UNIVERSITY OF WASHINGTON
AERONAUTICAL LABORATORY

REPORT 801

An Experimental Investigation of Feasibility of a V/STOL Test Section in UWAL 8 x 12 Wind Tunnel by Using a 1/8 Scale Model of the Tunnel

TITLE

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SUMMARY

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Feasibility of adding a large test section upstream of the 8 x 12 test section of the F. K. Kirsten wind tunnel was experimentally investigated by a scale model of the existing wind tunnel. The validity of the unmodified model was first verified by comparing model tunnel flow with full scale 8 x 12 tunnel flow. Finally, the model tunnel was modified by adding a 21 x 19 - 60 foot test section upstream of the 8 x 12 test section. Corner vanes and propeller anti-swirl vanes were shown to have sufficient effectiveness to control flow angles and velocity distribution in both test sections. A final adjustment was achieved which gave satisfactory flow in both test sections.

It is concluded that the proposed modification of the present 8 x 12 test section wind tunnel to accommodate a large test section for V/STOL aircraft wind tunnel testing is feasible.

Author

I. Introduction

V/STOL* aircraft at low forward speeds have the unique characteristic of causing large downwash angles, approaching 90° at the hovering condition. A consequence is that this type of aircraft experiences large changes in pitching moments in the transition region between the hovering and cruising condition thus introducing unusual handling problems. Such difficulties must be fully investigated before flight, preferably by using a model in a wind tunnel which has the capability of providing an aerodynamic environment equivalent to the transition conditions of the aircraft. Consequently the wind tunnel must be able to provide an accurately controlled low test air velocity (approaching zero), and a minimum wall interference error.

The problem of the wall interference can be relieved by requiring a small ratio of the model to test section size. The difficulty and high cost of constructing accurate small models, together with the low Reynolds number resulting, makes it either impractical or unacceptable to use the normal size wind tunnel. Thus the only way to obtain a small ratio of the model to test section size is to build a large test section. Facilities with larger

*Vertical or Short Take-Off and Landing

test sections have been developed and used by the NASA and some aircraft companies throughout the country, but those few facilities now existing will not be able to meet the demands of the industry for a routine development wind tunnel testing of their V/STOL aircraft design.

The present UWAL** 8 x 12 foot, 250 mph, wind tunnel could be modified to add a large test section by relocating the bellmouth of the existing tunnel further upstream. A large test section could be produced in this manner with a cross section of 300 or 400 square feet upstream of the existing 8 x 12 test section. The velocity in this large test section would be very low (zero to 60 or 80 mph) and would be accurately controlled, in spite of model power input, due to the relatively large power required by the whole tunnel circuit. Such a modification was proposed in UWAL Rep. 744.

A first step in the proposed modification program was to build a pilot model of the present wind tunnel, and to try these changes in that model. The value of such a model tunnel has been substantiated by the NASA in their study of the 7 x 10 foot tunnel modification at Langley, and by the Boeing Company's extensive use of their model tunnels. At the same time, an analytical study of the

**University of Washington Aeronautical Laboratory above proposed modification was made to explore the flow field in a two-test-section tunnel. This study (UWAL Rep. 773) was encouraging and its results were used to choose the experiments to be conducted in the model tunnel.

Thus the objectives of the experimental work were developed as follows:

1. To verify that the model tunnel flow is a true reproduction of flow in the full scale tunnel.
2. To determine if a high quality flow environment can be produced in the proposed new test section.
3. To find if any changes occur in the 8 x 12 test section as a result of adding the proposed new test section.

It is the purpose of this report to describe the design of the model tunnel and to present the experimental work carried out to answer the three questions stated above.

II. Description of Model Tunnel and Equipment

1. Model Tunnel

The design and construction of a pilot model tunnel of the UWAL 8 x 12 foot wind tunnel was started in June, 1963. It was desired that the model tunnel be as large as possible in order to obtain an accurate flow survey and reasonable Reynolds Number. Space limitation dictated the scale of the model tunnel to be as small as possible. The final scale was selected to be 1/8. The power loss due to Reynolds Number effects was predicted using the data obtained in the Boeing Company's 1/20 scale model tunnel. The scaling law used was to match the propeller advance ratio (V/nD) and tip Mach Number which results in speeds identical to those values of the full scale tunnel.

The model tunnel is erected on its side in the lobby of the full scale tunnel for easy access to major parts of the tunnel. See Photo 1. For the sake of convenience and to correspond with the full scale tunnel the upper return duct is designated "west" and the lower duct "east," and the panel closest to the operating console corresponds to the ceiling of the full scale tunnel. All dimensions, sign conventions, and vertical and horizontal directions used in this report are in the sense of the full scale tunnel, unless otherwise specified. Photo 1 shows the basic model tunnel with its 8 x 12 test section ceiling panel removed for access to the test section. One ceiling panel down stream of each propeller is removable for return duct access. The bellmouth turning vanes, diffuser turning vanes, and propeller anti-swirl vanes are adjustable in their angles of incidence. The sections of the tunnel containing the propellers and drive motors can be rolled out on a pair of cabinet drawer slides for ease of maintenance and inspection.

Each propeller, which has seven aluminum blades, is driven by a 400 cycle, 14 HP induction motor through a set of straight bevel (coniflex) gears located within the nacelle. The gear ratio is a 23/25 reduction. These gears are lubricated by a jet of oil meeting the military specification MIL-L-15017. The two motors are not mechanically synchronized with each other, but the propellers are well synchronized because of the torque characteristic of induction motors, since the motors are electrically in parallel from the same variable frequency power source.

The first modification to be constructed was the largest that can possibly be built within the limits of the building site, a building extension of 75 feet.

Both return ducts, downstream of the propellers, were extended 75 feet full scale with an expansion only in the vertical direction at the same constant angle of expansion (3.9° half angle) as in the full scale tunnel. The bellmouth end of the basic tunnel configuration was designed and constructed to match this vertical expansion of the return ducts which yielded a bellmouth of 29.5 x 29.75 feet high full scale. This end is also made detachable from the rest of the tunnel, enabling the bellmouth end to be extended lengthwise to accommodate a large test section. This large test section size was chosen to be 21 x 19 feet high full scale. Figure 1 shows the relative proportions. The large test section then follows a contraction ratio of 2.22 and the model 8 x 12 test section has a contraction ratio of 4.31. The model 21 x 19 test section is 60 feet long full scale, and uses 15 feet for its contraction. It expands 2.0 in. total in 60 feet distributed on all four sides to correct for the calculated displacement thickness of a turbulent boundary layer. Atmospheric slots are provided in two side walls of the 21 x 19 test section. The atmospheric slots in the model 8 x 12 test section were closed when the large test section extension was added. Photo II shows the model tunnel with its 21 x 19 test section added.

A maximum dynamic pressure obtained so far in the model 8 x 12 test section is 110 psf (about 208 mph) at a propeller speed of 7000 rpm.

2. Flow Survey Probes

A small stiff probe was constructed to measure flow angles in the model 8 x 12 test section. The probe consists of four (4) hypodermic needles cut at 45° and one (1) at 90° to the center line, bundled together to form a probe similar to a Prandtl tube. This probe was calibrated in the full scale tunnel because of its non-standard tip shape. See Figure 2 for the probe calibration curve and a sketch of the probe. The probe is inserted into the model 8 x 12 test section through a slot provided in the ceiling. A "checkerboard" panel attached to the model tunnel locates the probe in the test section at predetermined locations corresponding to those surveyed in the full scale tunnel. See Photo III.

Another probe, a standard Prandtl tube, was constructed to survey flow angles in the model 21 x 19 test section. The stem of this probe extends from the ceiling to the floor of the model test section. Since this is a standard Prandtl tube, the calibration curve for the UWAL No. 1 probe was used to reduce the data obtained by this probe. See Photo IV. Because the velocity in the 21 x 19 test section is low, the probe is connected to a manometer inclined at 10° from the horizontal plane.

3. Location of Survey Points

The model 8 x 12 test section was surveyed for upflow, crossflow and dynamic pressure in the vertical plane of the balance trunnion at 7 different vertical levels at 11 different east and west direction points covering an area of 75% of the height and 70% of the width of the 8 x 12 test section.

The model 21 x 19 test section is provided with five (5) vertical survey planes which are at 10 foot full scale intervals along the test section. The probe can be located at any vertical station at predetermined east and west locations. Upflow, crossflow and dynamic pressure were surveyed at 7 different vertical levels at 7 different east and west points at stations 1, 3, and 5 covering a volume of 88% of the height, 67% of the length and 80% of the width of the 21 x 19 - 60 foot long full scale test section.

III. Testing Procedure

The validity of the basic model tunnel was first verified by confirming the correlation of upflow, crossflow and dynamic pressure distribution between the model and full scale 8 x 12 test sections with the tunnel in its original unmodified configuration. The repeatability of the flow pattern in the model 8 x 12 test section was also confirmed.

The second group of runs were made after installing the 60 foot long 21 x 19 test section. The first flow survey in the 21 x 19 test section was conducted without any modification to the basic portion of the model wind tunnel. Upflow, crossflow and dynamic pressure were measured by using the Prandtl tube described in the previous chapter and an inclined manometer. Development work was carried out as necessary to produce acceptable flow quality in the 21 x 19 test section. A complete flow survey in the V/STOL test section was conducted when the final improved flow pattern was established.

Upon completion of the flow survey in the 21 x 19 test section, it was necessary to investigate any changes in the flow pattern in the 8 x 12 test section due to the addition of the V/STOL test section. A survey of upflow, crossflow and dynamic pressure in the model 8 x 12 test section was again conducted and the results were compared with the data previously obtained.

IV. Results and Discussion

A measure of power required to operate the model tunnel with and without the 21 x 19 test section is shown in Figure 3. This figure shows the operating angle of attack of the propeller blades for a given condition of the tunnel configuration. With the addition of the large test section, the angle of attack was reduced indicating a reduction in the power required. This power reduction is attributable to the fact that the velocity at the bellmouth turning vanes is lower than the original tunnel configuration by a factor of 0.65 which reduces the corner loss. It therefore can be concluded that the amount of reduction in the corner loss due to the lower velocity is greater than the additional friction loss due to the 75 foot length extension. Thus it can also be concluded that the maximum velocity obtainable in the 8 x 12 test section will not be impaired with the addition of the 75 foot extension.

Results of upflow, crossflow and dynamic pressure surveys in the unmodified model 8 x 12 test section are compared with those of the full scale tunnel to evaluate the degree of flow similarity between the two test sections. Results of upflow surveys are compared and presented in Figure 4. The general pattern of upflow angularities in the full scale 8 x 12 test section is reproduced amazingly well in the unmodified model tunnel

8 x 12 test section as shown in the figure.

Results of crossflow surveys which are presented in Figure 5 also show a surprisingly good correlation between the unmodified model and full scale 8 x 12 test sections. There are no significant discrepancies in the crossflow angularities between the two test sections.

Dynamic pressure distribution was surveyed in the same vertical plane where the upflow and crossflow were surveyed. The results of this survey are presented in Figure 6 which shows a comparison of the dynamic pressure distribution between the unmodified model and full scale 8 x 12 test sections. The measured dynamic pressure for each survey point was divided by the tunnel indicated dynamic pressure. The data presented in Figure 6 shows a difference in the absolute values of the dynamic pressure ratio between the model and full scale 8 x 12 test sections. The discrepancy is due to the fact that the location of the reference dynamic pressure source relative to the model tunnel is different from that of the full scale tunnel. Thus the measured reference dynamic pressure is not exactly the same as that of the full scale tunnel. It also should be noted that no correction was made in the model tunnel 8 x 12 test section for the boundary layer growth. The primary interest of the results shown in Figure 6 is the flatness of each curve which indicates a balanced velocity distribution in the plane where the survey was made in the test section. Results presented in these Figures 4, 5, and 6, indicate that the flow in the model 8 x 12 test section is truly a good reproduction of the flow in the full scale 8 x 12 test section.

With the addition of the 21 x 19 test section to the basic model tunnel, another complete survey of upflow, crossflow and dynamic pressure in the model 8 x 12 test section was conducted, and presented again in Figures 4, 5, and 6, respectively. The changes in crossflow angularities are insignificant, and virtually no change appears in upflow angularities and dynamic pressure distribution. Results of flow angularity surveys in the 21 x 19 test section without any modification to the tunnel are shown in Figures 7, 8, and 9. These flow patterns for the original configuration of the 21 x 19 test section have quite large local flow angles. Dynamic pressure distribution shown in Figures 10, 11, and 12 indicated that the velocity is generally higher at the east side of the test section than the west. The immediate object of the model tunnel then was to reduce the magnitude of the flow angularity and to obtain an evenly distributed dynamic pressure in the 21 x 19 test section.

A series of runs was made to investigate the cause of the large flow angularity in the V/STOL test section. These runs consisted of finding the effects of vortex generators in the diffuser, propeller blade angle reduction, angle of incidence of the propeller anti-swirl vanes, and the adjustment of the bellmouth turning vanes. None of these methods resulted in an appreciable improvement of the flow pattern in the 21 x 19 test section, but it was discovered during the investigation that the west return passage had more drag than the east. An extensive search for the extra drag in the west return duct was conducted but ended fruitless. Therefore in order to expedite the attainment of a high quality flow in the 21 x 19 test section, it was concluded to add more drag in the east return duct thereby obtaining somewhat better ballanced drag between the two return passages. This was accomplished by installing a layer of an ordinary household insect screen at the downstream end of the east return duct. With the screen in the return duct, the adjustment of the bellmouth turning vanes was found to be effective in controlling the flow pattern in the 21 x 19 test section.

The final flow pattern in the 21 x 19 test section was obtained by adjusting the bellmouth turning vanes, and presented in the plastic overlay form in Figures 7, 8, and 9. A considerable improvement of the flow angularities in the V/STOL test section can be clearly seen in these figures. Dynamic pressure distribution in the test section was also significantly improved and shown in Figures 10, 11, and 12.

During the aforementioned investigation of the large flow angularity source, the angle of incidence of the propeller anti-swirl vanes proved to have a sensitive effect on the velocity profile in the return ducts. The total head profile in each return duct was measured and the effect of the adjustment of the swirl vane angle of incidence is shown in Figures 13 and 14.

The effect of the 21 x 19 - 60 foot test section on the flow angularity in the 8 x 12 test section is virtually none as shown in Figures 4 and 5. The dynamic pressure distribution in the 8 x 12 test section was also found to be unchanged as presented in Figure 6. This fulfills one of the basic requirements that the present excellent aerodynamic quality in the 8 x 12 test section shall not be degraded.

V. Conclusions

Wind tunnel testing of V/STOL aircraft models with a large downwash angles necessitates a large test section in order to obtain a small ratio of the model to test section size to minimize the tunnel wall interference. Feasibility of adding such a large test section to the present UWAL wind tunnel was experimentally investigated by using a 1/8 scale model of the present 8 x 12 wind tunnel.

Evaluating the results obtained from the model tunnel, it is concluded that:

1. It is feasible to add a 21 x 19 - 60 foot long test section without degrading the present excellent aerodynamic quality of the 8 x 12 test section.
2. Flow angularity in the 21 x 19 test section is controllable by adjusting the bellmouth turning vanes.
3. There will be no additional power required to operate the above investigated configuration of the two-test-section UWAL wind tunnel.

The present configuration of the model tunnel has a 75 foot full scale length extension of which 15 feet is used for the contraction. The minimum length required to establish a good aerodynamic environment in the V/STOL test section has not yet been determined, but work is continuing with this objective.

REFERENCES

1. Robert G. Joppa, V/STOL Wind Tunnel Testing and UWAL Facilities, UWAL Report No. 744, 1962.

2. Robert G. Joppa and Victor M. Ganzer, An Aerodynamic Feasibility Study of Two-Test Section Wind Tunnels for V/STOL Testing, UWAL Report No. 773, 1964.

3. Ralph B. McCormick, Wind Tunnel Summary Report No. 301-12-1 Total Pressure Loss Survey in the Boeing Wind Tunnel, BWT-Test No.-301.12, 1954.

Photo 1 Basic 8 x 12 Model Tunnel Without Extension

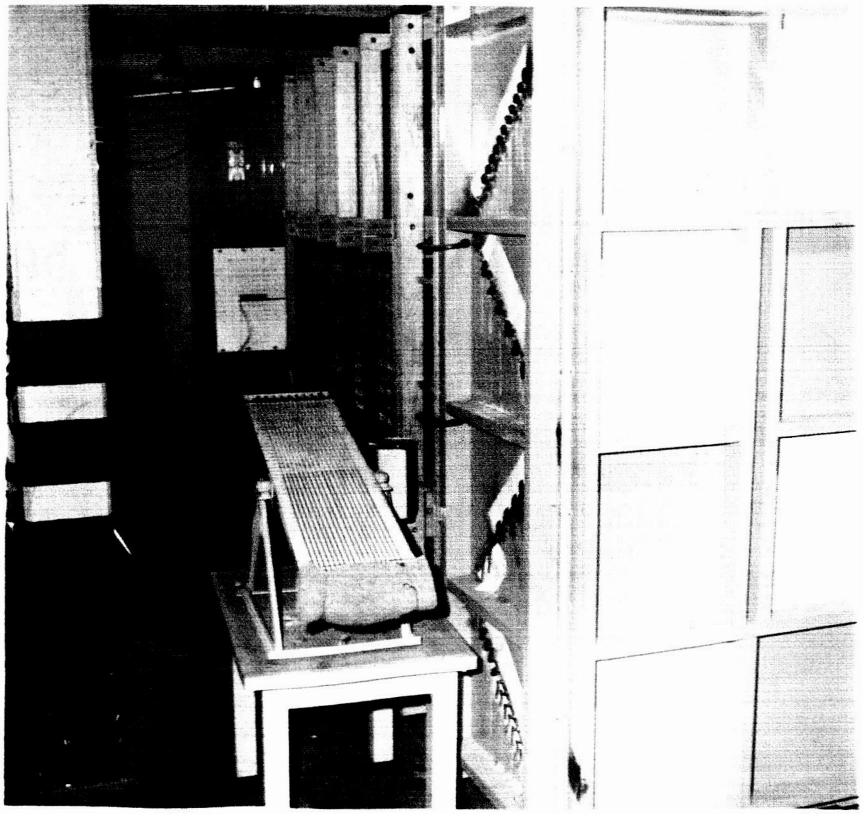


Photo 2 Model Tunnel With 75 Foot Extension Added

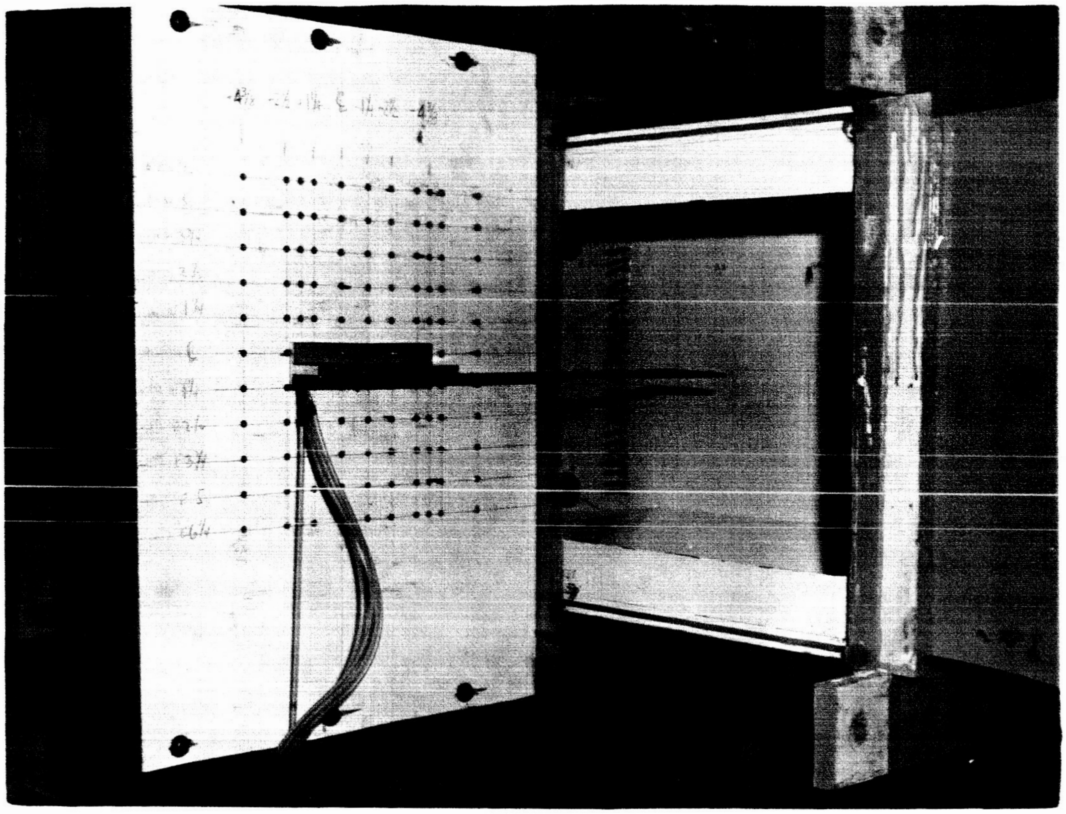


Photo 3 Survey Probe in 8 x 12 Test Section

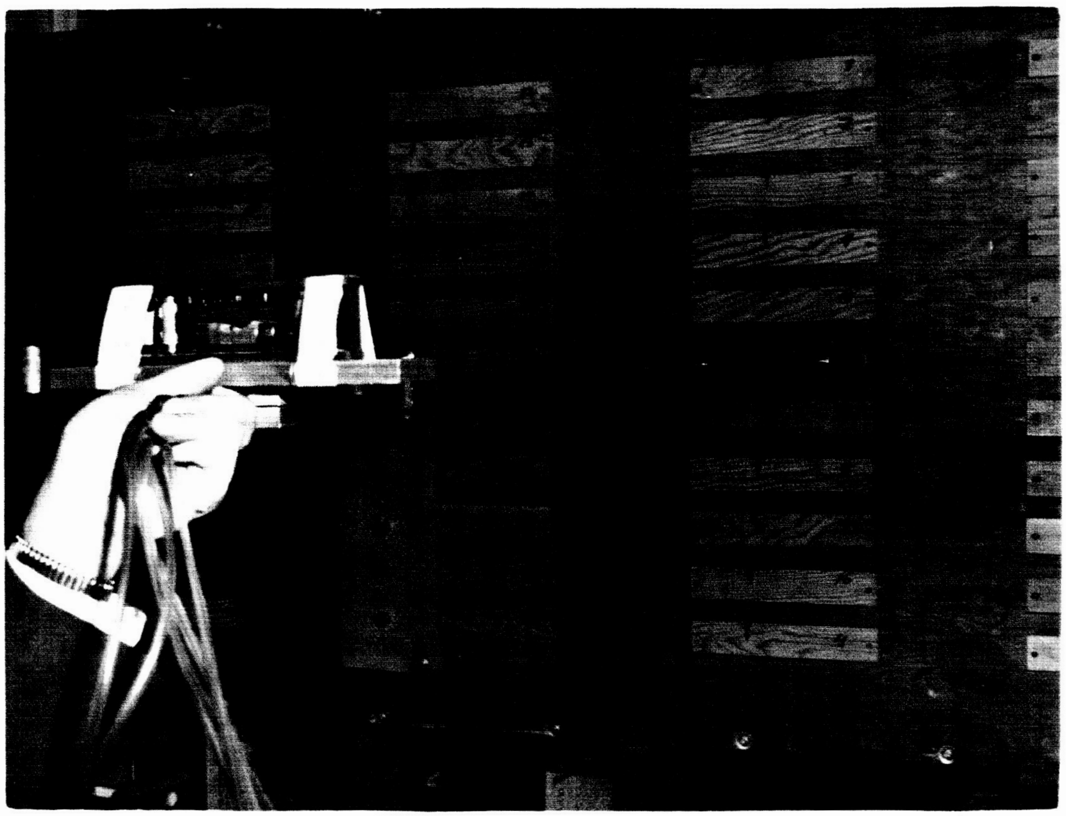
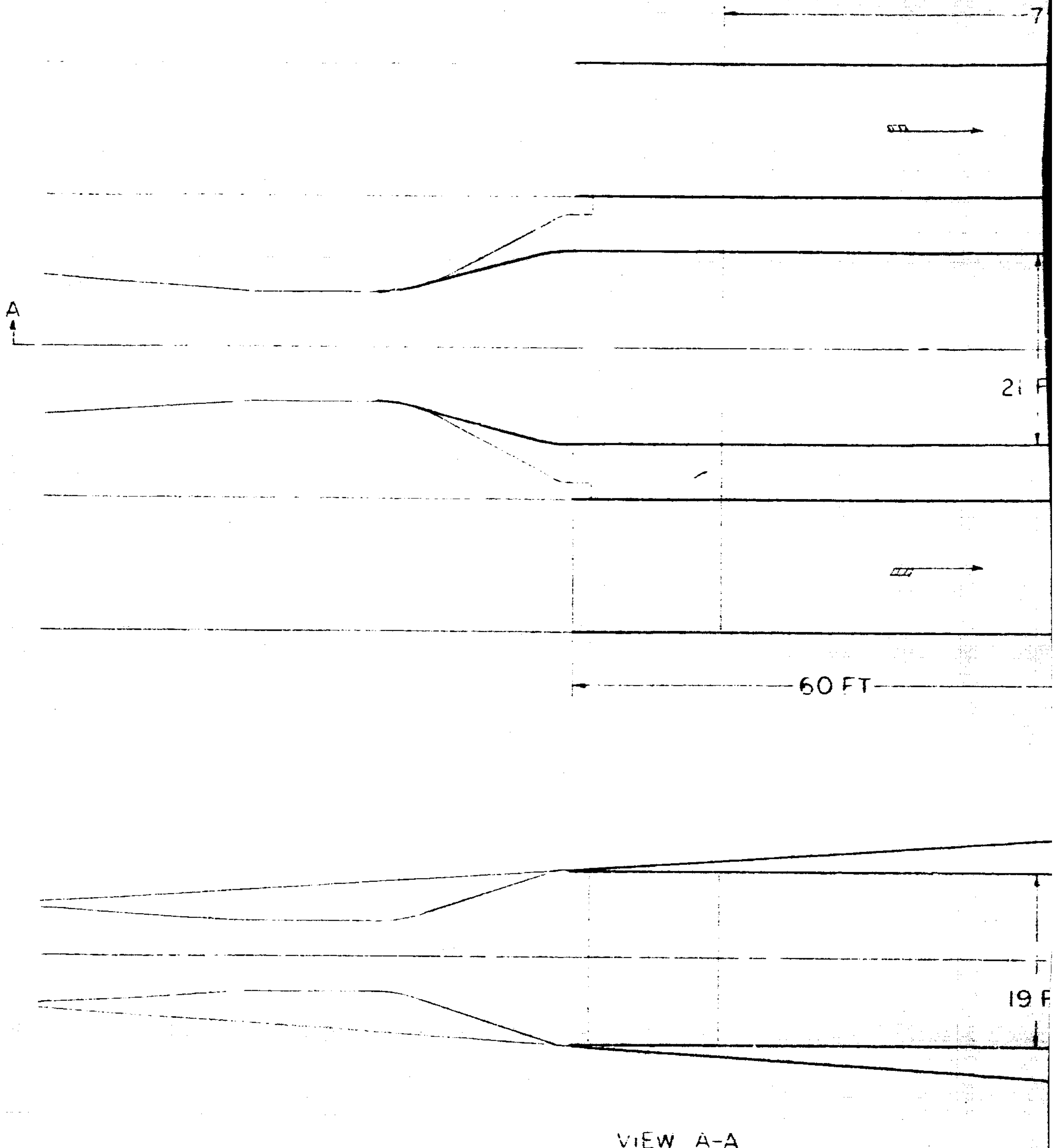
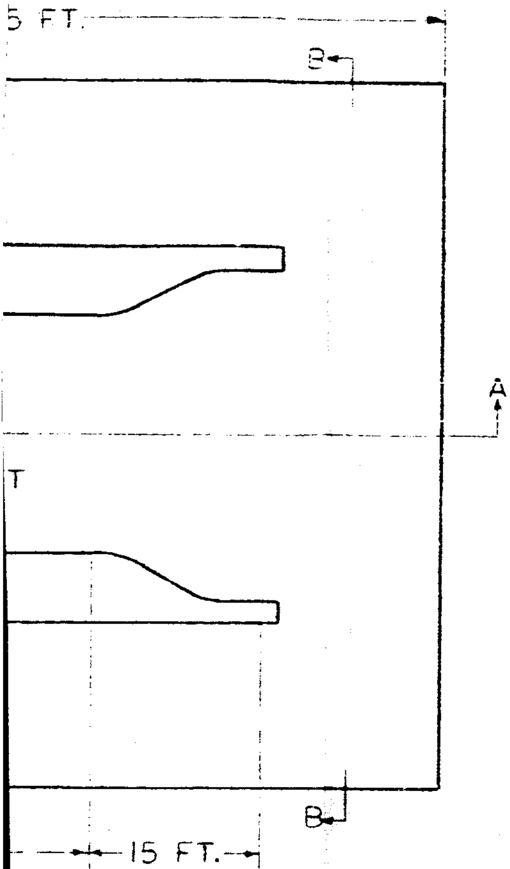


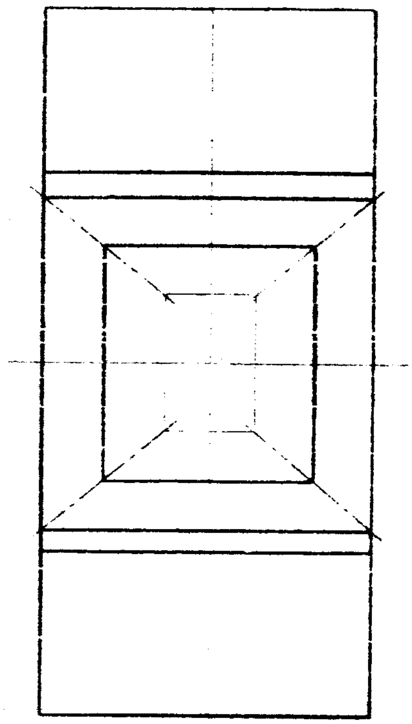
Photo 4 Survey Probe in 21 x 19 Test Section



BASIC DIMENSIONS OF THE

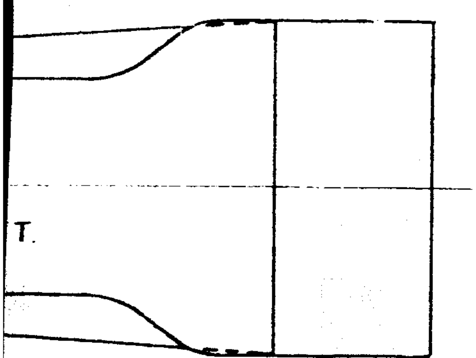
FIG 1





VIEW B-B

LIGHT LINES INDICATE THE EXISTING TUNNEL.
HEAVY LINES INDICATE THE PROPOSED MODIFICATION.



LARGE TEST SECTION

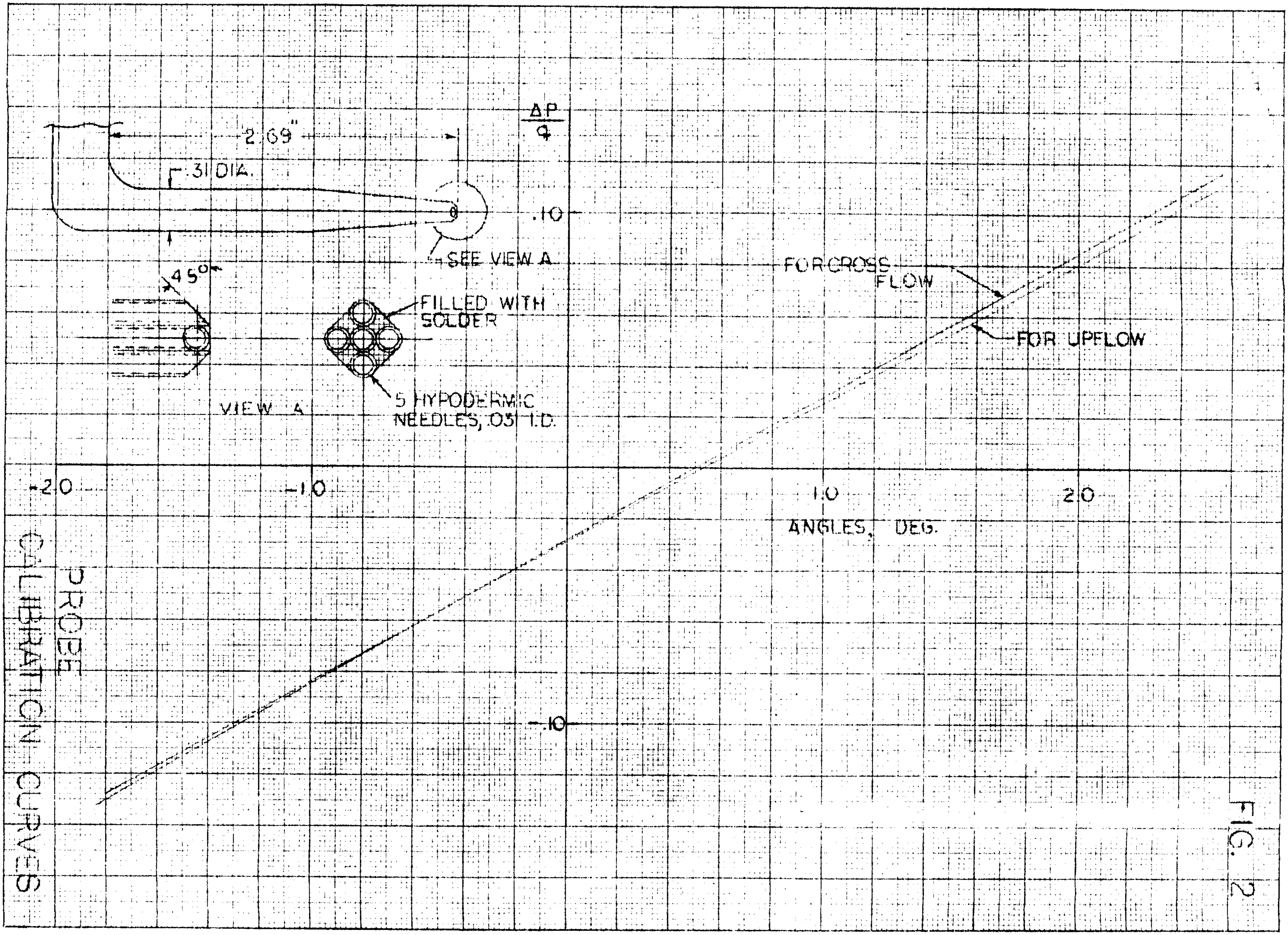
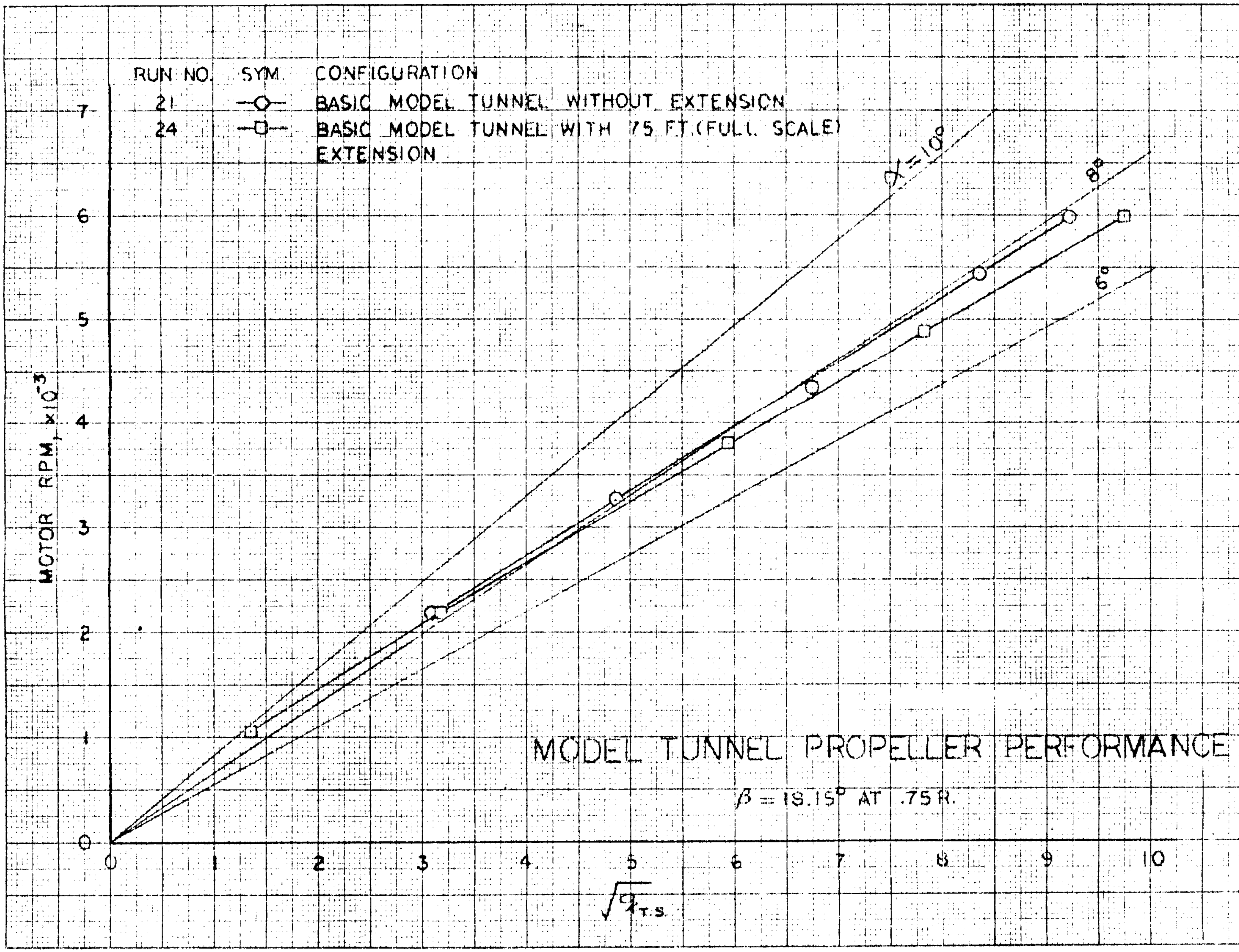


FIG. 2

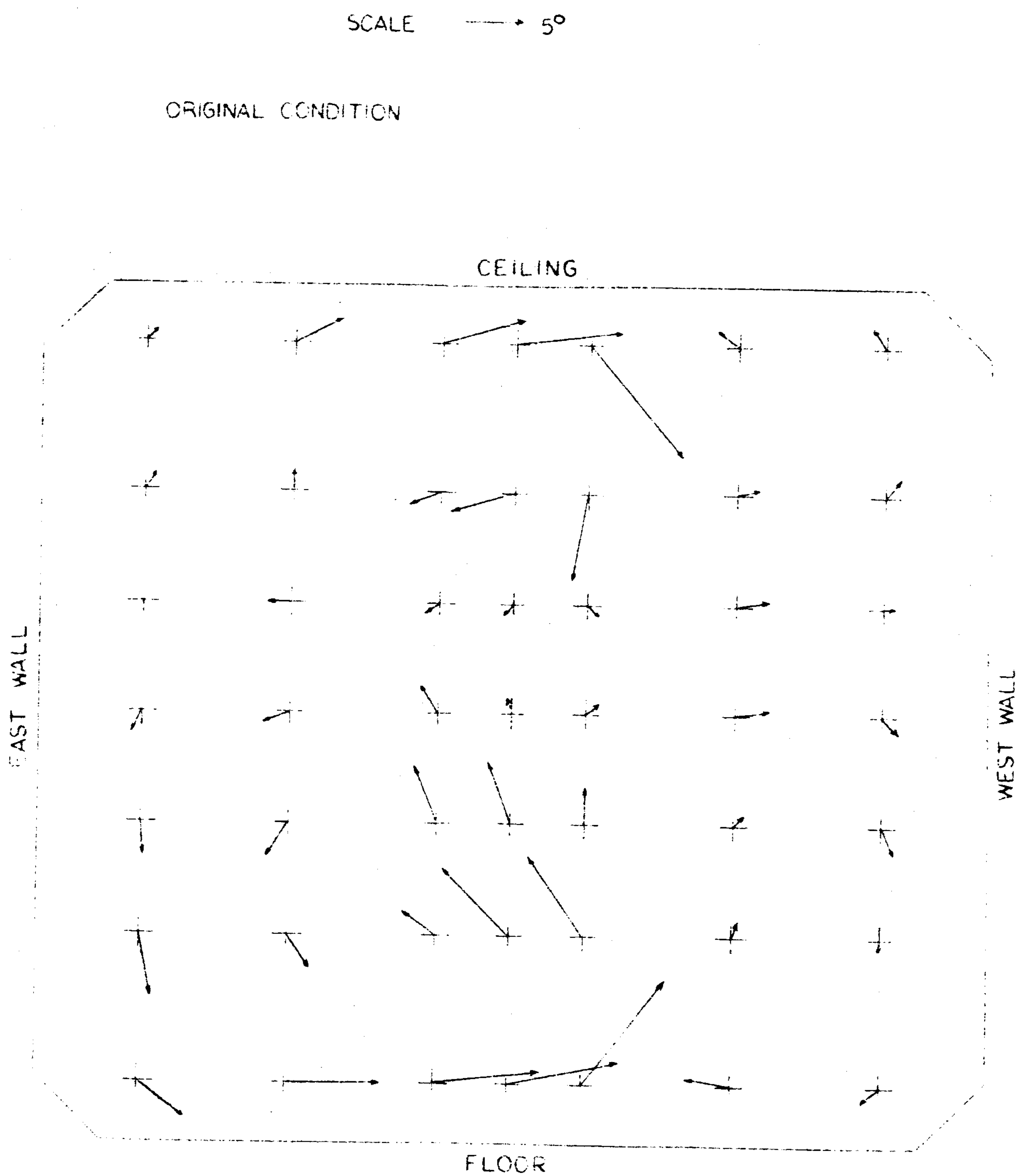
PROBE CALIBRATION CURVES



MODEL TUNNEL PROPELLER PERFORMANCE

FIG. 3

FIG. 7



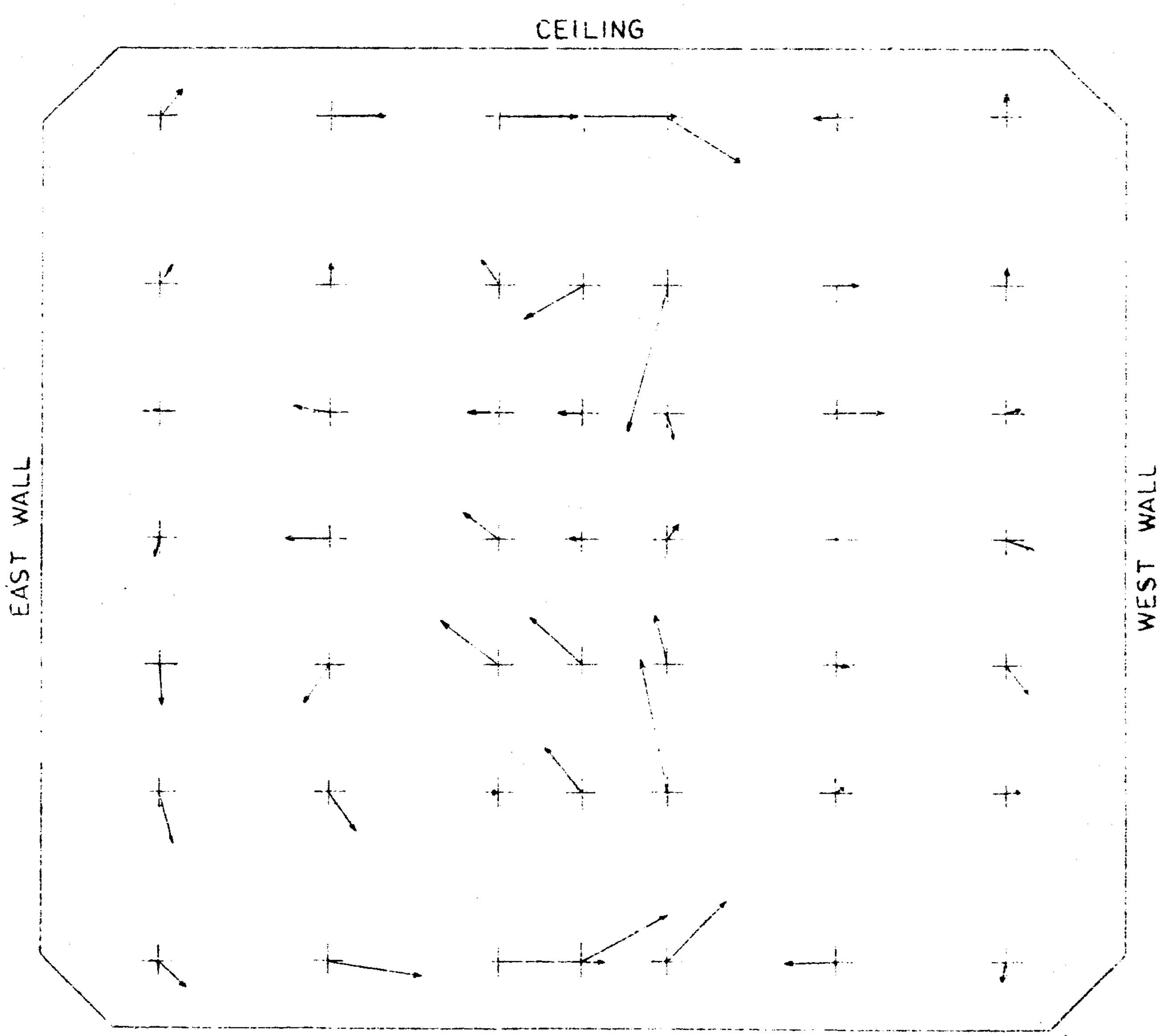
VIEW LOOKING DOWN STREAM IN 21 X 19 TEST SECTION

FLOW ANGLES, STATION 1

FIG. 8

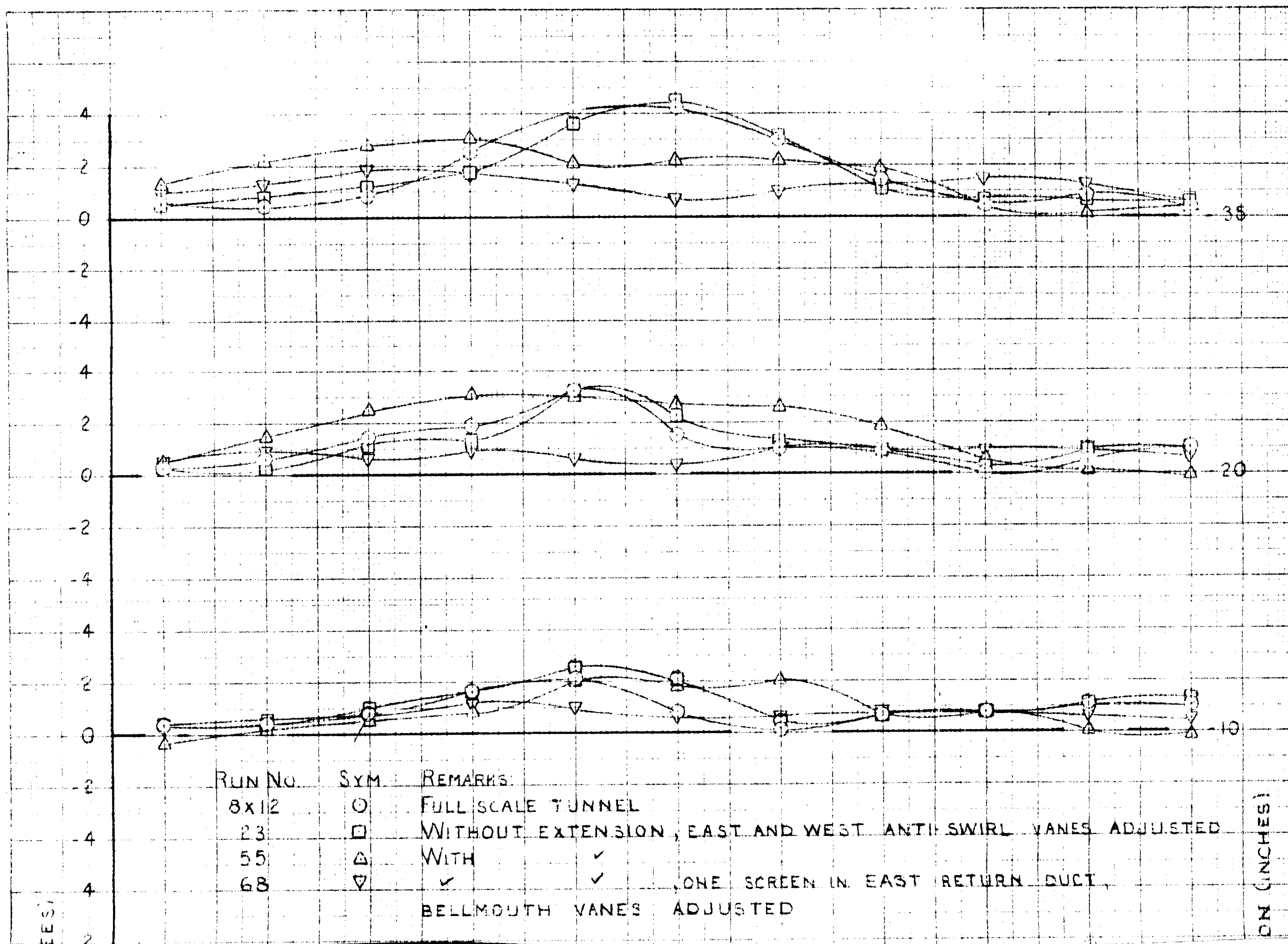
SCALE → 5°

ORIGINAL CONDITION

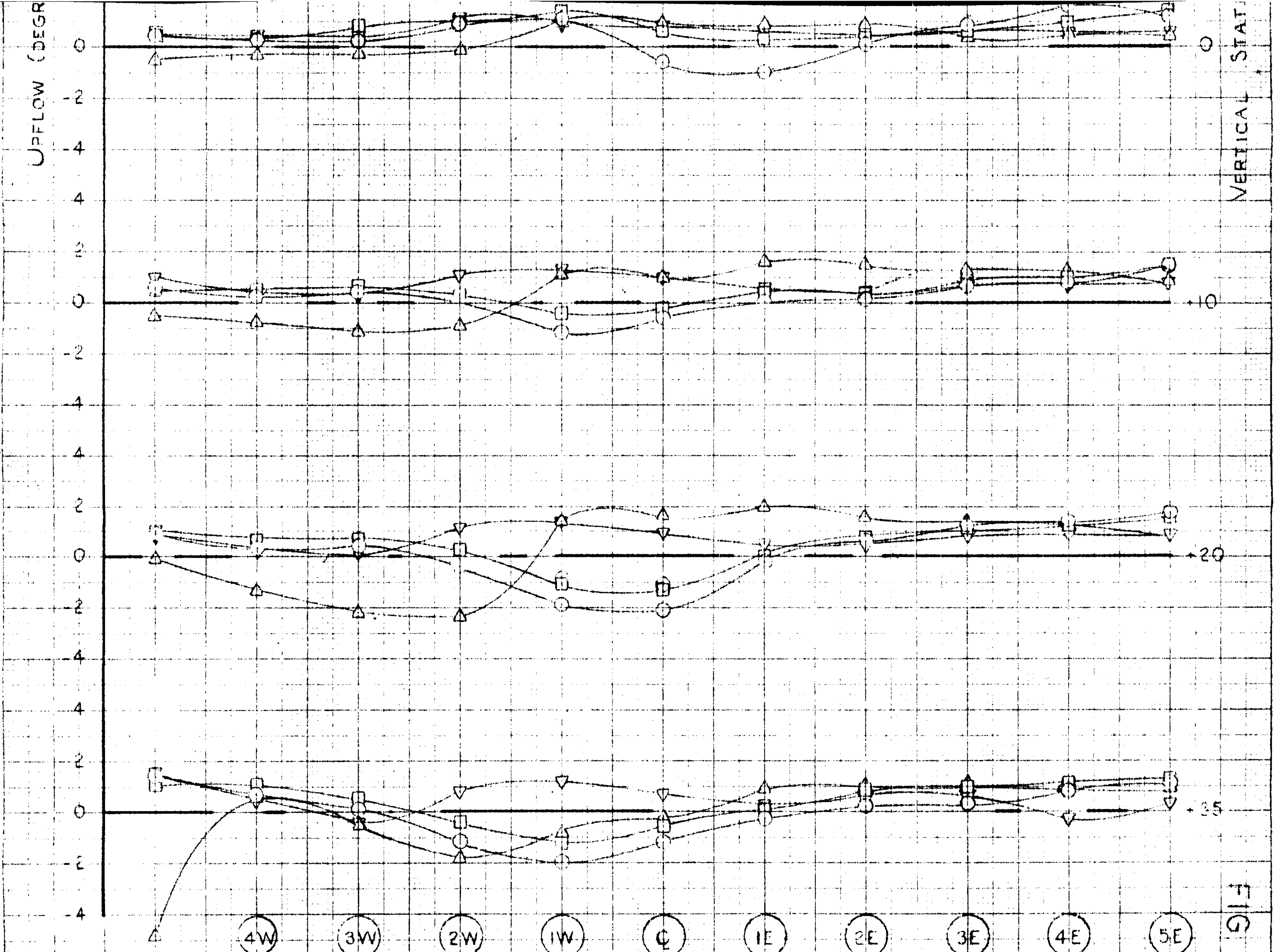


VIEW LOOKING DOWN STREAM
IN 21 X 19 TEST SECTION

FLOW ANGLES, STATION 3

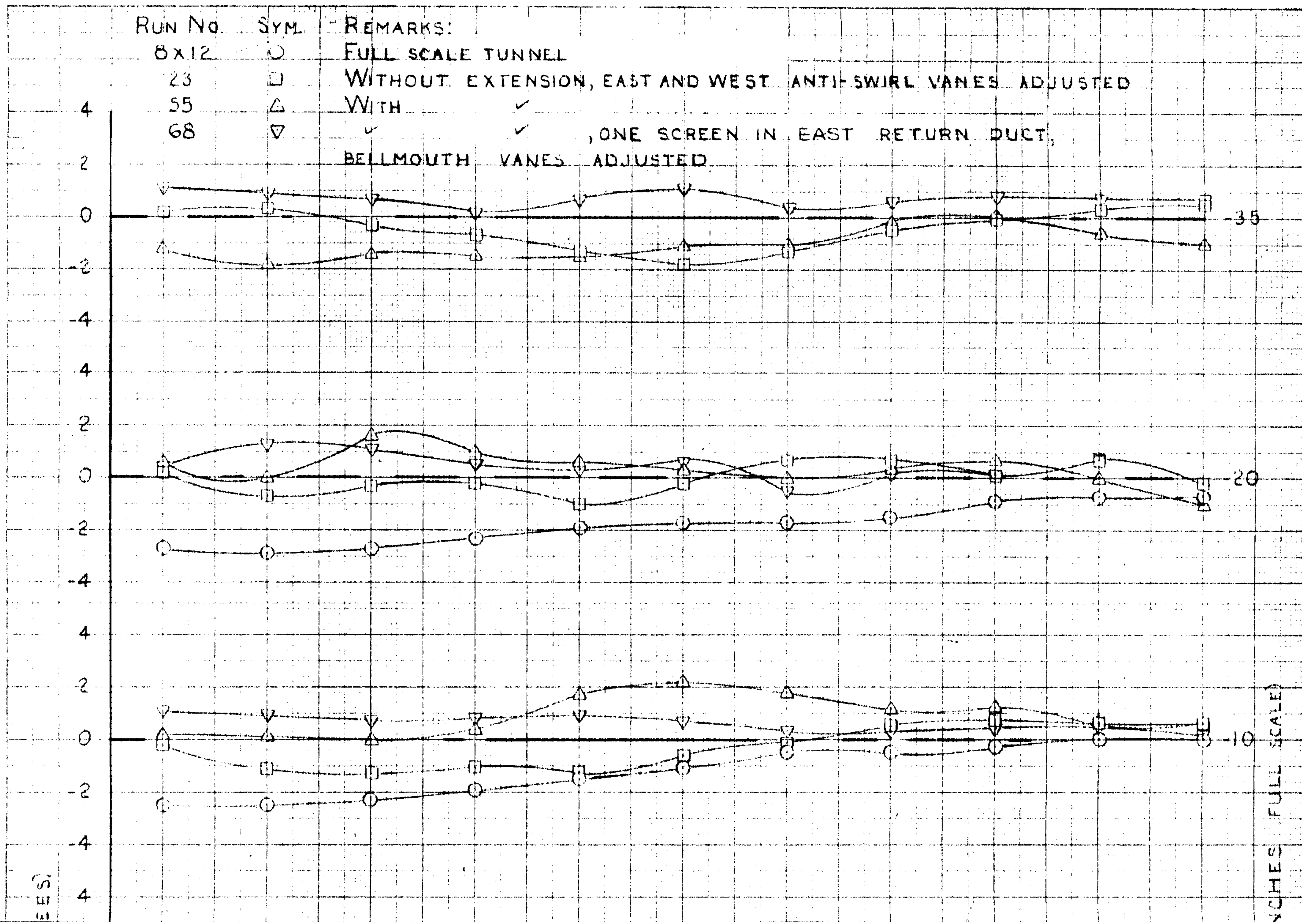


4
2
0
-2
-4
35
20
10
RUN NO. SYM REMARKS:
8x12 ○ FULL SCALE TUNNEL
23 □ WITHOUT EXTENSION, EAST AND WEST ANTI-SWIRL VANES ADJUSTED
55 △ WITH ✓
68 ▽ ✓ ✓ , ONE SCREEN IN EAST RETURN DUCT, BELLMOUTH VANES ADJUSTED
ON (INCHES)
EES)



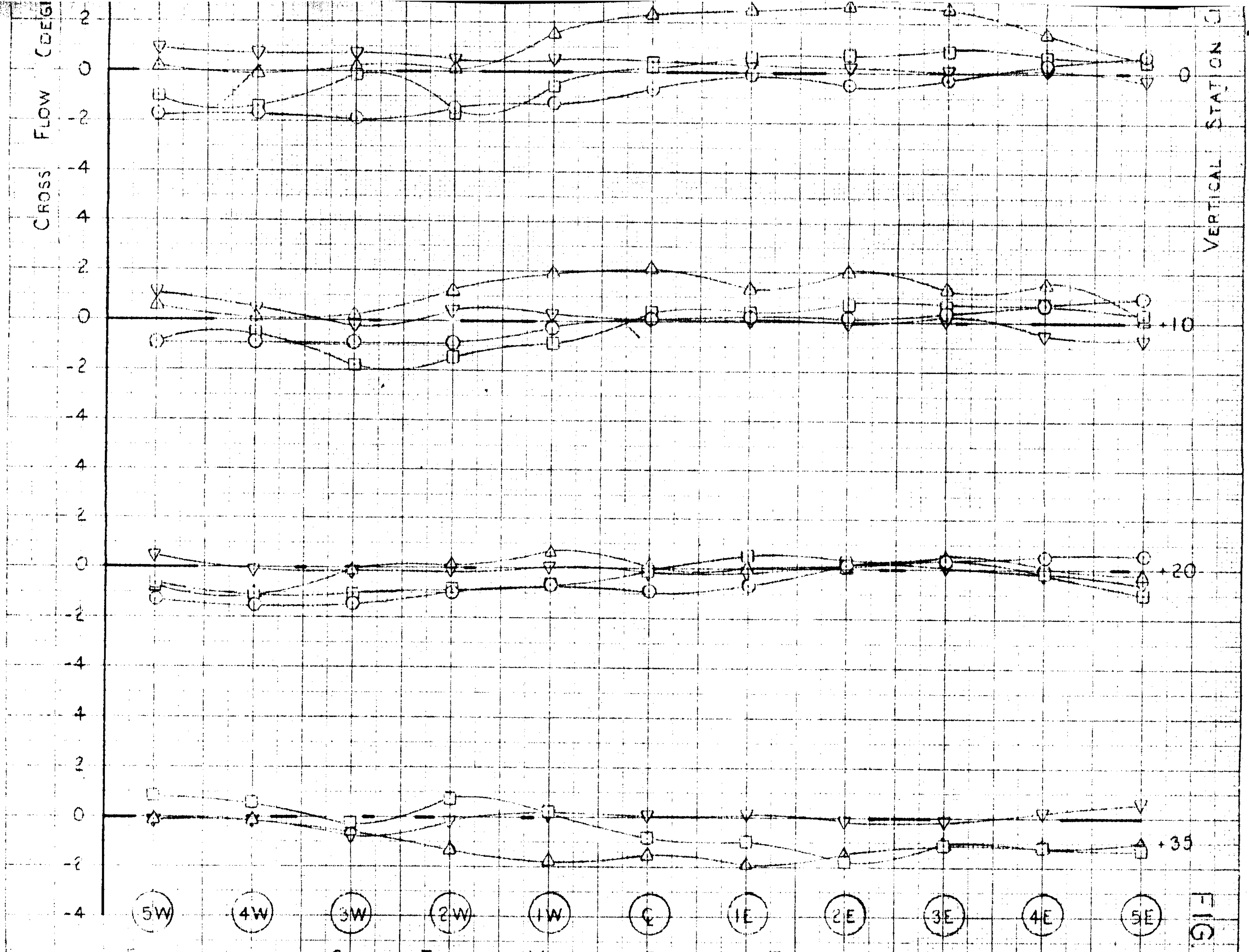
UPFLOW IN VERTICAL PLANE OF TRUNNION
8x12 TEST SECTION

FIG. 4

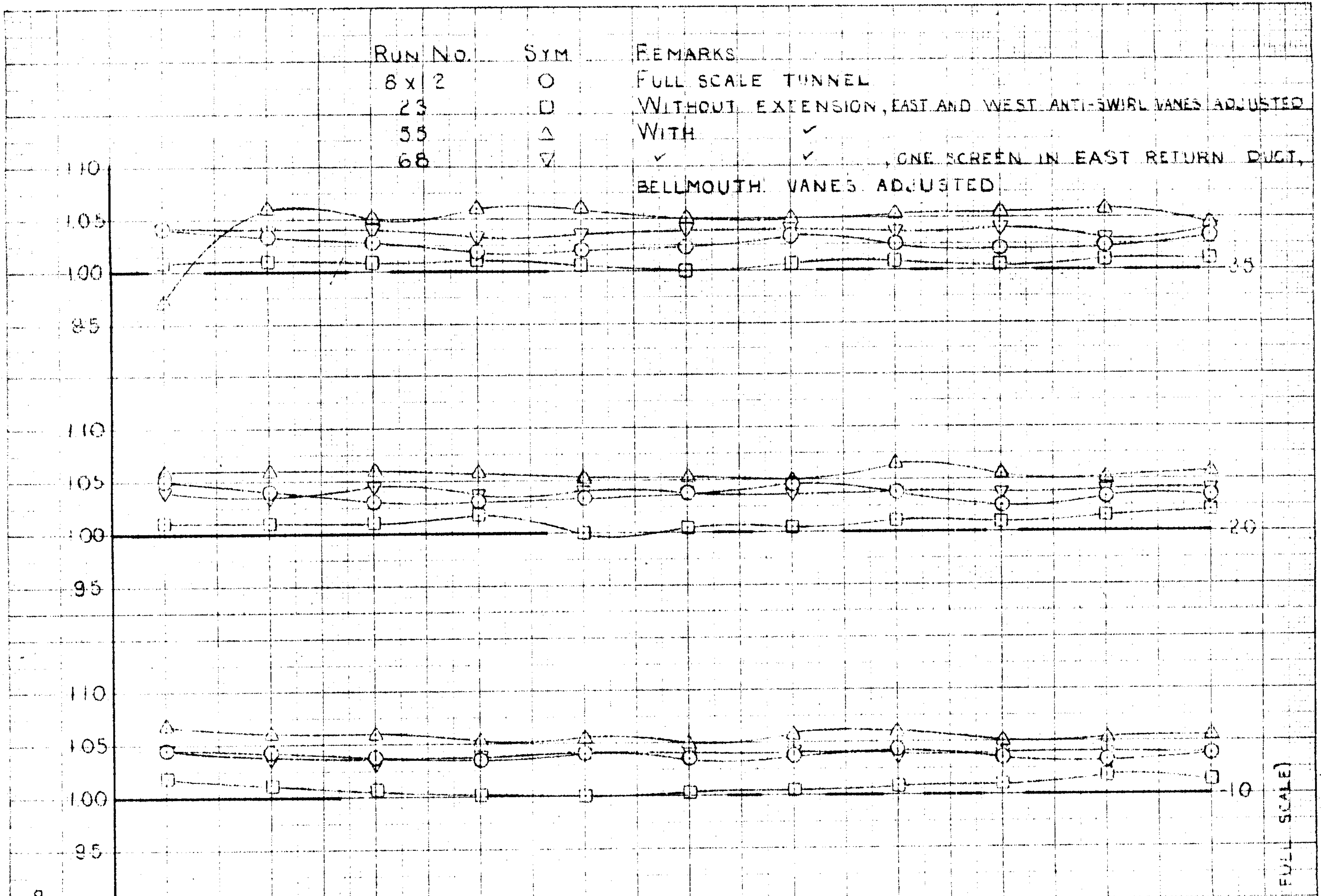

RUN NO. SYM. REMARKS:
8x12 ○ FULL SCALE TUNNEL
23 □ WITHOUT EXTENSION, EAST AND WEST ANTI-SWIRL VANES ADJUSTED
55 △ WITH ✓
68 ▽ ✓ ✓ , ONE SCREEN IN EAST RETURN DUCT, BELLMOUTH VANES ADJUSTED
4
2
0
-2
-4
35
20
10
(INCHES FULL SCALE)

2

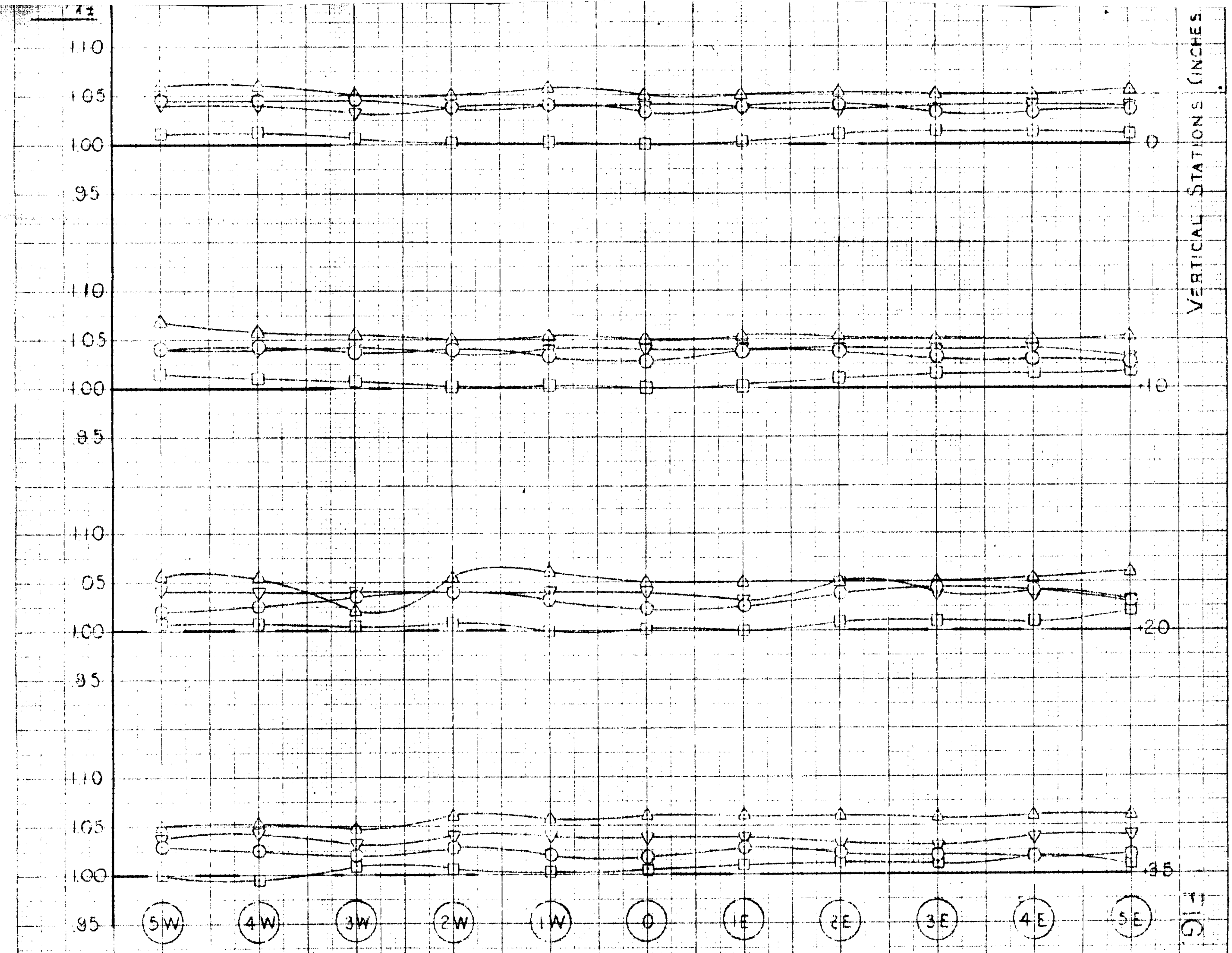
FIG. 5



CROSS FLOW IN VERTICAL PLANE OF TRUNNION
8x12 TEST SECTION



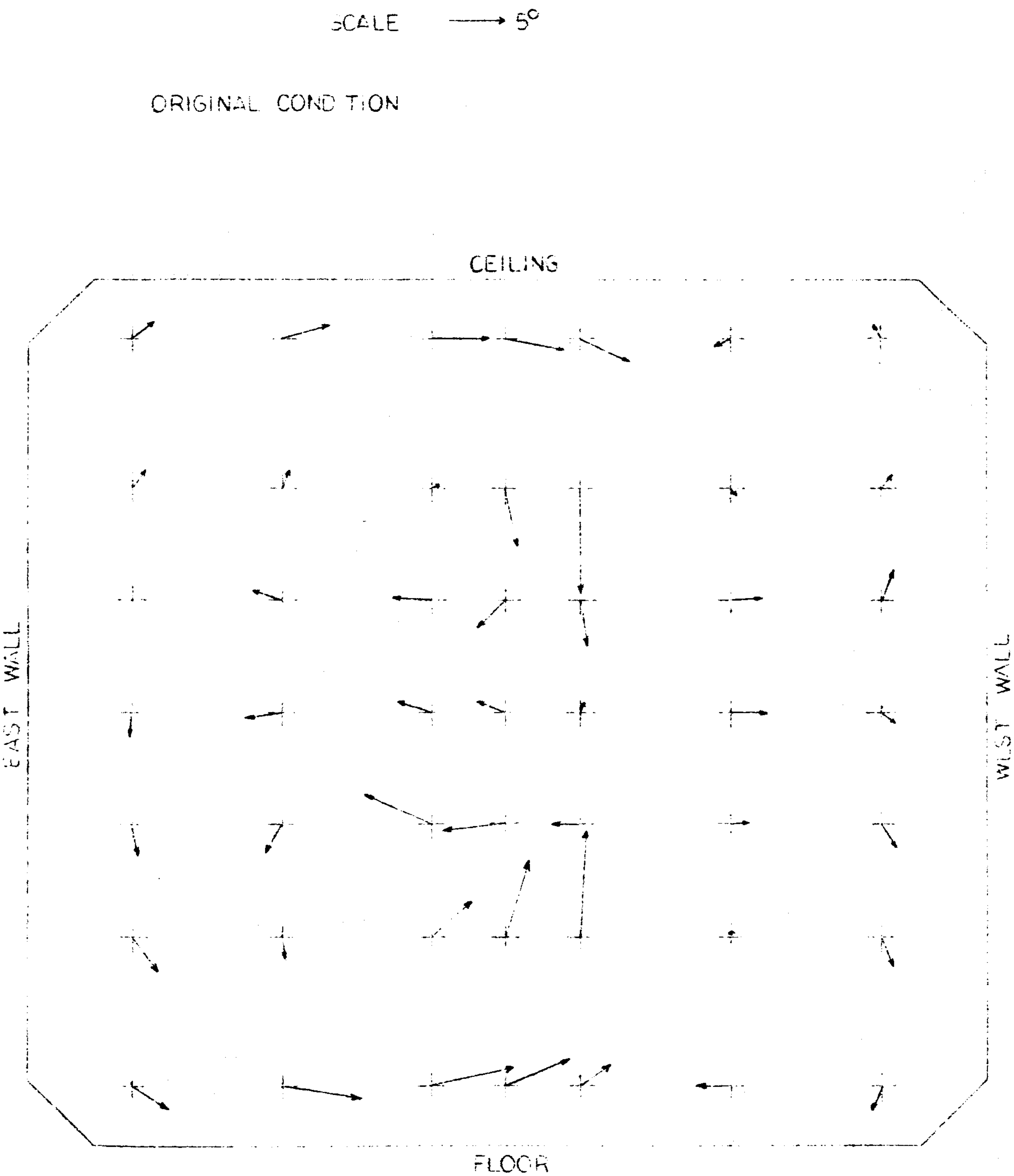
RUN NO. | SYM | REMARKS
8 x 12 | ○ | FULL SCALE TUNNEL
23 | □ | WITHOUT EXTENSION, EAST AND WEST ANTI-SWIRL VANES ADJUSTED
55 | △ | WITH ✓
68 | ▽ | ✓ ✓ , ONE SCREEN IN EAST RETURN DUCT, BELLMOUTH VANES ADJUSTED
1.10
1.05
1.00
.95
-35
-20
-10
FULL SCALE



Dynamic Pressure Distribution in Vertical Plane of Trunnion
8x12 Test Section

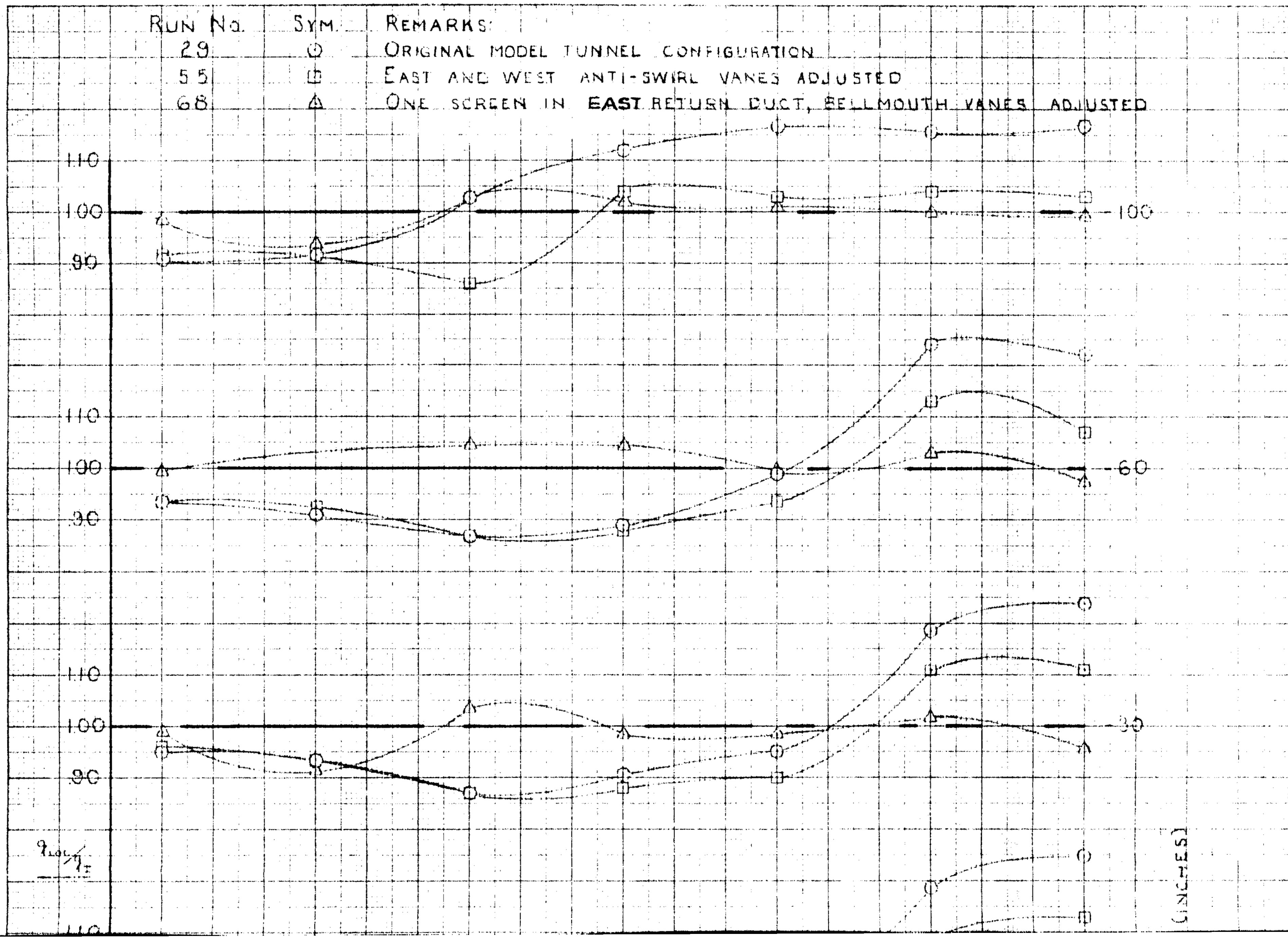
FIG. 6

FIG. 9



VIEW LOOKING DOWN STREAM
IN 21 X 19 TEST SECTION

FLOW ANGLES, STATION 5


RUN No.
29
55
68
SYM.
REMARKS:
ORIGINAL MODEL TUNNEL CONFIGURATION
EAST AND WEST ANTI-SWIRL VANES ADJUSTED
ONE SCREEN IN EAST RETURN DUCT, BELLMOUTH VANES ADJUSTED
110
100
90
100
60
30
(INCHES)

2

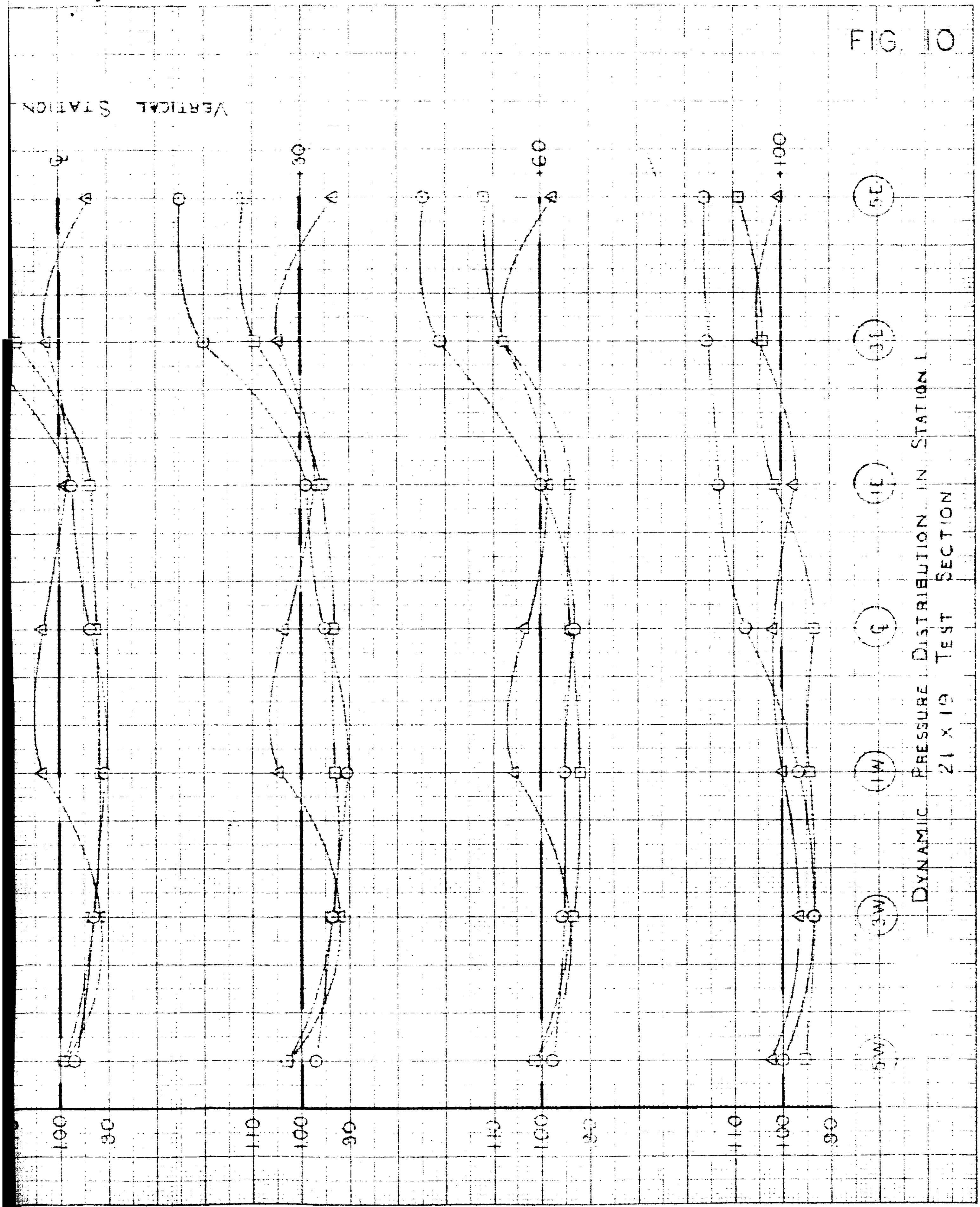
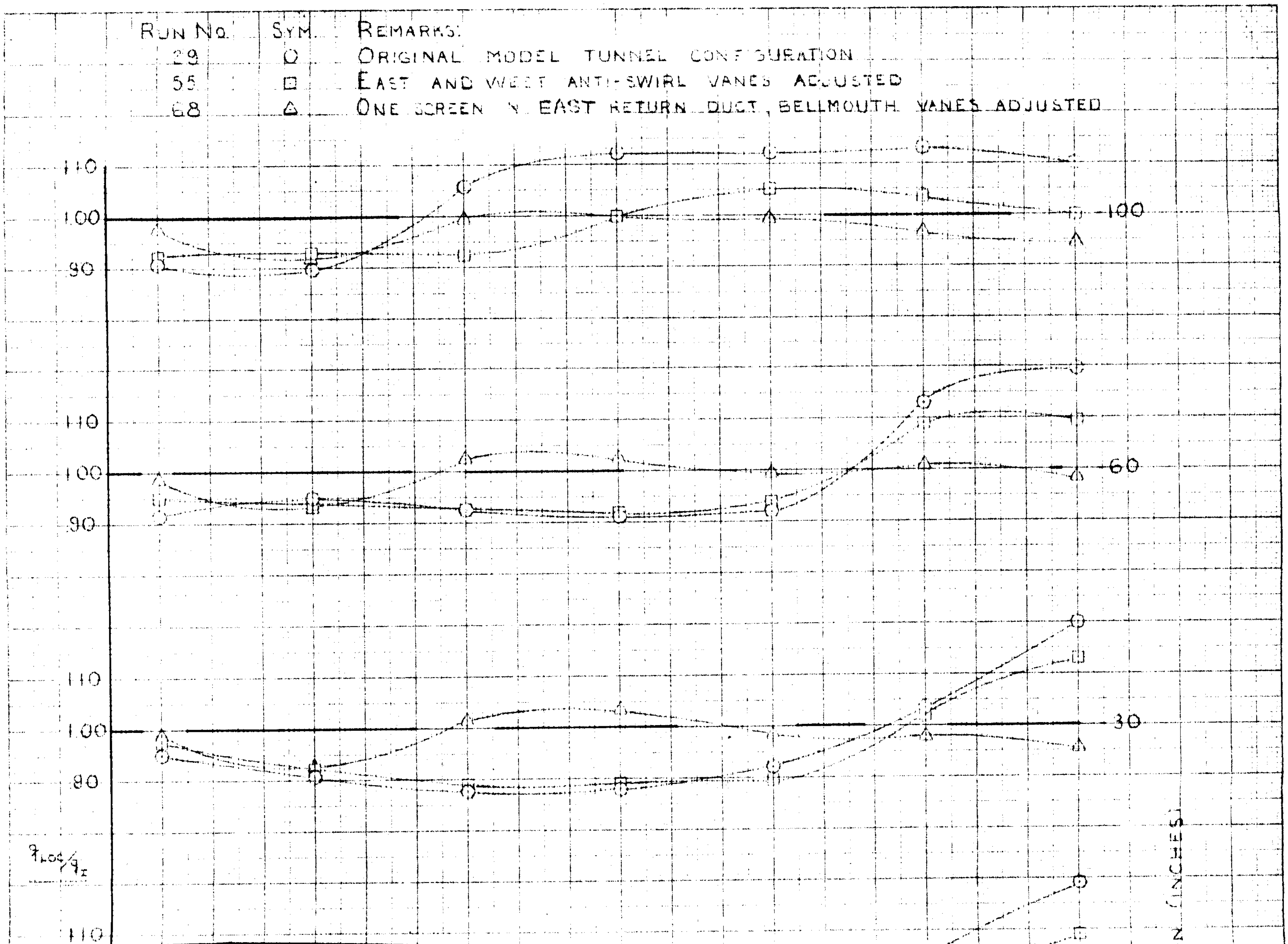


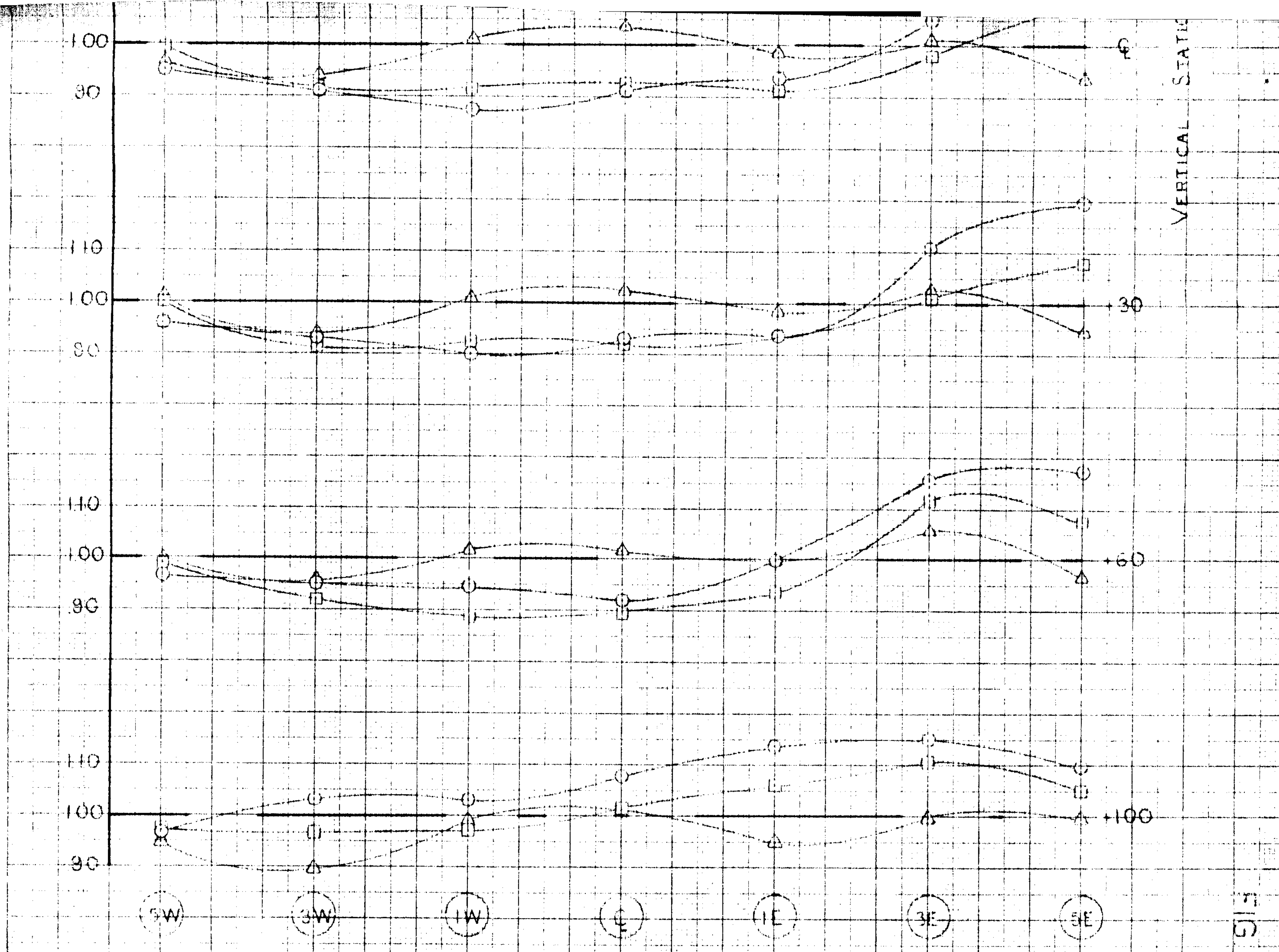
FIG. 10

DYNAMIC PRESSURE DISTRIBUTION IN STATION I
21 x 19 TEST SECTION



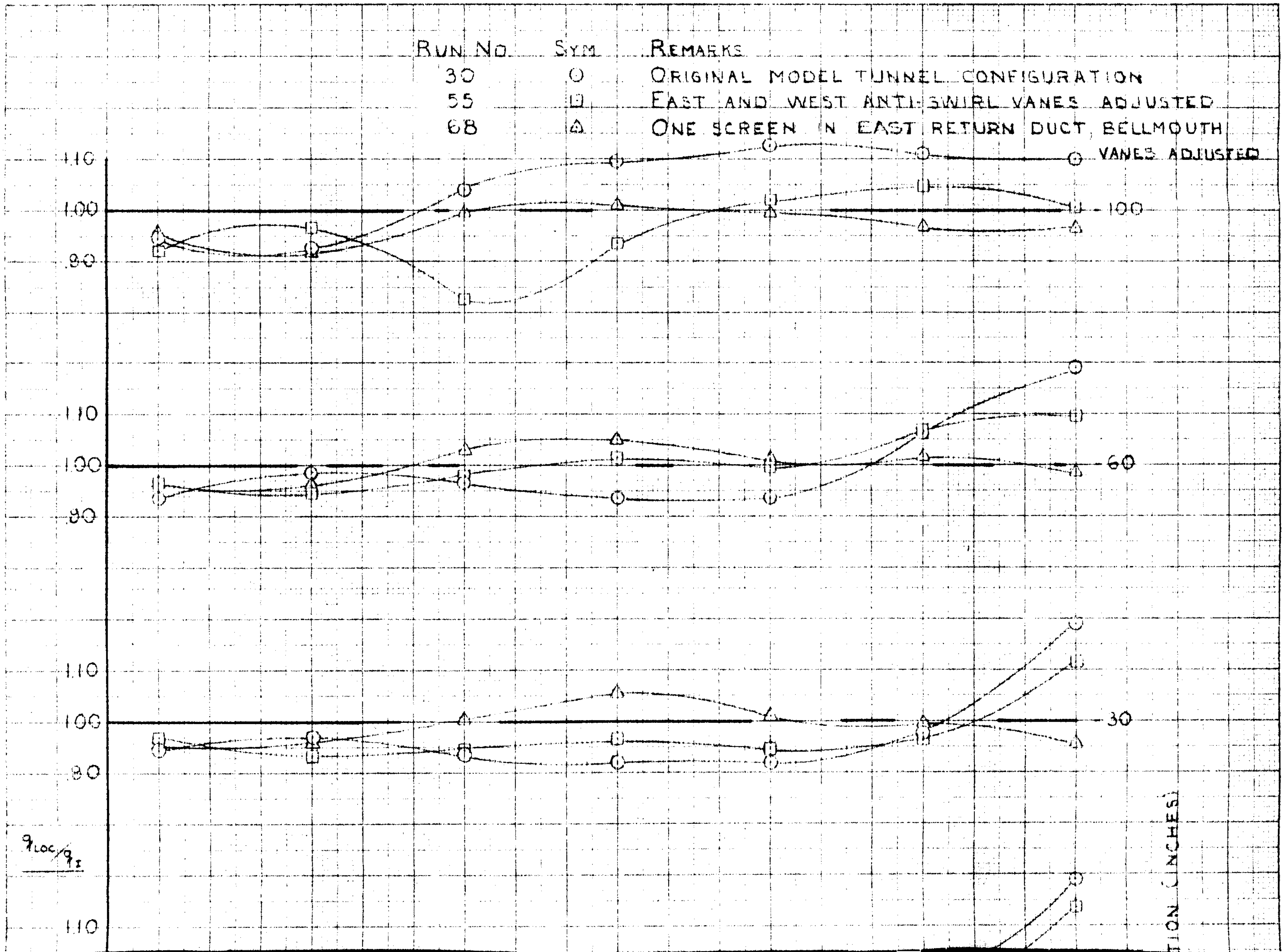
RUN No.
SYM.
REMARKS:
29
ORIGINAL MODEL TUNNEL CONFIGURATION
55
EAST AND WEST ANTI-SWIRL VANES ADJUSTED
68
ONE SCREEN N. EAST RETURN DUCT, BELLMOUTH VANES ADJUSTED
110
1.00
.90
100
60
30
.80
q_Loc/q_I
Z (INCHES)

2



DYNAMIC PRESSURE DISTRIBUTION IN STATION 3
21 x 19 TEST SECTION

FIG. 11



RUN NO. SYM. REMARKS
30 ○ ORIGINAL MODEL TUNNEL CONFIGURATION
55 □ EAST AND WEST ANTI-SWIRL VANES ADJUSTED
68 △ ONE SCREEN IN EAST RETURN DUCT, BELLMOUTH VANES ADJUSTED
1.10
1.00
.90
100
60
30
q_{LOC}/q_I
TION (INCHES)

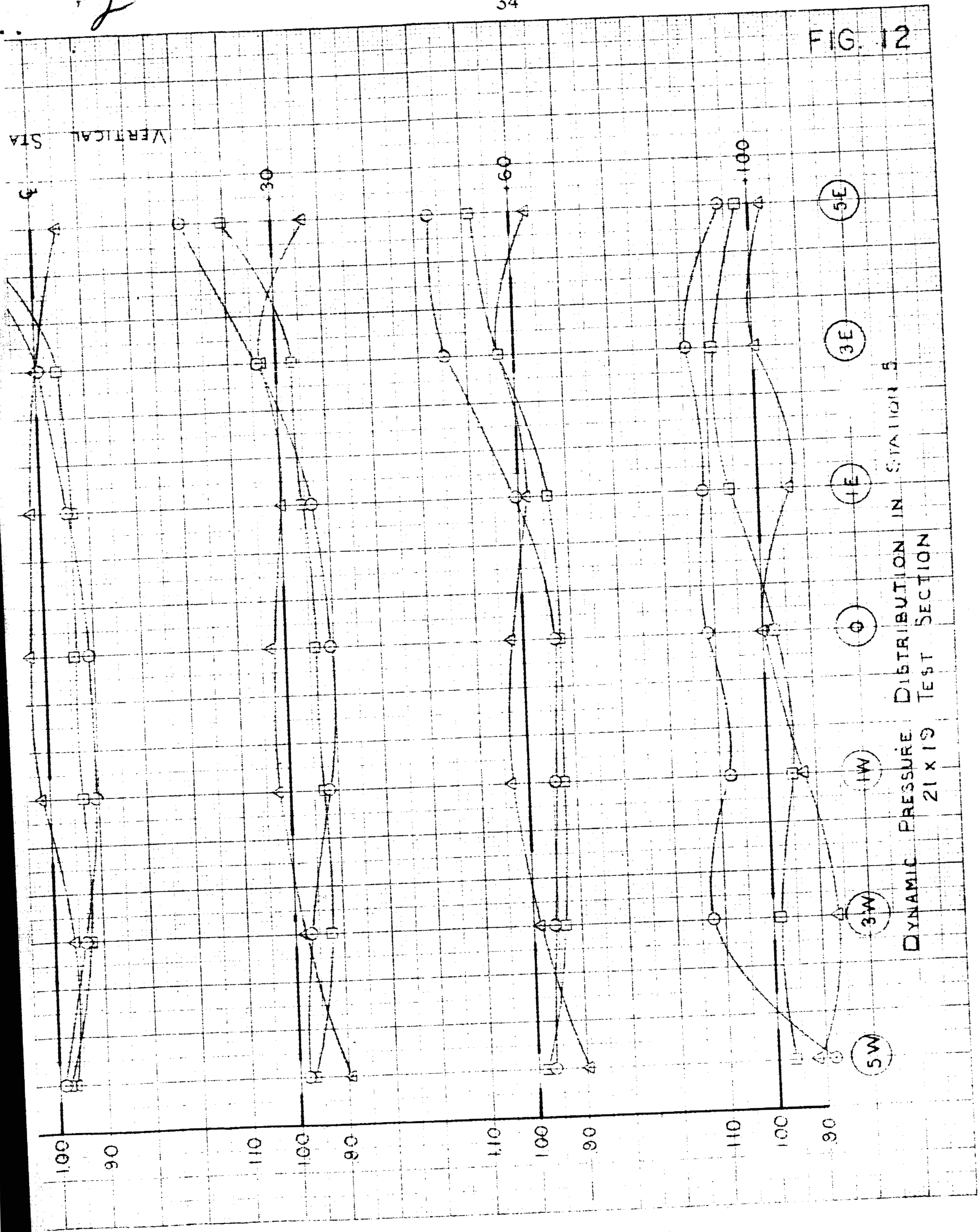
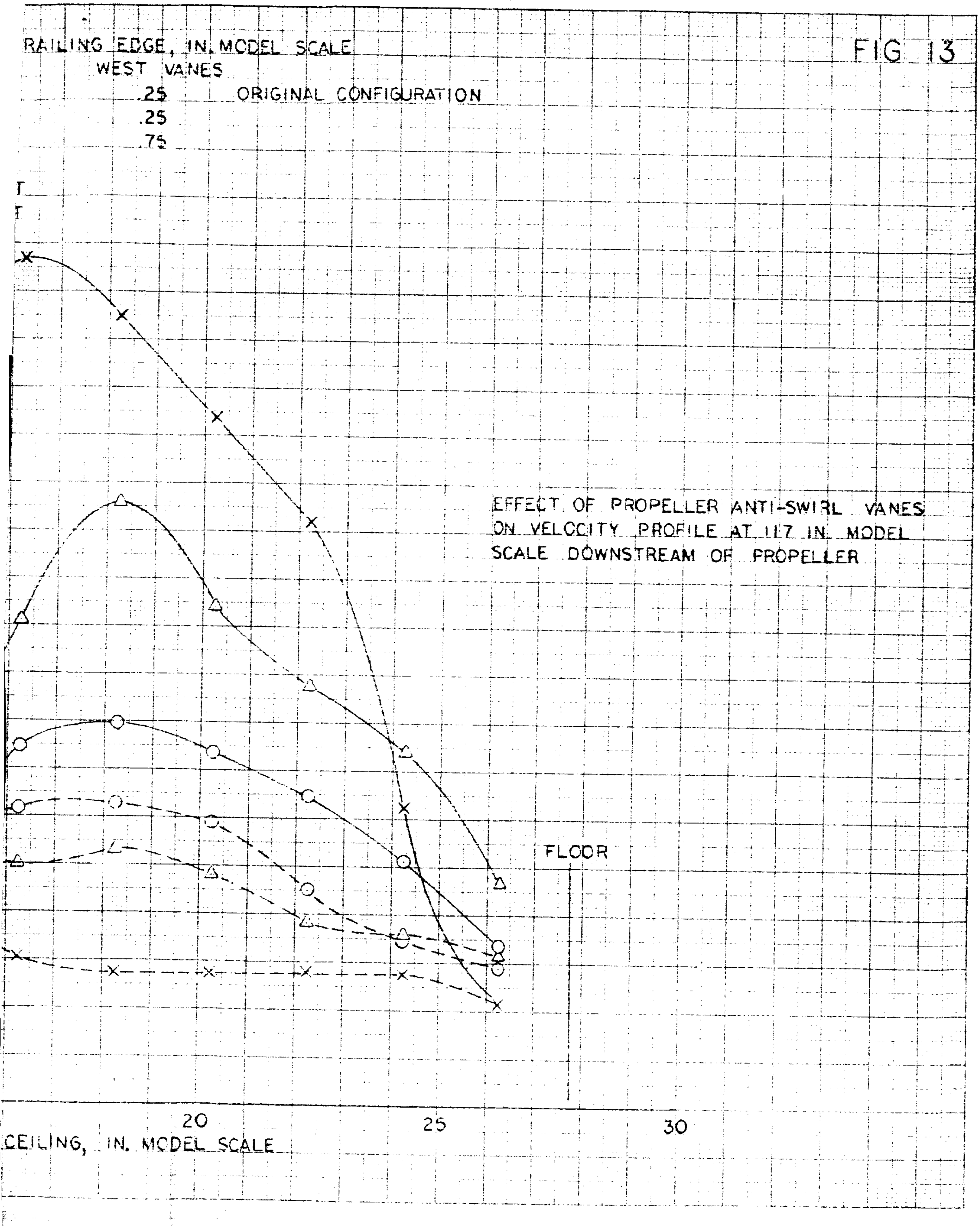
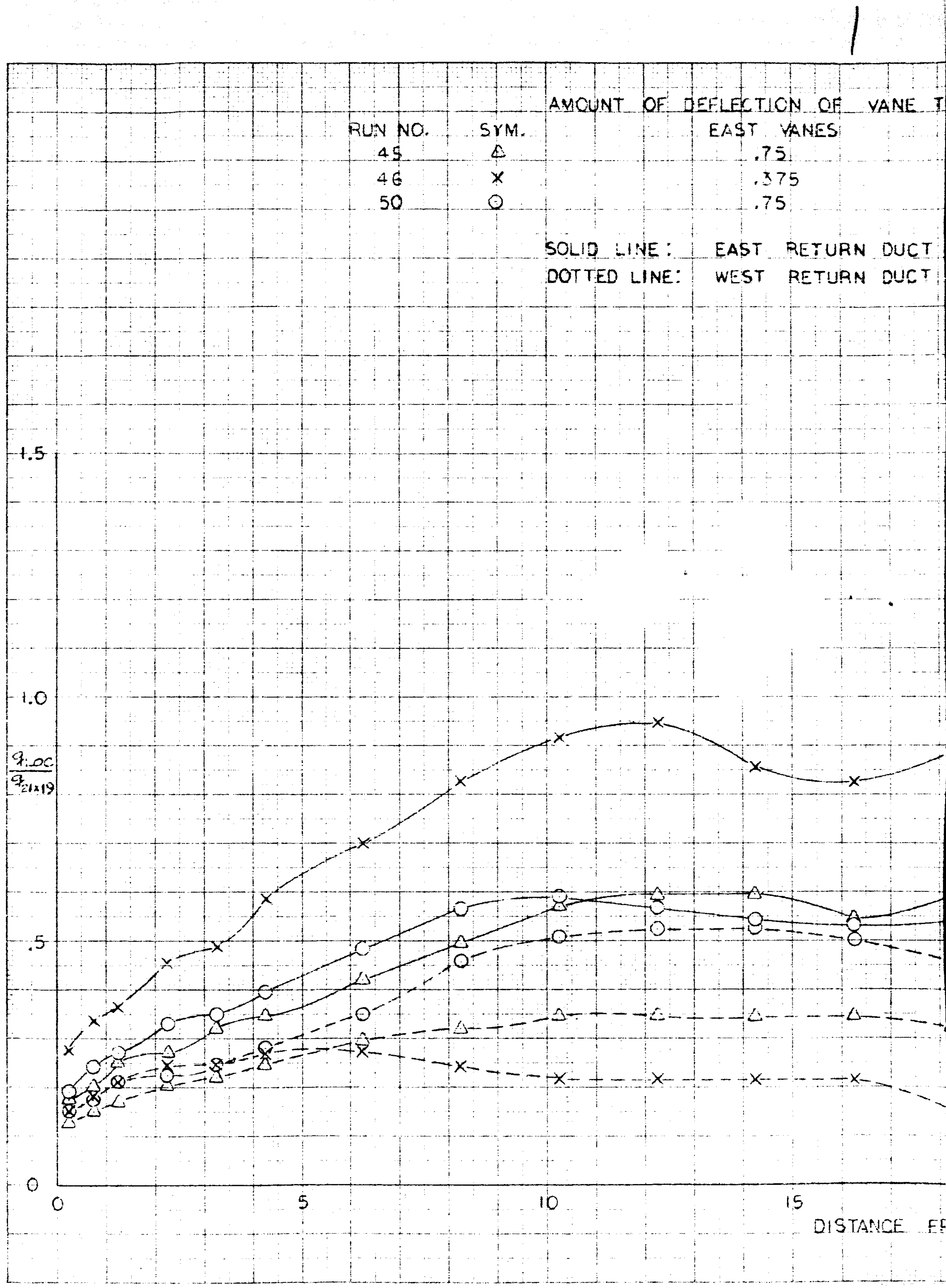


FIG. 12

DYNAMIC PRESSURE DISTRIBUTION IN STATION 5
21 x 19 TEST SECTION


RAILING EDGE, IN. MODEL SCALE
WEST VANES
.25 ORIGINAL CONFIGURATION
.25
.75
FIG 13
EFFECT OF PROPELLER ANTI-SWIRL VANES ON VELOCITY PROFILE AT 117 IN. MODEL SCALE DOWNSTREAM OF PROPELLER
FLOOR
20
25
30
CEILING, IN. MODEL SCALE


1
AMOUNT OF DEFLECTION OF VANE T
RUN NO. SYM. EAST VANES
45 △ .75
46 × .375
50 ⊙ .75
SOLID LINE: EAST RETURN DUCT
DOTTED LINE: WEST RETURN DUCT
1.5
1.0
.5
0
$\frac{q_{loc}}{q_{21 \times 19}}$
0
5
10
15
DISTANCE FR

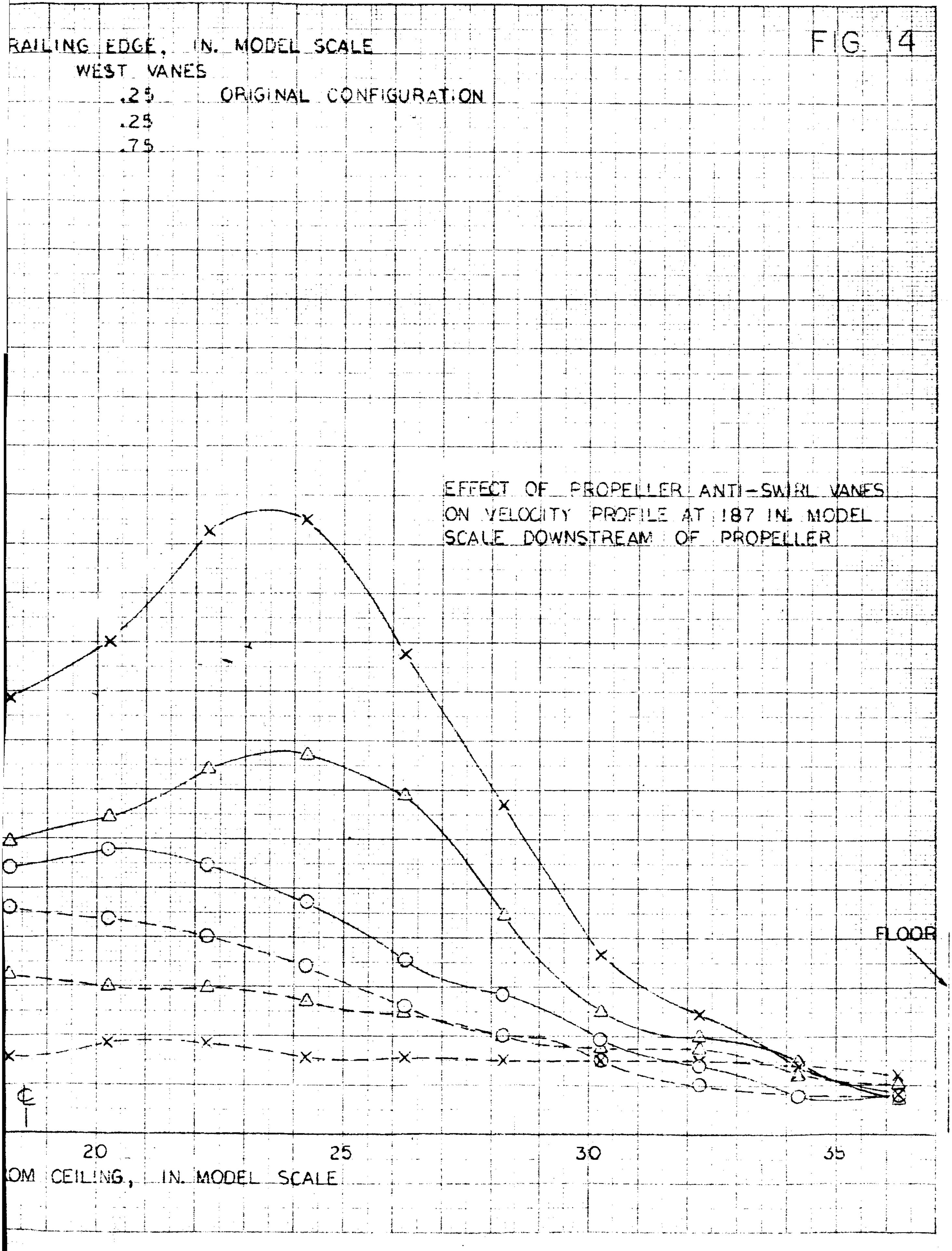

RAILING EDGE, IN. MODEL SCALE
WEST VANES
.25 ORIGINAL CONFIGURATION
.25
.75
EFFECT OF PROPELLER ANTI-SWIRL VANES ON VELOCITY PROFILE AT 187 IN. MODEL SCALE DOWNSTREAM OF PROPELLER
FLOOR
℄
20
25
30
35
OM CEILING, IN. MODEL SCALE

FIG. 14