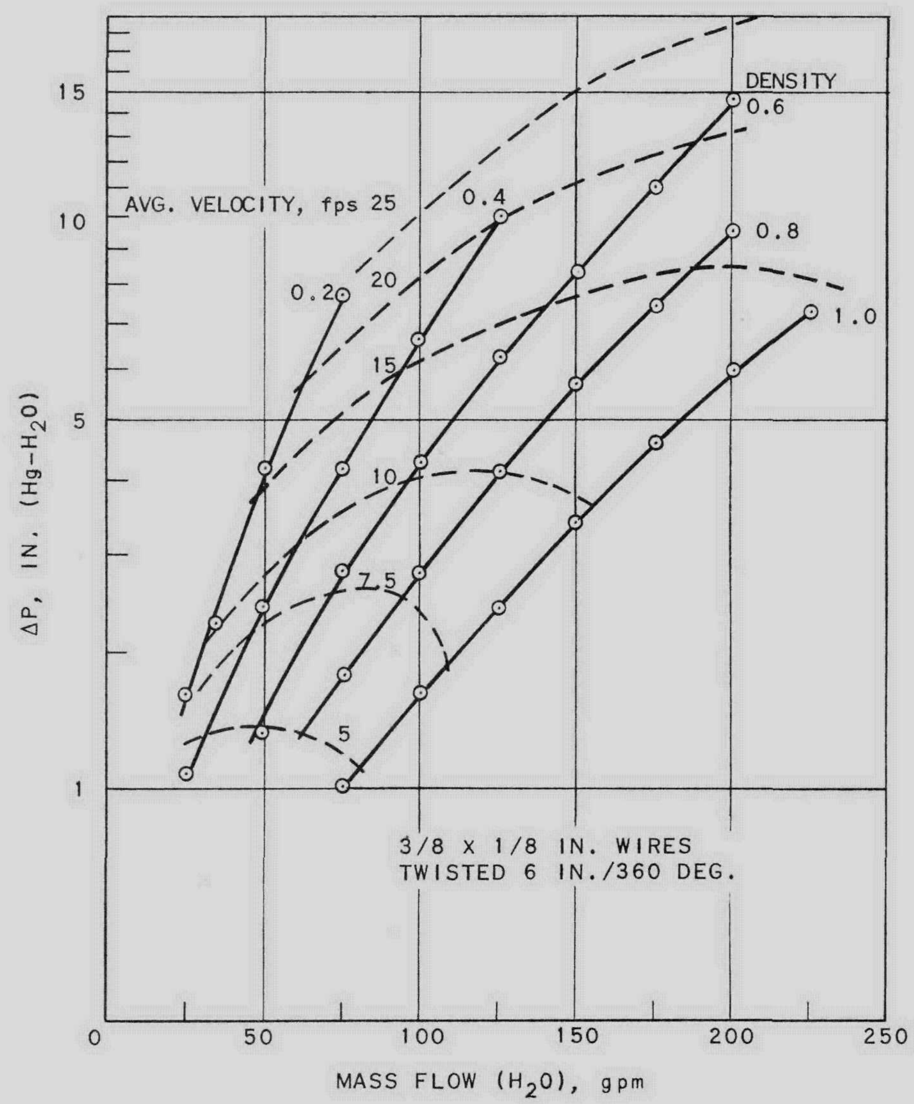


FIG. 15
MASS FLOW VS PRESSURE DROP.
WATER AND AIR MIXTURES.

RE-7-12117-A
A.B.SCHULTZ:E.F.,12-29-53

RE-7-12115-A

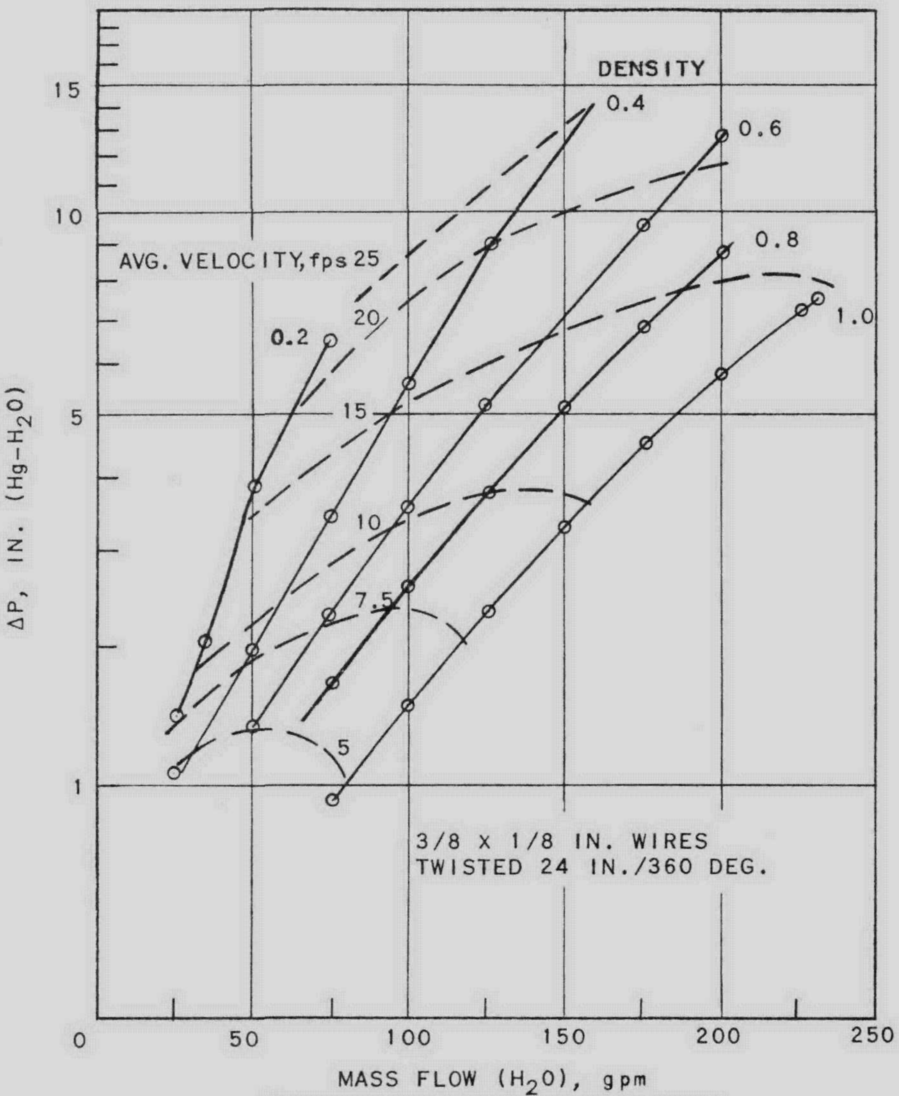
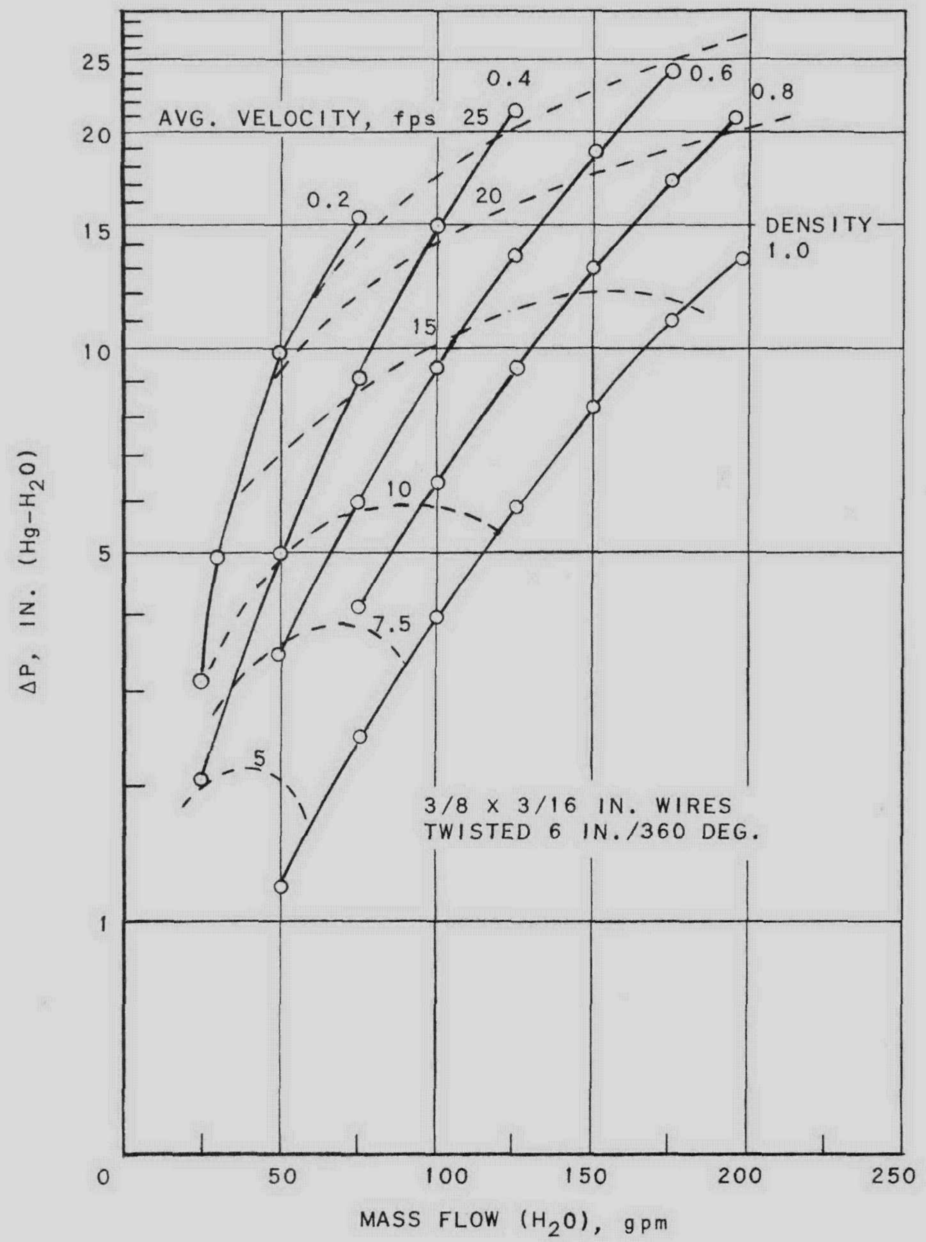


FIG. 16
MASS FLOW VS PRESSURE DROP.
WATER AND AIR MIXTURES.

RE-7-12115-A
A.B.SCHULTZ:W.S.,12-29-53

RE-7-12118-A



RE-7-12118-A
A.B.SCHULTZ:H.C.,12-29-53

FIG.17
MASS FLOW VS PRESSURE DROP.
WATER AND AIR MIXTURES.

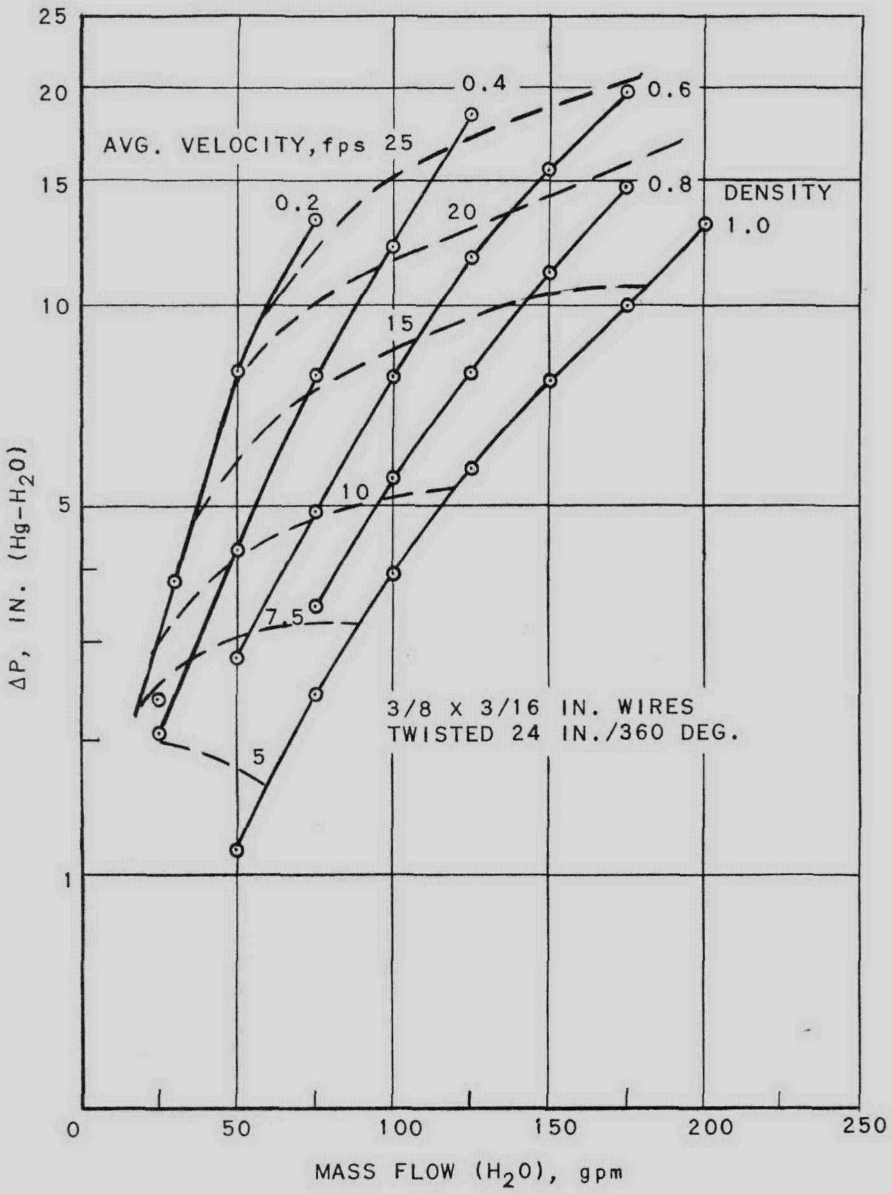


FIG. 18
MASS FLOW VS PRESSURE DROP.
WATER AND AIR MIXTURES.

RE-7-12116-A

RE-7-12116-A
A.B.SCHULTZ:F.J.S.,12-29-53

843 025

RE-7-12114-A

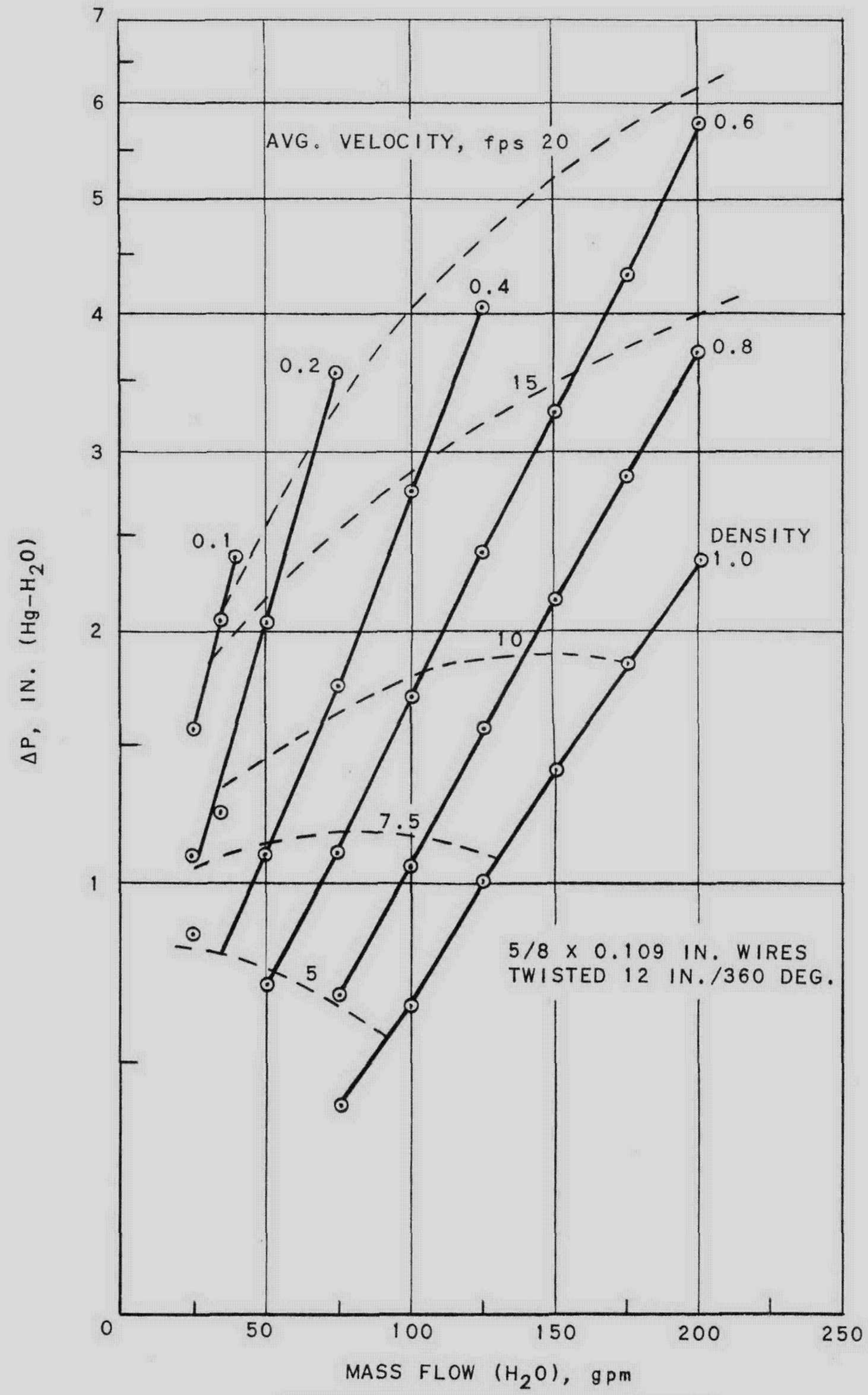


FIG. 19
MASS FLOW VS PRESSURE DROP.
WATER AND AIR MIXTURES.

RE-7-12114-A
A.B.SCHULTZ:E.A.K.,12-29-53

RE-7-12113-A

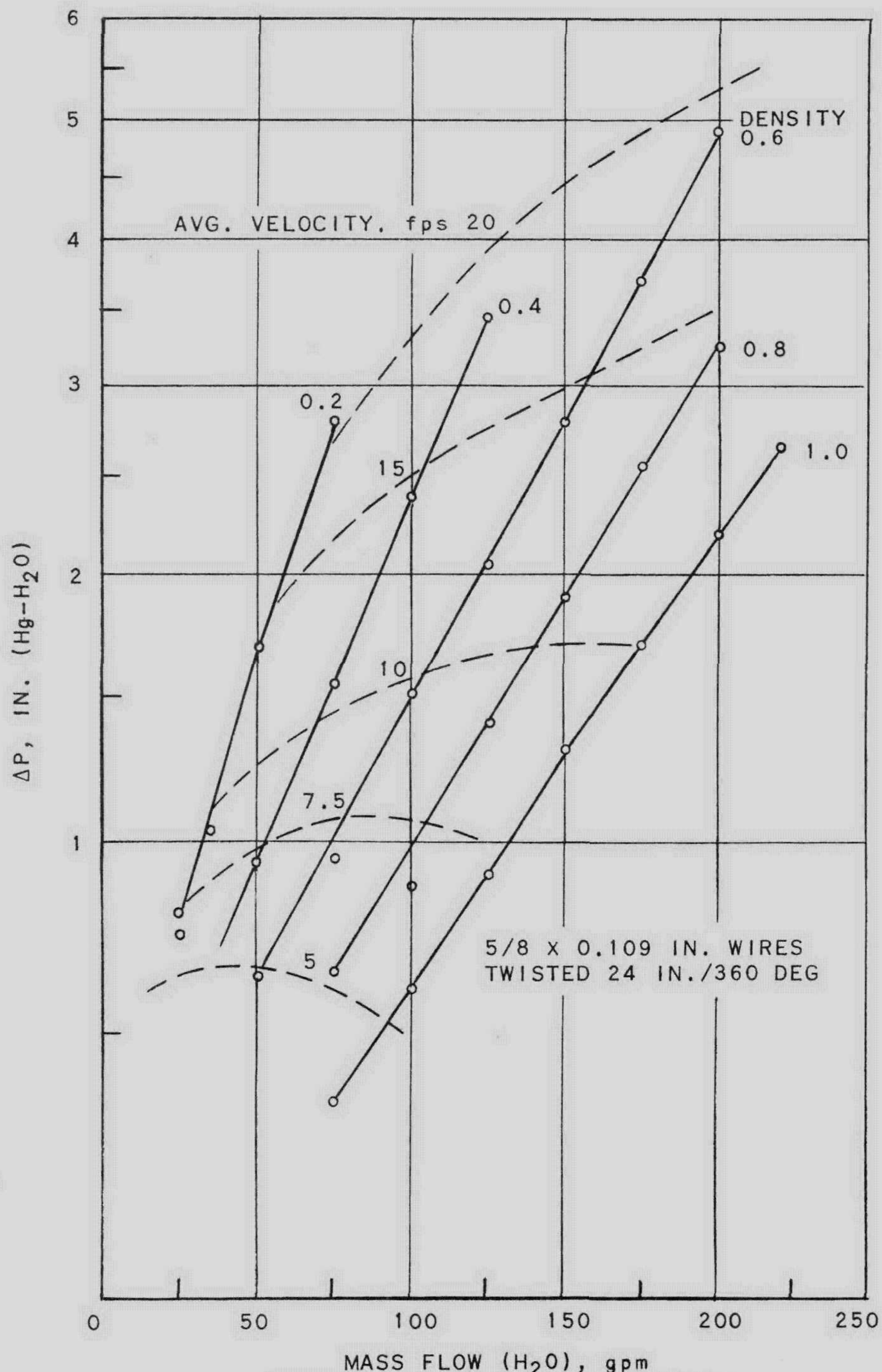


FIG. 20
MASS FLOW VS PRESSURE DROP.
WATER AND AIR MIXTURES.

RE-7-12113-A
A.B.SCHULTZ:D.Q.,12-29-53

The bubbling tests showed that with the 6-in. pitch ribbons, the bubbles spread to approximately 3/4 of the channel. With the 24-in. pitch ribbons, the bubbles spread to only a scant 1/4 of the channel.

A condition not anticipated was an apparently uncontrollable surging of the air and water mixtures. Even though the flow of the mixture was fairly uniform at the bottom (Fig. 21) it developed into a surging action as it reached the top (Fig. 22). This condition was apparent in all the mixed runs but was most violent in the lowest density conditions where the mixture alternated from a dead stop to a fast surge at a frequency of approximately 120 cycles/min. Occasionally, at low flow and low density, the flow would even reverse for a fraction of a second. At high flow rates and high density, the surging was not so apparent, but high-speed movies taken show that the condition still exists. It has since been learned that this condition is always present in air-lift wells.

V. EXPERIMENT VS. THEORY

Calculations were made to attempt to correlate the experimentally determined pressure drops with theoretical data at a flow rate of 10 fps. The method of calculating skin friction loss for flat plates and for parallel ribbons is outlined in Appendix A. Losses due to the twists of the ribbons were calculated on a kinetic energy loss basis as well as by reference to literature (Appendix B).

Several methods of correlation were tried, but no good relationship could be found which would be applicable to all cases. A number of these comparisons are shown in Table II, the most significant entries of which are Items (14) and (15), where the measured resistances of twisted ribbons are compared to calculated values for similar flat plates. Comparisons of measured parallel ribbons and calculated parallel ribbons (Item 10), calculated parallel ribbons and calculated flat plates (Item 9), and measured parallel ribbons and calculated flat plates (Item 13) are also of interest. Items (16) and (18), which show the measured differences due to the twists, should be compared to Items (17) and (19), respectively, which are the calculated differences.*

In interpreting the data, the following explanations of the first three items should be noted:

Item (1): The calculated value for flat plates assumes parallel plates the full width of hex, spaced the same distance as the corresponding twisted wires, and includes the wetted surface of the hexagon channel to determine the hydraulic diameter "d."

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*The calculated values for Items (17) and (18) are based on the method outlined in Appendix B.

30

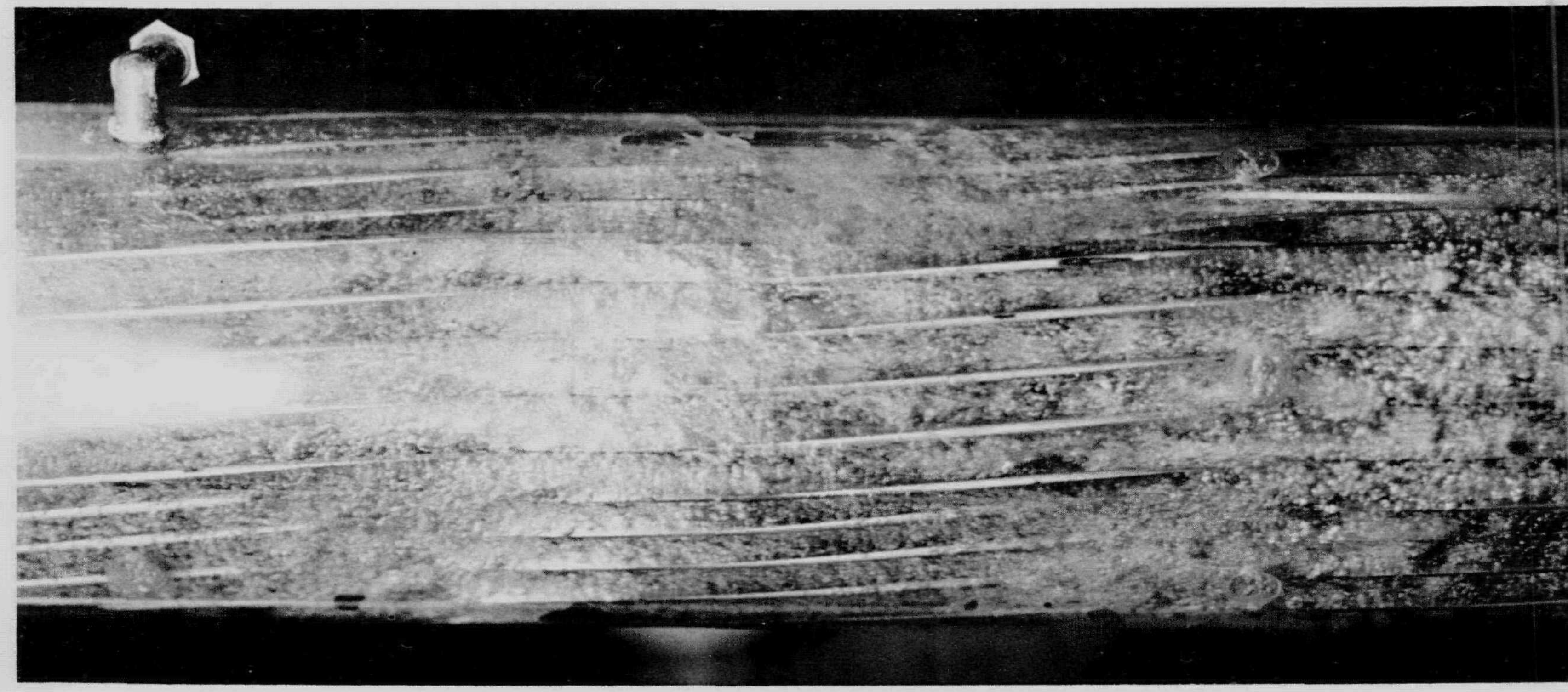


FIG. 21
HIGH-SPEED PHOTOGRAPH
OF WATER AND AIR MIXTURE

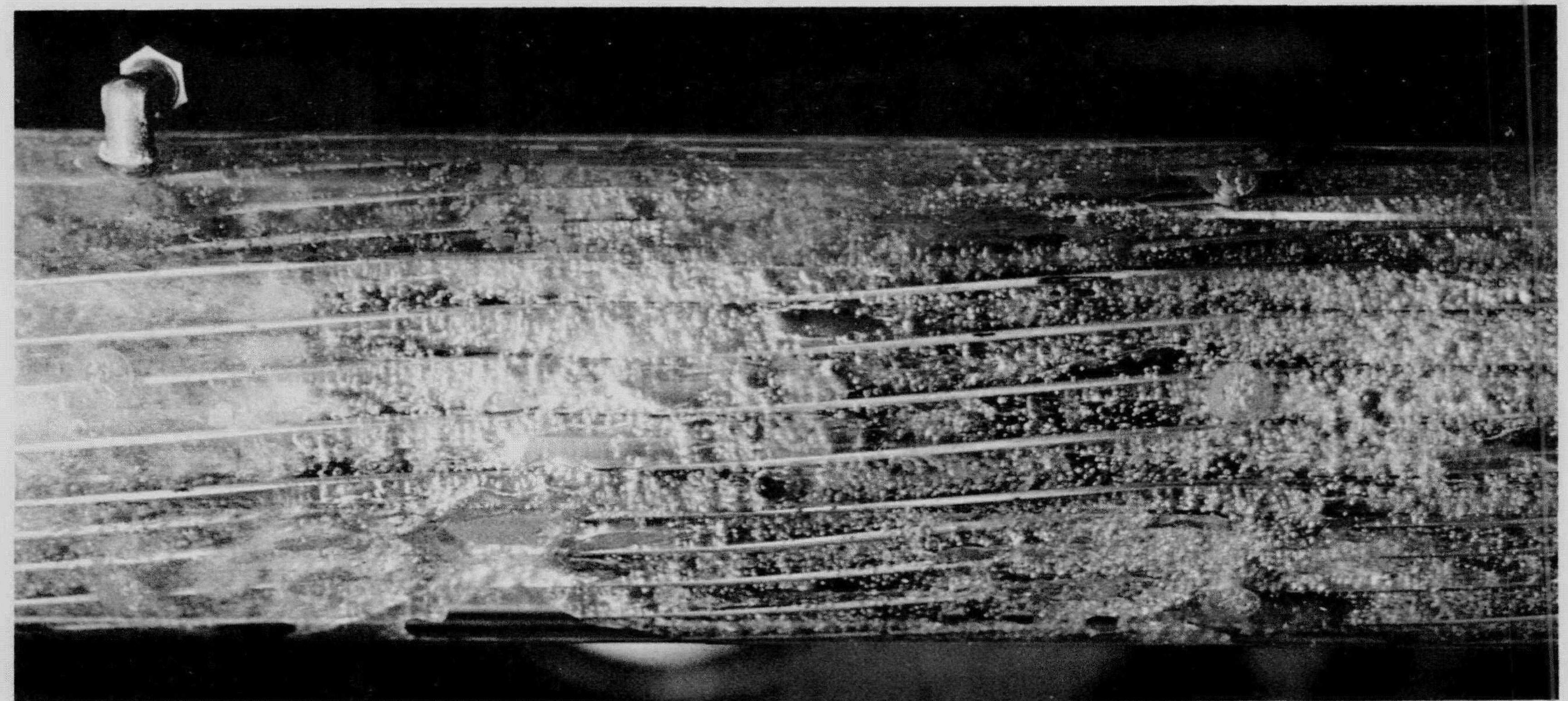


FIG. 22
HIGH-SPEED PHOTOGRAPH OF SURGING

32

Table II

PRESSURE DROP IN 33-INCH TEST SECTION EXCLUDING ENTRY AND EXIT LOSSES - VELOCITY 10 fps

Size of Twisted Ribbons, In.	Pressure Drop, In. (Hg-H_2O)			
	3/8 x 1/16	3/8 x 1/8	3/8 x 3/16	5/8 x 0.109
(1) Calculated flat plates	2.39	3.30	5.03	1.52
(2) Calculated parallel ribbons	2.78	4.06	6.33	1.69
(3) Measured parallel ribbons	2.53	3.55	5.30	1.70
(4) Measured 12-in. pitch ribbons	2.68	--	--	1.85
(5) Measured 6-in. pitch ribbons	2.85	3.65	5.40	--
(6) Wetted surface of (1)	56.2	56.2	56.2	33.45
(7) Wetted surface of (2)	63.8	67.5	73.2	36.45
(8) Ratio (7)/(6)	1.14	1.20	1.30	1.09
(9) Ratio (2)/(1)	1.16	1.23	1.26	1.11
(10) Ratio (3)/(2)	0.91	0.87	0.84	1.01
(11) Ratio (4)/(3)	1.06	--	--	1.09
(12) Ratio (5)/(3)	1.13	1.03	1.02	--
(13) Ratio (3)/(1)	1.06	1.075	1.05	1.12
(14) Ratio (4)/(1)	1.12	--	--	1.22
(15) Ratio (5)/(1)	1.19	1.11	1.075	--
(16) Measured difference (4)-(3)	0.15	--	--	0.15
(17) Calculated difference for (16)	0.08	--	--	0.16
(18) Measured difference (5)-(3)	0.32	0.10	0.10	--
(19) Calculated difference for (18)	0.32	0.30	0.30	--
(20) Metal to water ratio	1:4.45	1:1.8	1:0.975	1:4.43
(21) Flat Plate, "d"	0.454	0.351	0.250	0.668
(22) Flat Plate, R_e	51,600	40,000	28,500	76,100
(23) Flat Plate, f	0.0225	0.024	0.026	0.021
(24) Parallel ribbon, "d"	0.400	0.297	0.210	0.615
(25) Parallel ribbon, R_e	45,500	33,800	24,000	70,000
(26) Parallel ribbon, f	0.023	0.025	0.0275	0.0215

Item (2): The calculated value for parallel ribbons includes the entire wetted surface of the ribbons plus the wetted surface of the hexagon channel to determine the hydraulic radius "d."

Item (3): The measured value for parallel ribbons is for ribbons twisted to 24-in. pitch per 360 degrees. The increment of pressure drop due to the 24-in. pitch in negligible.

VI. CONCLUSIONS

From the empirical data obtained, the flow characteristics of any proposed twisted ribbon core configuration can be estimated. In general, the resistance to coolant flow of relatively wide ribbons (i.e., approximately 6:1 ratio of width to thickness, twisted 360 degree for each 15-20 widths) will be about 20% greater than calculated for flat plates of the same thickness and spacing. About 10% is due to the added wetted surface of the edges of the ribbons and about 10% to the energy losses caused by the twists. As the ribbons become thicker (i.e., approximately 2:1 ratio of width to thickness), the losses due to the twists decrease and the pressure drop is only about 10% greater than calculated for flat plates. In general, the increased resistance of the twists is much less than was generally anticipated.

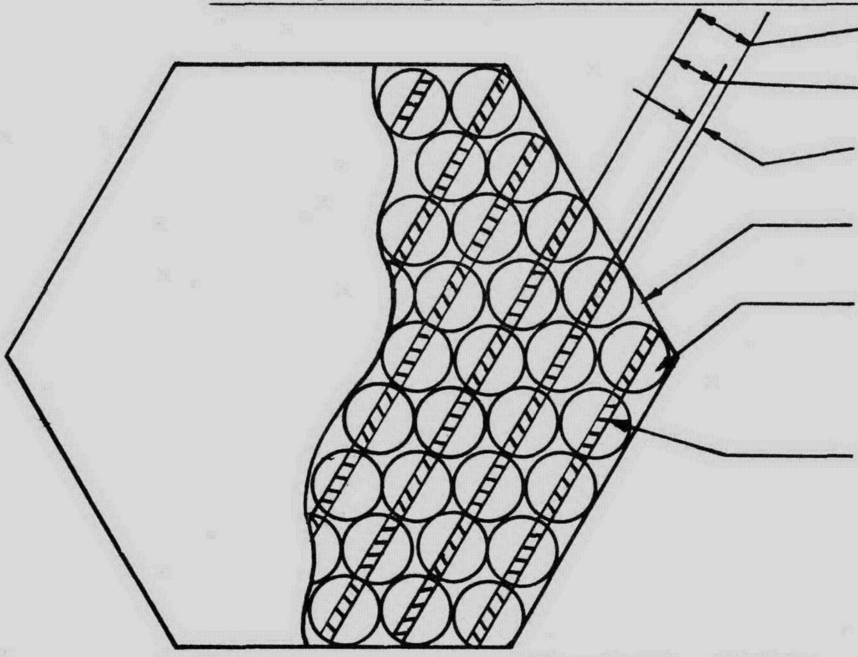
APPENDIX A

CALCULATED PRESSURE DROP

The classical method of calculating resistance to flow in channels, as outlined in standard references,[1] is used. In this method the hydraulic radius is found by dividing the total flow area by the total wetted surface.

CASE I - CALCULATED PRESSURE DROP THROUGH PARALLEL FLAT PLATES

Including wetted surface of walls of hex and projected area of ribbons, but neglecting edges of ribbons (assuming flat plates):



Perimeter of plates = 61 x 0.75 = 45.7 in.

Perimeter of hex = 10.4

Total wetted surface = 56.1 in.

Area of hexagon = $0.868\ D^2 = 0.868 \times 3^2 = 7.80$ sq in.

Area of ribbons = 61 x 3/8 x 1/16 = 1.43

Flow area = 6.37 sq in.

Hydraulic radius = 6.37/56.1 = 0.1135 in.

Hydraulic diameter = d = 4 x 0.1135 = 0.454 in.

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[1] For example, "Flow of Fluids through Valves, Fittings and Pipe," Crane Co. Technical Paper No. 409, May, 1942, pp. 6 and 9.

35

Water velocity = v = 10 fps at a bulk flow of 200 gpm

Water viscosity = ν = 0.68 centistokes at 100F

Reynolds Number = $R_e = \frac{7742\ dv}{\nu} = \frac{7742 \times 0.454 \times 10}{0.68} = 51{,}600$

Water density = 62.0 lb/cu ft at 100F

Friction factor = f for smooth surfaces = 0.0225

Pressure drop ΔP for a length L of 33 in. = $\Delta P = \frac{0.00129\ f \rho v^2 L}{d} =$

$$\frac{0.00129 \times 0.0225 \times 62.0 \times 100 \times 33}{12 \times 0.454} = 1.09 \text{ psi}/0.455 = 2.39 \text{ in. } (Hg-H_2O)$$

(The multiplier 0.455 = correction factor of 0.926 for water over mercury in the manometer x 0.491 conversion factor for psi to in. mercury. This is for convenience in comparing directly with actual test readings. The values on the curves can be converted to psi by multiplying by 0.455. To obtain pressure drop per foot of length multiplied by

$$\frac{0.455 \times 12}{33} = 0.165\text{)}$$

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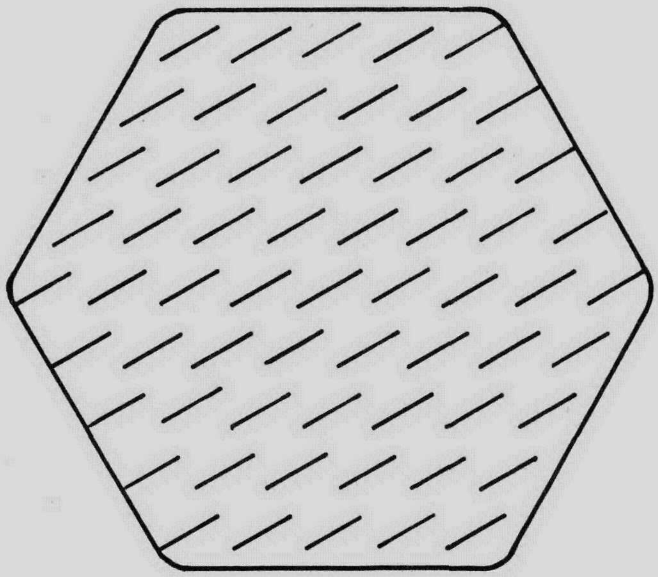
36

CASE II - CALCULATED PRESSURE DROP THROUGH PARALLEL RIBBONS

Including wetted surface of walls of hex and projected area and edges of ribbons:



Perimeter of ribbons = 61 x 0.875 = 53.4 in.

Perimeter of hex = 10.4

Total wetted perimeter = 63.8 in.

Flow area = 6.37 sq in.

Hydraulic radius = 6.37/63.8 = 0.100 in.

Hydraulic diameter = 0.100 x 4 = 0.400 in.

$$R_e = \frac{7742 \times 0.400 \times 10}{0.68} = 45{,}500$$

$$f = 0.023$$

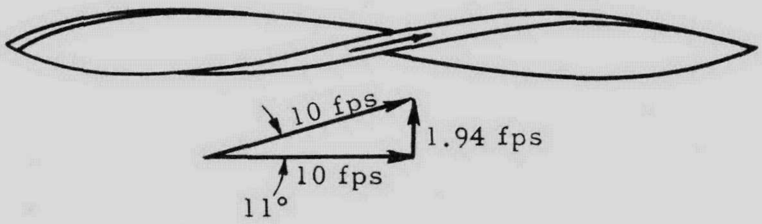
$$\Delta P = \frac{0.00129 \times 0.023 \times 62.0 \times 100 \times 33}{12 \times 0.400} = 1.265 \text{ psi}/0.455 = 2.78 \text{ in. } (Hg-H_2O)$$

37

APPENDIX B

CALCULATED PRESSURE DROP DUE TO TWISTS

In calculating the pressure drop due to twists, it is assumed that all the energy of rotation or twist is lost at each point where the wires touch to momentarily form flat plates. This occurs 6 times per 360° of twist. In the 6-in. pitch ribbons this occurs 33 times in 33 in. of length. It is assumed that 5/6 of the water continues in parallel flow near the axes of the ribbons and only 1/6, located at the periphery of the ribbons, undergoes this periodic change of angular velocity. The angle of the helix for 6-in. pitch equals 11°. At 10 fps longitudinal velocity (198 gpm = 1650 lb/min) the rotational or tangential v = 10 x tan 11° = 1.94 fps.



The kinetic energy loss is KE = $1/2\ Mv^2 = \dfrac{1650 \times 1.94^2 \times 33}{2 \times 32.2 \times 6} = 530$ ft-lb/min

This represents 530/1650 = 0.32 ft of head or 0.32 x 0.433 = 0.14 psi/0.455 = 0.32 in. (Hg-H_2O) pressure drop due to the twist. This compares favorably with the observed value of 0.32 obtained by the difference between the 6-in. and 24-in. pitch ribbons at this flow rate. The calculated kinetic energy loss for the 24-in. pitch ribbons is $\dfrac{6^2}{24^2} \times 0.32 = 0.32/16 = 0.02$ and is neglected.

An alternate method is to use the resistance of a Miter Bend[2] for each change of angle and again assume 1/6 of the water is subject to this added resistance. For a 20° angle, K = 0.02 and the pressure loss ΔP for a 33-in. length $= \dfrac{K\rho v^2}{144\ (2g)} \times \dfrac{33}{6} = \dfrac{0.05 \times 62.0 \times 10^2 \times 33}{144 \times 2 \times 32.2 \times 6} = 0.184$ psi/0.455 = 0.40 in. (Hg-H_2O), which approximates the measured value.

The above analysis appears to be applicable only to relatively wide, thin ribbons where a portion of the flow parallels the edges of the ribbons and is subjected to sharp changes of direction at the contact points. As the ribbons become thicker and approximate elliptical shapes, the coolant apparently flows around the ribbons more nearly parallel to the axis of the cluster and is not subject to these sudden reversals and consequent losses of energy (see Items (16), (17), (18), and (19) of Table II).

[2] Ibid pp. 15 and 23.

APPENDIX C

MANUFACTURE OF TWISTED RIBBONS

The wire-twisting tool used to form the twisted ribbons is shown in Figure 23. The tool consists of 3 discs, each fitted with 2 hardened rollers and guide bushings. In all cases, the 2 rollers have parallel axes. The first pair of rollers are straight cylinders; the successive rollers are barrel-shaped to accommodate the twist of the ribbons. In practice, (1) the discs are first rotated so the axes of all the rollers are parallel; (2) the flat wire is passed through all 3 discs and caught with a gripping device mounted on a thrust bearing so that it may rotate with the ribbon; (3) the axes of the discs are twisted to predetermined angles to give the proper twist to the wire; (4) the discs are clamped in a fixture on a draw bench; and (5) the gripping device is pulled by the carriage and the twisted ribbon emerges.

The resulting ribbons are cut to length, the pitch adjusted by manual twisting, and then the ribbons are welded to end plates. The adjustment of pitch is necessary because of apparently uncontrollable small pitch variations. This is due to a variation in hardness in the steel strips which results in variable spring-back as the strips emerge from the rollers. Commercial cold-rolled round-edge flat wire was used on which no control of hardness is claimed. In actual production of fuel wires this can be made subject to careful control and the resulting pitch should be quite accurate. If, however, variation does occur, it is a simple matter to adjust each one as required.

To make various sizes of ribbons the diameters of the rollers (hence their separation) and the diameter of guide bushing are varied as required.

The quality of the twisted ribbons used in the tests was very good for the wide, thin wires. This was reflected by the fact that only a 50-lb pull was sufficient to draw-twist the 3/8 in. x 1/16 in. wire to 6 in. pitch, thus indicating very little energy input. For the 3/8 in. x 3/16 in. wire, however, the pull was disproportionately high, and the energy expended was reflected by cold-working of the edges of the flat wire where it contacted the rollers. This was less evident on the 3/8 in. x 1/8 in. wire and did not appear at all on the 3/8 in. x 0.109 in. wire.

This does not necessarily mean that during twisting the cladding of relatively thick fuel wires will suffer accordingly, because the difficulty can be corrected by using a design shown in Figure 24. In this version the successive rollers do not have parallel axes; the axes are arranged perpendicular to the twisted edges of the wire. In this way the wire does not scuff across the face of the roller; it passes through smoothly with a minimum of friction and distortion of the surface. This has been demonstrated by twisting

39

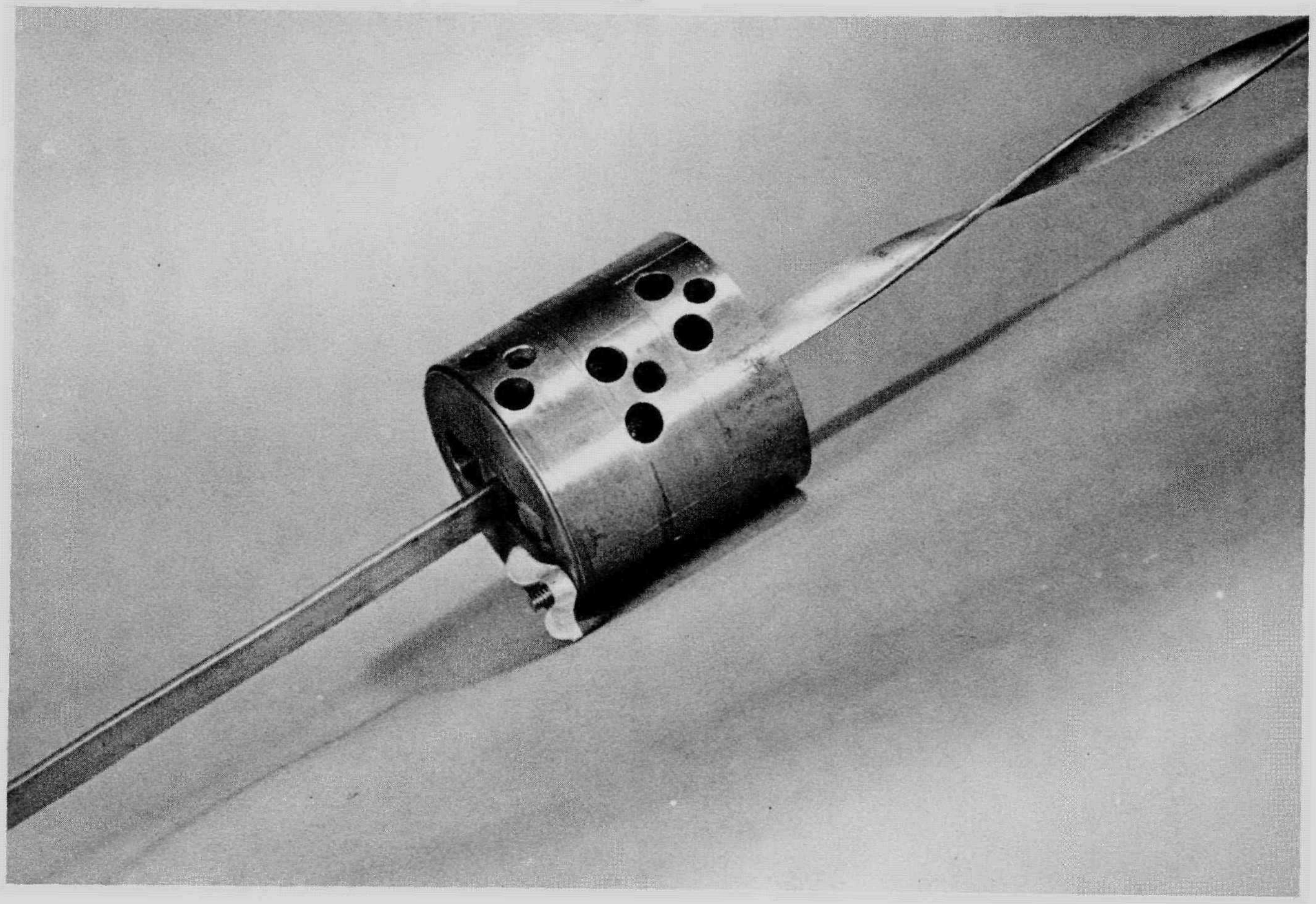


FIG. 23
WIRE-TWISTING TOOL FOR $\frac{3}{8}$ -AND $\frac{5}{8}$ -INCH WIRES

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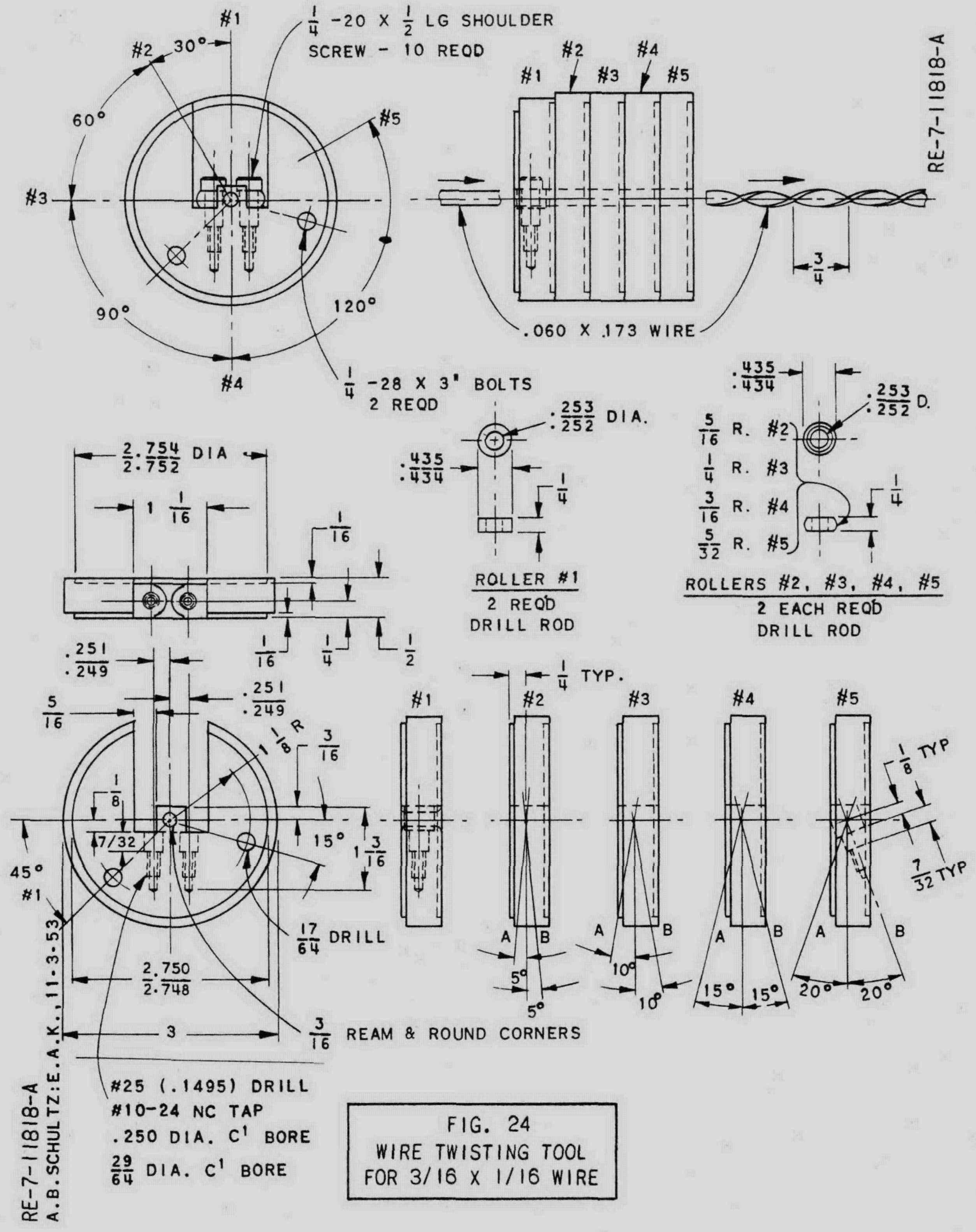

FIG. 24
WIRE TWISTING TOOL
FOR 3/16 X 1/16 WIRE

DECLASSIFIED

3/16 in. x 1/16 in. 2S aluminum wire to a 1-1/2-in. pitch without lubricant and with excellent results. With proper attention to the detail design of the rolling fixture, similar results appear to be possible with any combination of clad fuel wire.

By employing guide spacers and larger diameter rollers as shown in Figure 25, smaller wires may be twisted with the same basic tools. In this case the wire size is 0.048 in. x 0.139 in.

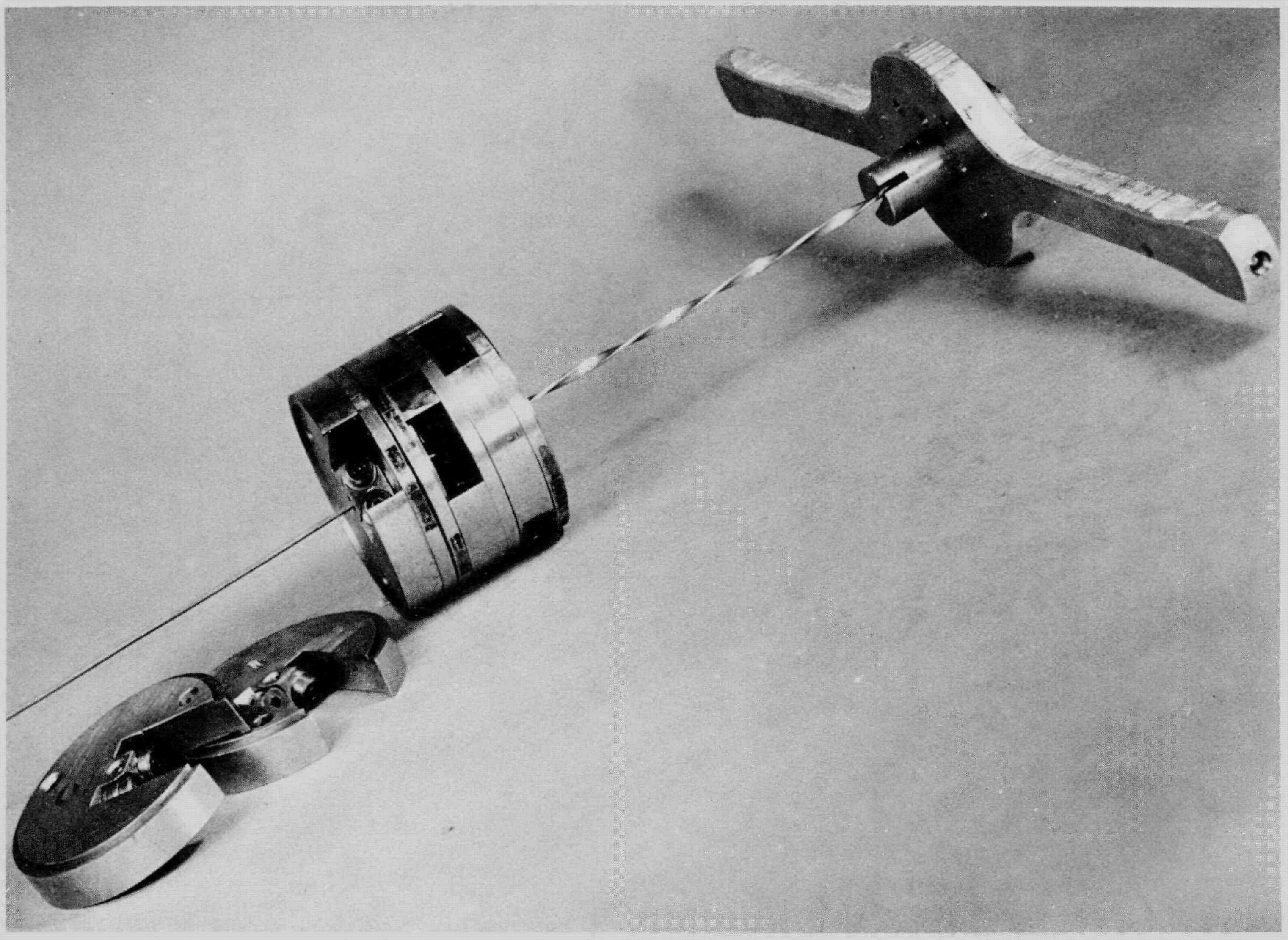

FIG. 25
WIRE-TWISTING TOOL
FOR 0.048x0.139 IN. WIRES