NASA Technical Memorandum 81792

NASA-TM-81792 19810015579

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JUNE 1981

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Evaluation of Turbulence Reduction Devices for the Langley 8-Foot Transonic Pressure Tunnel

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National Aeronautics
and Space Administration

Scientific and Technical
Information Branch

1981

SUMMARY

Model tests were made of devices for reducing turbulence in the Langley 8-Foot Transonic Pressure Tunnel to permit laminar-flow airfoil tests. The test model consisted of a cooler, turning vanes, and settling chamber (immediately upstream of the contraction) in which various combinations of screens and honeycomb were tested. Conventional hot wires were used to measure the axial and lateral turbulence reduction for the different turbulence-reduction devices. The final configuration chosen consisted of a honeycomb followed by five screens. Results are presented herein to document this selection.

INTRODUCTION

The NASA Aircraft Energy Efficiency (ACEE) Project includes the investigation of a laminar-flow control (LFC) airfoil model in a wind tunnel to conduct research and to demonstrate the use of suction to achieve laminar flow at high subsonic speeds (Mach 0.8). The investigation requires an airfoil section having extensive supercritical flow on the upper surface. For reasons outlined herein, the tests were conducted in the Langley 8-Foot Transonic Pressure Tunnel.

In order to reduce the flow disturbances in the tunnel to the level required for such tests, it was necessary to reduce both the vorticity and noise in the test section. The results of tests to define the flow-disturbance characteristics of the tunnel in its untreated condition are presented in reference 1, the results of tests to devise a means of reducing the static-pressure disturbances are reported in reference 2, and means of reducing the vorticity with screens and honeycomb in the settling chamber are reported herein and in reference 3. These latter tests were conducted with a one-half-scale model of the fourth corner and settling chamber of the tunnel. Various combinations of screens and honeycomb were tested using hot-wire anemometry techniques to measure turbulence. Reference 3 presents the results of some general tests to determine the effect of configuration and installation factors that influence the effectiveness of screens and honeycomb; the present paper presents data specifically used to decide on the honeycomb-screen configuration to be installed in the Langley 8-Foot Transonic Pressure Tunnel. Because of the difficulties described herein and in reference 3 in developing the model and test techniques, in interpreting the data, and because of the shortage of time for determining the configuration for the tunnel, data of poorer quality than desired were used. In particular, data were obtained at different times during the development of the model and test techniques and were therefore not precisely quantitatively comparable; also, data from incomplete test series which consequently did not yield a full understanding of the results being obtained were used. Therefore, the process behind the selection of the manipulator configuration to be installed in the tunnel should be put on record. This paper is, in effect, a somewhat more formal version of oral presentations that have been made to explain the selection process.

After the selection of the configuration for the tunnel had been made, the model was used for more orderly and more fundamental research to improve the understanding of the performance of honeycomb and screens and perhaps to get a better understanding of the fluid mechanics involved. The results of these subsequent tests are presented in reference 4.

Identification of commercial products in this report is used to adequately describe the model. The identification of the commercial products does not constitute official endorsement expressed or implied, of such products or manufacturers by the National Aeronautics and Space Administration.

SYMBOLS

All values are given in both SI and U.S. Customary Units. The measurements and calculations were made in U.S. Customary Units.

M	free-stream Mach number
M_{TS}	Mach number at various stations along the test section
p	free-stream static pressure, Pa $(lb/ft)^2$
p'	rms static-pressure fluctuations, Pa (lb/ft^2)
q	free-stream dynamic pressure, Pa (lb/ft^2)
R	unit Reynolds number
R_c	Reynolds number based on wing mean aerodynamic chord
u	free-stream velocity, m/sec (ft/sec)
u'	rms axial velocity fluctuations, m/sec (ft/sec)
v'	rms lateral velocity fluctuations, m/sec (ft/sec)
x	tunnel station
γ	ratio of specific heats

Abbreviations:

H/C	honeycomb
rms	root mean square
4 M	screen-mesh designation (see table I)
1/4 H	honeycomb deignation (see table I)

BACKGROUND

Research objectives of the ACEE Project require that the LFC airfoil tests be conducted at essentially full-scale cruise Reynolds numbers, which vary from about 20×10^6 for small transports (e.g., the DC-9) to about 50×10^6 for large transports (e.g., the Boeing 747). It is also believed that unit Reynolds number simulation above a value of about 10×10^6 per meter (3×10^6 per foot) might reduce the chance of success and is unrealistic in any event, the upper value of unit Reynolds number at cruise being about 6×10^6 per meter (2×10^6 per foot) for transport aircraft. On the basis of these values, the chord of the model should not be less than about 2 m (7 ft) to achieve even the 20×10^6 value of chord Reynolds number without exceeding the 10×10^6 per meter (3×10^6 per foot) unit Reynolds number criterion. It would be desirable to conduct the airfoil tests at higher total pressures to approach the 50×10^6 value of chord Reynolds number and at lower total pressures to reach the 6×10^6 per meter (2×10^6 per foot) value of unit Reynolds number.

Wind-tunnel and flight-test data needed in order to estimate the permissible turbulence level in the wind tunnel are summarized in the plot shown in figure 1 (previously presented in ref. 1). The plot shows a scatterband of turbulence levels at which full-chord laminar flow could be obtained with optimum suction for minimum drag on wings and bodies of revolution. If one takes a pessimistic view and uses the bottom of the scatterband (see dashed lines in fig. 1), the achievement of a chord Reynolds number of 20×10^6 requires that the disturbance level in the tunnel in terms of the velocity fluctuation u'/u be no greater than 0.05 percent. If one takes a favorable view and uses the top of the scatterband (see dashed lines in fig. 1), the achievement of a chord Reynolds number of 50×10^6 requires that the value of u'/u be no greater than 0.04 percent. On this basis, it was recommended that the selected tunnel should have a disturbance level no greater than 0.04 to 0.05 percent.

The NASA Ames 12-Foot Pressure Tunnel and Langley 8-Foot Transonic Pressure Tunnel (hereafter called simply the 12-ft and 8-ft tunnels) were the principal candidate wind tunnels for the experiment. Surveys of the flow quality were made in both of these tunnels. The results are presented in detail in reference 1, and a few particular results have been excerpted for presentation herein. Results for a Mach number of 0.80 are presented in figure 2 for the velocity fluctuations u'/u and in figure 3 for the static-pressure fluctuations p'/p. Hot-wire anemometers and miniature pressure gages were used to measure the dynamic data, the miniature pressure gages being cavity mounted within ogive cylinder probes. These data show that at the higher values of unit Reynolds number required for the LFC airfoil tests (e.g., 6×10^6 per meter (2×10^6 per foot)), the disturbance level in the 12-ft tunnel was no less than about one-half that of the 8-ft tunnel, even though it has eight turbulence-reduction screens in the settling chamber and the 8-ft tunnel has none. The data also show that both tunnels had much higher turbulence levels than are permissible for the LFC airfoil tests (5 to 10 times more) and would require extensive turbulence-reduction treatment.

The data of figures 2 and 3 also show, as can be ascertained from the tunnel performance envelope, that the 12-ft tunnel cannot achieve values of unit Reynolds number above about 6×10^6 per meter (2×10^6 per foot) at $M = 0.80$.

It would be possible with a 3-m-chord (10-ft) model to achieve the minimum target of 20×10^6 chord Reynolds number, but it would not be possible to achieve the desired higher values. The 8-ft tunnel, on the other hand, can achieve values of unit Reynolds number of 20×10^6 per meter (6×10^6 per foot) which, with a 2-m-chord (7-ft) model, would give approximately the maximum target value of chord Reynolds number of 50×10^6. (It is possible to reach a maximum model aspect ratio for testing in either tunnel.)

Because the 12-ft tunnel did not have a Reynolds number capability as high as that desired and because it was questionable whether its turbulence level could be reduced by a factor of 5 as required (since it already had eight turbulence reduction screens), the decision was made to conduct the LFC airfoil experiment in the 8-ft tunnel. The flow-disturbance level in the 8-ft tunnel would have to be reduced by a factor of nearly 10. (See ref. 1.) But since it had no disturbance-reduction devices, and since it had a high (20:1) contraction ratio, the flow disturbances could be reduced to the required levels with proper turbulence- and noise-reduction devices.

Reference 1 points out that for the 8-ft tunnel at the higher Mach numbers, velocity fluctuations calculated from measured pressure fluctuations using the expression $u'/u = p'/p\gamma M$ agree with those obtained with a hot wire. This can be seen readily from figures 2 and 3 since the value of γM is nearly 1 (actually 1.1) for $M = 0.80$. Reference 1 also points out that at lower Mach numbers the velocity fluctuations calculated from the pressure fluctuations are much less than those measured with a hot wire. The results of reference 1 further show that cross correlations of data measured with static-pressure transducers mounted flush with the tunnel wall (beneath the boundary layer at two longitudinal stations on the test-section wall) indicate an upstream propagation of static-pressure waves at Mach numbers up to 0.90. But at a Mach number of 0.95, at which the flow is choked at the rear of the test section, there is no such upstream propagation. The data, therefore, indicate that at $M = 0.80$, fluctuating static pressures dominated the disturbances in the test section; in addition, these fluctuating static-pressure disturbances were moving upstream from the diffuser.

Velocity fluctuations referred to as turbulence herein can be caused by vorticity or static-pressure fluctuations. Hot-wire instrumentation measures the mass-flow and total-temperature fluctuations. Assuming that the total-temperature fluctuations are negligible, the simultaneous recordings of the static-pressure fluctuations can be used in calculating these velocity fluctuations. In any case, the measurements of velocity fluctuations made by hot wires are referred to herein as turbulence.

The first task, therefore, seemed to be to eliminate the upstream-propagating static-pressure fluctuations. The results of tests with a number of devices for choking the flow are presented in reference 2. Figures 4 and 5, taken from reference 2, show the effect of choke plates which were two-dimensional bulges 2.5 cm (1.0 in.) high across all four walls near the rear of the test section. Figure 4 shows that at $M = 0.81$, the choked flow reached a Mach number of 1.13 over the choke plates. The data of figure 5 show that for this configuration at $M = 0.80$, the level of static-pressure fluctuation p'/p was reduced from 0.35 percent to 0.05 percent by choking the flow.

Calculation of the acoustic velocity fluctuations by the expression $u'/u = p'/p\gamma M$ gives a value of 0.045 percent, which is down to the target level of 0.04 to 0.05.

The next problem was to define the devices for reducing vorticity propagating downstream from the settling chamber since the data of reference 1 indicate that even at Mach numbers of 0.20 and 0.60, the velocity disturbance level in the test section was unacceptably high ($u'/u \approx 0.10$ percent) and that it increased with increasing Mach number. At these low Mach numbers, the disturbances had to be attributed to vorticity since they could not be explained on the basis of static-pressure fluctuations. For example, at $M = 0.20$, the value of u'/u calculated from the expression $p'/p\gamma M$ was only about 0.03 percent compared with measured values of u'/u of about 0.10 percent. At $M = 0.60$, the value of u'/u calculated from $p'/p\gamma M$ was only about 0.12 percent compared with a value of about 0.20 percent measured with a hot wire.

Since the goal represented an extraordinarily low level of turbulence for a high Reynolds number transonic tunnel, it was anticipated that a combination of honeycomb and screens would be required. A search of the literature indicated very limited information about the effect of honeycomb on turbulence (see ref. 5), and the configuration of the corner just ahead of the contraction of the 8-ft tunnel was so different from that of other tunnels that the applicability of the literature on the effect of screens was questionable. It was, therefore, decided to conduct some experiments with a model of the 8-ft tunnel corner to define a honeycomb and/or screen configuration.

APPARATUS AND TESTS

Model

The configuration of the corner of the 8-ft tunnel ahead of the contraction, which was the subject of the modeling, is shown in figure 6. There is a cooler consisting of eight rows of closely spaced finned tubes. The tube outside diameter is 2.5 cm (1.0 in.), the fin diameter is 5.6 cm (2.2 in.), and the fins are evenly spaced, three per centimeter (eight per inch). The pressure drop through this cooler has been measured to be about 8q ($\Delta p/q = 8$). With such a high pressure drop, the air coming out of the cooler exits in a direction almost normal to the cooler; therefore, the cooler causes the air to perform the first 45° of its turn, and 45° turning vanes are used to complete the turn. The temperature fluctuations from the cooler model do not simulate the temperature fluctuations on the full-scale tunnel. If there were temperature fluctuations, they would be recorded by the hot-wire instrumentation and would appear to be turbulence.

The cooler might be expected to effectively damp out any incoming disturbance (probably large-scale turbulence) and to generate its own turbulence of smaller scale. Reference 1 presents measurements in the tunnel showing this to be true. The turbulence levels upstream of and immediately downstream of the cooler were of about the same magnitude (u'/u being about 20 percent), but the scale of turbulence downstream of the cooler was only about 5 percent of that upstream. This smaller scale turbulence would be expected to decay

more rapidly from viscous effects, so the cooler might be responsible to a considerable extent for the fact that the 8-ft tunnel has surprisingly low levels of turbulence for a tunnel with no screens. The 45° turning vanes of the 8-ft tunnel might also cause less turbulence than the usual 90° turning vanes. Because of the unusual characteristics of the 8-ft tunnel, an experimental approach to defining the turbulence-reduction devices (or mainpulators) and optimum location seemed to be required.

The model constructed for the tests was approximately a one-half scale model of a 0.91-m (3.00-ft) square stream tube of the flow along the center line of the tunnel in the corner and settling chamber region as indicated in figure 6. A sketch of the model appears in figure 7, and the model is described in some detail in reference 3. The model was constructed mainly of parts previously used in model experiments for the National Transonic Facility. The corner section was new, however, and represented a section of the corner of the 8-ft tunnel at one-half scale; the cooler, for example, was made of commercially available finned tubes that were very nearly one-half scale of those in the tunnel.

The turbulence manipulators (honeycomb and/or screens) were located at appropriate distances downstream from the corner to represent a location corresponding to that on the center line of the tunnel. The hot wires used to measure the turbulence downstream of the screens were located 30.5 cm (12 in.) downstream of the last manipulator and were intended to indicate the turbulence of the flow entering the contraction of the tunnel.

The model was originally powered by an axial-flow fan at the station indicated in figure 7. As in the section entitled "Assessment and Development of the Model," however, this fan caused noise which contaminated the experiment; it was therefore removed and a new drive system consisting of three fans 20.3 cm (8.0 in.) in diameter (in an over-under arrangement) in a box lined with sound-absorbing material was used to power the model. These fans had a large number of blades and operated at a high speed so that they created high-frequency noise which could be absorbed readily by the acoustic lining in the box.

The physical characteristics of the turbulence manipulators available for the tests are indicated in table I. They consisted of screens of six different mesh sizes having an open area ratio of about 60 percent. Three of each of the finer screens were available for the tests. Aluminum honeycomb of four different cell sizes was available for the tests, and the 0.64-cm (0.25-in.) cell honeycomb was available in two material gages.

Instrumentation and Data Reduction

The instrumentation system used varied during the test program. Initially, during the model flow survey, three scanivalves and barocell pressure transducers were used. Two pitot-tube systems were installed at the farthest downstream instrumentation cross section of the model. (See fig. 7.) These sensors were connected to long pressure tubing (over 3 m (10 ft) in length) which was in turn connected to barocells and digital voltmeters. This system was used to measure the duct velocity, which was used as the reference velocity, and the system was not changed during the tests.

An accelerometer was used in some tests to detect duct wall and hot-wire support system vibrations to verify that the hot-wire output did not originate from support vibrations rather than fluid turbulence.

The principal hot-wire system, used to measure the flow downstream of the manipulators, consisted of three channels manufactured by DISA Electronics.[1] Three channels manufactured by Thermo-Systems Inc. were used at times for diagnostic work and to record the flow qualities at other stations of the model. The hot wires at the principal measurement station downstream of the manipulators had fixed locations during the test. One of the Disa hot-wire channels was used for a single-wire probe, and the other two channels were used for a cross-wire probe. The single-wire probe was generally 2.5 cm (1.0 in.) off the duct center line, and the cross-wire probe was 2.5 cm (1.0 in.) off the center line in the opposite direction. (Thus, the two sensors wee 5.0 cm (2.0 in.) apart laterally.) These three wires were located in a plane that was 30.5 cm (12.0 in.) downstream of the last manipulator and approximately 53.3 cm (21.0 in.) upstream of the pitot tube.

Two standard acoustic microphone systems were used during the testing. Both of these systems were flush mounted in the wall of the duct and were isolated from wall vibrations. One microphone was mounted approximately 40.5 cm (16.0 in.) on the center line downstream of the trailing edge of the turning vanes, and the other microphone was in the plane of the pitot tubes. These microphones were used to detect any acoustic waves traveling up or down the duct. Such acoustic waves could be sensed by the hot wires and could be misinterpreted as turbulence.

All hot-wire and acoustic data were recorded on an FM tape recorder. The pitot digital voltmeter outputs were manually read and recorded. The hot-wire voltages were monitored on an oscilloscope, and the output voltages were manually read and recorded before recording on the tape recorder. The manually recorded hot-wire output voltages were processed with an electronic computer after each series of tests. Standard hot-wire data reduction equations were used and are presented in the appendix of reference 3. The FM magnetic tape records were processed with more elaborate and time-consuming computing equipment.

TEST CONDITIONS

For the LFC airfoil experiment in the 8-ft tunnel, the design point was $M = 0.82$ and $R = 10 \times 10^6$ per meter (3×10^6 per foot), and the test-section area was to be reduced to 3.5 m^2 (37.7 ft^2) by the special flow liner, which results in a contraction ratio of nearly 27:1. These conditions result in a unit Reynolds number of 0.3×10^6 per meter (0.1×10^6 per foot) in the settling chamber with a velocity of about 7.3 m/sec (24.0 ft/sec) at a pressure of about 0.7 atm (1 atm = 101.3 kPa). At the atmospheric pressure conditions of the present model, this value of unit Reynolds number is achieved at a velocity of about 4.9 m/sec (16.0 ft/sec); for the half-scale model, full-scale chord

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[1]DISA Electronics, division of DISAMATIC, Inc.

Reynolds number based on turning vane chord or cooler tube diameter) is achieved at a velocity of about 9.8 m/sec (32.0 ft/sec). The tests were, therefore, run over a range of speeds from 7.6 to 15.2 m/sec (25.0 to 50.0 ft/sec), and the values of turbulence presented herein are those obtained by averaging the results obtained at four test speeds in this range, discounting any erratic points. Erratic points were frequently evident at speeds near 10.0 m/sec (33.0 ft/sec), perhaps because of some resonant vibration of the probes.

It is interesting to note, with regard to subsequent analysis, that with a half-scale model test speed of 9.8 m/sec (32.0 ft/sec) and full-scale tunnel speed of 7.3 m/sec (24.0 ft/sec), the frequencies of the model based on equal Strouhal numbers are 2.67 times those of the full-scale tunnel. For example, a 100.0-Hz high-pass filter used in many of the tests corresponds to a 37.5-Hz filter at full scale.

ASSESSMENT AND DEVELOPMENT OF THE MODEL

Surveys of the velocity across the channel with a pitot tube showed the velocity to be fairly uniform except within the boundary layer, which was between 2.5 and 5.0 cm (1.0 and 2.0 in.) thick at the manipulator station (ref. 3). Measurements of the turbulence with the hot wires showed a turbulence level in terms of axial and lateral turbulence (u'/u and v'/u) of 2.2 and 2.5 percent, respectively, which indicated that the turbulence was approximately isotropic and of the same level as that shown for the settling chamber of the tunnel in reference 1. Such agreement was not surprising because in the full-scale tunnel, the turbulence downstream of the cooler was mainly that generated by the cooler and turning vanes. It seemed to be independent of the level or character of turbulence ahead of the cooler. In such a case, a scale model would be expected to generate approximately scale-model turbulence.

The foregoing tests indicated that the model was valid and that tests of the manipulators could proceed. Because of the shortage of time available for defining the manipulators of the 8-ft tunnel, an attempt was made to develop an acceptable final answer directly instead of building up an understanding of flow mechanisms. The first manipulator tested was the one indicated by the literature as the best possible for the space available in the short settling chamber of the tunnel. This configuration is shown in figure 8. In the downstream direction, it consisted of a honeycomb followed by barely adequate space for a person to stand while cleaning the screens. Then came five screens, the first three being of progressively finer mesh, spaced 100 to 200 mesh spaces apart.

When this manipulator configuration was tested, it reduced the axial turbulence only by a factor of about two. Although the tests and events that followed were not always in the most logical order, an understanding of the problem resulted and solutions were developed. (See fig. 9.) Figure 9 is intended to be pictorial and not necessarily quantitatively accurate since the instrumentation system and model were being developed at this time. Consequently, data from one test were not necessarily directly comparable to those from another test.

It was found that a number of the screens could be removed without an increase in the turbulence. Thus, some disturbance was forming a "floor" beneath which the disturbances could not be reduced. Cross correlation of the static pressures measured by the two microphones spaced along the channel indicated strong static-pressure waves, or noise, moving upstream. Since the drive fan immediately behind the measurement station was obviously noisy, it was removed, and the model was repowered with the small high-speed fans in the acoustic box. A substantial improvement resulted, but there was obviously still a "floor" in the experiment. Removing a 60-Hz spike caused by the ac power to the instruments helped, and vibration isolation helped, but there were still static-pressure waves in the channel. Some of these static-pressure waves were standing waves related to organ pipe tones since they had the proper frequency multiples for a closed-end pipe and did not vary with test airpeed. Much of the energy was at very low frequencies that would probably not affect boundary-layer stability in the LFC airfoil experiment; therefore a 100-Hz high-pass filter was used (corresponding to a 37.5-Hz filter for full scale). These and many lesser changes lowered the "floor" to a value of u'/u of about 0.25 percent. One large source of noise remained, however, which might exist in the 8-ft tunnel too. This was a loud humming caused by the air flow through the cooler. The cooler noise and the complete process of cleaning up the experiment is described in more detail in reference 3.

Figure 9 also shows that lateral turbulence continued to decline when the fourth and fifth screens were added whereas axial turbulence did not. This might be interpreted as an indication that axial turbulence could be expected to decrease in a similar manner if remaining contaminants were removed from the experiment. On the other hand, it might be interpreted as indicating that some factor such as cooler noise, which might also exist in the 8-ft tunnel, would keep the axial component of turbulence from decreasing below the 0.25-percent level.

RESULTS AND DISCUSSION

Preliminary Configuration Assessments

During the foregoing period of development of the model, an expert consultant on reduction of wind-tunnel turbulence, Hassan M. Nagib of the Illinois Institute of Technology, was asked to recommend a manipulator configuration for the 8-ft tunnel. One feature of his recommendation was that honeycomb should have a screen of the proper mesh located immediately on its downstream face. His experiments had shown repeatedly that a honeycomb screen combination with the screen in this location was much more effective than with the screen farther downstream. Experiments with the model at Langley Research Center (LaRC), however, had repeatedly indicated no such effect, or had suggested the opposite conclusion (see ref. 3) that the combination was more effective with the screen downstream from the honeycomb. The consultant reasoned that the differing results might be caused by the larger scale of the turbulence in the LaRC model; he therefore recommended the configuration shown in figure 10. It featured two coarse screens of progressively smaller mesh ahead of the honeycomb to reduce the scale of the turbulence. These screens were not expected to be effective

in reducing turbulence themselves, but only in reducing the scale of the turbulence so that the succeeding manipulators would be more effective.

A series of special experiments was conducted to investigate whether the preliminary coarse screens were effective and whether a screen should be located on the downstream face of the honeycomb. The configurations involved in these experiments are illustrated and the results presented in table II. Data are shown with the 100-Hz high-pass filter and with a 2-Hz filter.

The top line of table II shows the turbulence level with no manipulators. The second line shows the data for the case of the two coarse screens and a honeycomb with a fine screen on the downstream face of the honeycomb. The third line shows that there is a greater reduction in turbulence if the fine screen is moved downstream from the honeycomb. The fourth and fifth lines show the effect of removing one or the other of the preliminary coarse screens. Removing either of these screens resulted in a small reduction in turbulence. The bottom line shows a comparison that may not be quite fair, but it suggests that if one is to pay the price in pressure drop and money of three screens, using three fine screens would be much more effective than using the coarse screens. Although higher levels of turbulence are indicated when the 2-Hz filter was used, the trend of the results is the same and conclusions that would be drawn are the same.

On the basis of the foregoing results, no further consideration was given to the use of a screen on the downstream face of the honeycomb. The coarse preliminary screens were considered further, however, since it was thought that they might have been more effective if there had been more fine screens downstream.

Honeycomb-Plus-Screen Configurations

The results of tests to determine the effect of honeycomb cell size were inconclusive, as indicated in reference 3, the differences being within the scatter of unrepeatability of tests. There was also no detectable difference in turbulence-reduction performance of 1/4 H honeycomb with the thinner or thicker material. Most of the subsequent tests were, therefore, conducted with the 1/4 H honeycomb made of the thicker material, but tests with the coarse preliminary screens were made with the 3/8 H honeycomb.

The results of tests of various configurations of honeycomb and screens are presented in figures 11 and 12. Figure 11 contains data measured with a 100-Hz high-pass filter, and figure 12 contains data measured with a 2-Hz filter. The figures, reading from left to right, show the effect of adding manipulators. For example, the lower scale on the abscissa, reading from left to right, indicates the cases of no manipulators (0), honeycomb alone (H/C), honeycomb plus one screen (1), honeycomb plus two screens (2), and so on, to honeycomb plus five screens (5).

For the tests with the coarse preliminary screens, the progression of screen mesh as screens were added was orderly. In all cases, the upstream screen was 4 M, the next 8 M, the first screen downstream of the honeycomb 28 M, and the next two 42 M. For tests with all fine screens, however, the

progression of screens was not orderly. In general, however, the downstream two or three screens were 42 M and the upstream screens had progressively coarser mesh going upstream. Within reason, however, mesh size was not nearly as important as the number of screens, provided that the farthest downstream screens were fine mesh. Hence, the plot has some validity and affords a convenient form for examining the data for one trying to decide how many and what kind of devices to put in a tunnel. Note that no tests were run with the coarse preliminary screens alone. Instead, the data were faired according to the hypothesis that these screens would not be expected to reduce the turbulence significantly but would reduce the scale of turbulence to make the succeeding manipulators more effective.

The most important result shown by figures 11 and 12 is that the configurations with all fine screens were much more effective in reducing turbulence than those with coarse preliminary screens for any given total number of screens. Other points, however, are worthy of note. For example, the data with the 2-Hz high-pass filters show the same qualitative result as those with the 100-Hz filters, the level of turbulence simply being higher because of the large amount of turbulent energy at very low frequencies. Also, all of the data show the "floor" in the axial turbulence discussed previously. The difference in the level of the "floor" in figure 11, for example, probably indicates the inconsistency in some of the spurious disturbances for data run at different times during the program. The data for any one series of configurations were generally run at approximately the same time and are more directly comparable.

Screen-Alone Configurations

The results of tests for various configurations of screens alone (no honeycomb) are presented in figures 13 and 14. For the tests with all fine screens, the progression of screen mesh for the various configurations was orderly. In all cases, the three screens farthest downstream were 42 M, and all of the screens upstream of these were 36 M. For tests with the coarse preliminary screens, the progression of screen mesh was less orderly. In all cases, the upstream screen was 4 M and the next screen was 8 M. The two or three screens farthest downstream were 42 M and any intermediate screens were of progressively coarser mesh moving upstream.

The data seem to bear out the hypothesis that the coarse preliminary screens cause the succeeding fine screens to be more effective in reducing turbulence. However, up to a total of 6 or 7 screens, the configurations with all fine screens yielded the lower turbulence. None of the data show the "floor" on axial turbulence since the turbulence does not get down to that level.

SELECTION OF CONFIGURATION

A comparison of data for screen-alone and honeycomb-plus-screen configurations is shown in figure 15. For this comparison, data for the screen-alone configurations with the coarse preliminary screens are presented. Use of seven screens seemed to give as much turbulence reduction as a configuration with all fine screens; furthermore, the coarse screens might provide some

protection from damage to the fine screens. Honeycomb-plus-screen configurations consisting of an upstream honeycomb with all fine screens are shown for the comparison because they gave markedly better results than configurations with the coarse preliminary screens for a given total number of screens.

A honeycomb-plus-screens configuration with five screens (total of six manipulators) was selected for the Langley 8-Foot Transonic Pressure Tunnel because it provides the greatest turbulence reduction of the configurations tested, especially in lateral turbulence which is reduced less by the wind-tunnel contraction than is axial turbulence. This configuration also has less pressure drop since the honeycomb has far less pressure drop than does a screen of the openness ratio considered. Specifications required screens to be of the finest mesh that could withstand the loads in the tunnel, and the openness ratio was required to be 60 to 70 percent.

Figure 15 also shows the estimated effect of the contraction. The effect on axial turbulence was determined from data in reference 1 at Mach 0.20 for which the hot-wire measurements were not dominated by noise. Data available on the effect of contraction on lateral turbulence were quite limited (ref. 6) at the time of the investigation, although additional information is now available in reference 7. In any event, the effect of the contraction in reducing lateral turbulence is less than that on axial turbulence; it is important, therefore, that the level of lateral turbulence in the settling chamber be low. The effect of the contraction on axial turbulence was simply applied to the measured value from the present model tests. It is realized, however, that the value in the tunnel settling chamber might be lower since the "floor" on axial turbulence in the model tests may be peculiar to these tests.

Figure 15 also shows for comparison the target value of turbulence reduction as determined for the laminar flow control airfoil experiment and the velocity perturbation due to noise calculated from the static pressure fluctuations measured in the tunnel with the choke.

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May 1, 1981

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TABLE I.- MANIPULATOR PHYSICAL PROPERTIES

(a) Screens

Designation	Number available	Mesh		Wire diameter		Open area, percent
		Wires per centimeter	Wires per inch	cm	in.	
4 M	1	1.58	4	0.1270	0.0500	64
8 M	1	3.15	8	.0660	.0260	63
20 M	3	7.87	20	.0230	.0090	67
28 M	3	11.02	28	.0190	.0075	62
36 M	3	14.17	36	.0165	.0065	59
42 M	3	16.54	42	.0140	.0055	59

(b) Honeycomb

Designation	Cell size		Cell length		Material gage	
	cm	in.	cm	in.	cm	in.
1/16 H	0.160	0.063	1.270	0.500	0.00254	0.001
1/8 H	.320	.125	1.905	.750	.00254	.001
1/4 H	.640	.250	3.810	1.500	.00254	.001
1/4 H	.640	.250	3.810	1.500	.00762	.003
3/8 H	.950	.375	7.620	3.000	.00762	.003

TABLE II.- ASSESSMENT OF COARSE PRELIMINARY SCREENS ON DOWNSTREAM FACE OF HONEYCOMB

[X indicates measurement station]

Screen	4 M	8 M	H/C	28 M	28 M	42 M	42 M	42 M	Percent turbulence measured with - 100-Hz filter u'/u	100-Hz filter v'/u	2-Hz filter u'/u	2-Hz filter v'/u
	—	(Tunnel empty)		—	x				1.35	1.59	2.40	2.10
					x				.65	.45	.78	.50
					x				.56	.49	.71	.49
					x				.52	.50	.65	.50
					x				.53	.49	.68	.51
								x	.26	.22	— —	— —

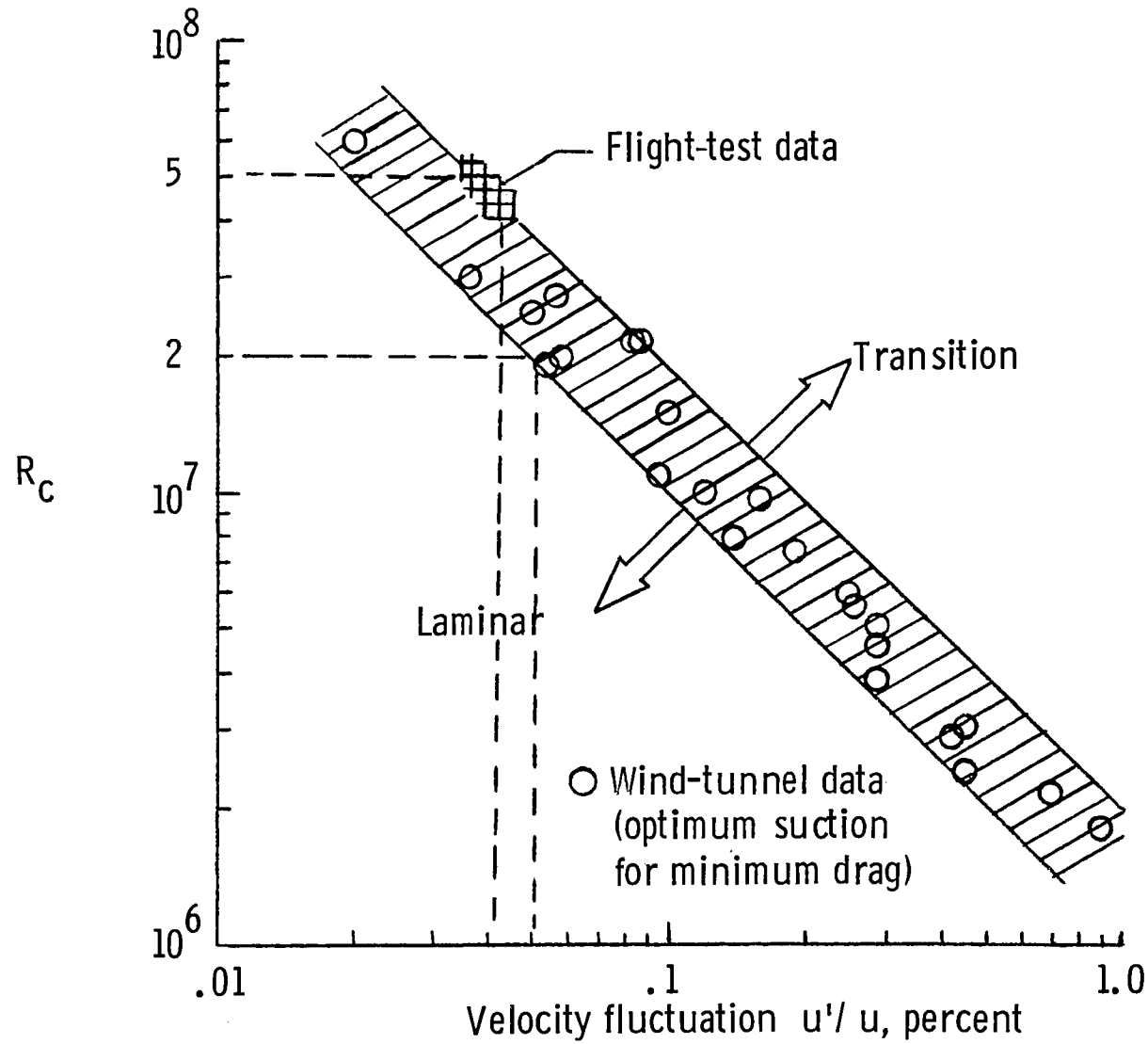


Figure 1.- Effect of velocity fluctuation on maintenance of full-chord laminar flow on wings and bodies with suction laminar flow control.

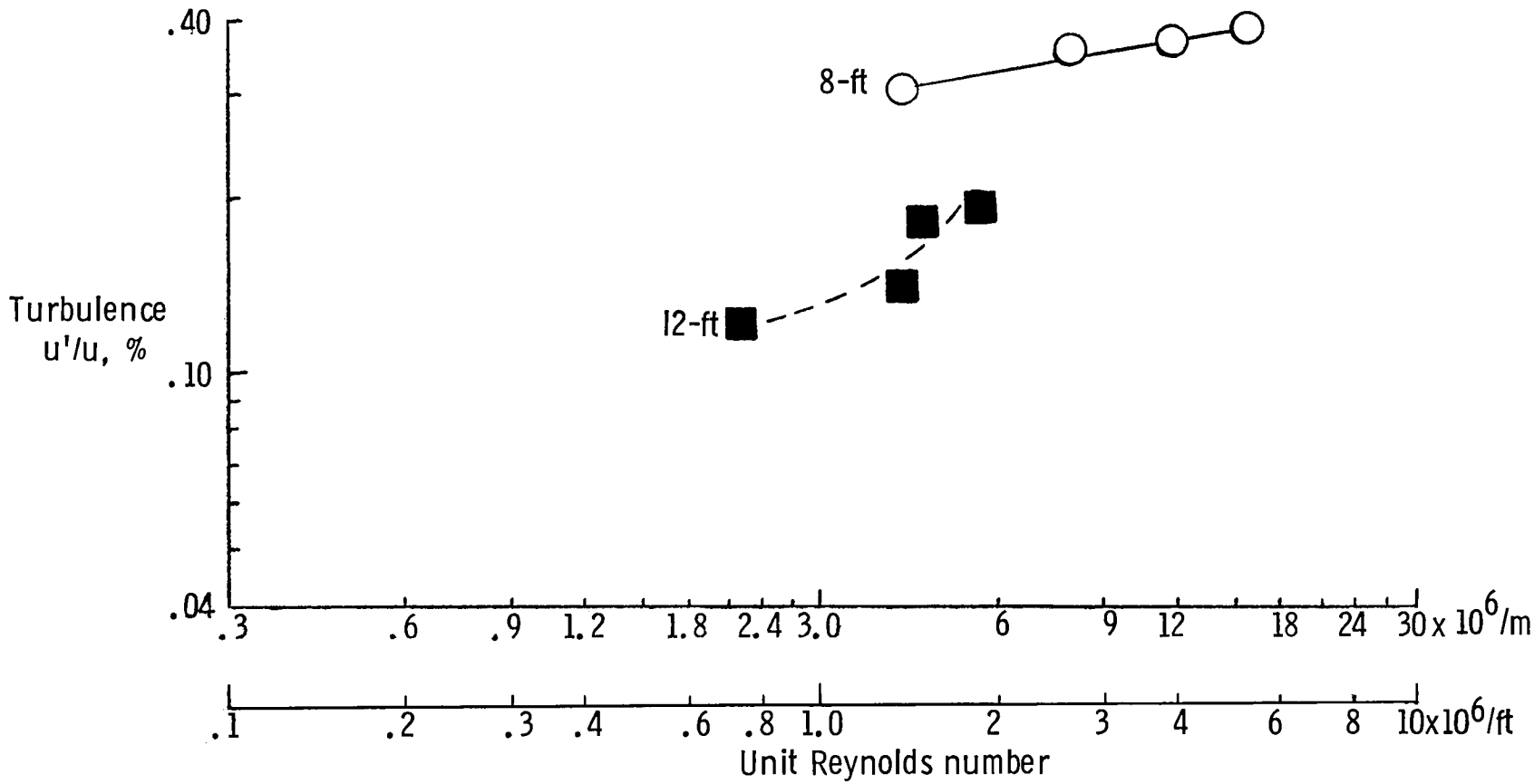


Figure 2.- Comparison of turbulence in Langley 8-Foot Transonic Pressure Tunnel and Ames 12-Foot Pressure Tunnel. M = 0.80.

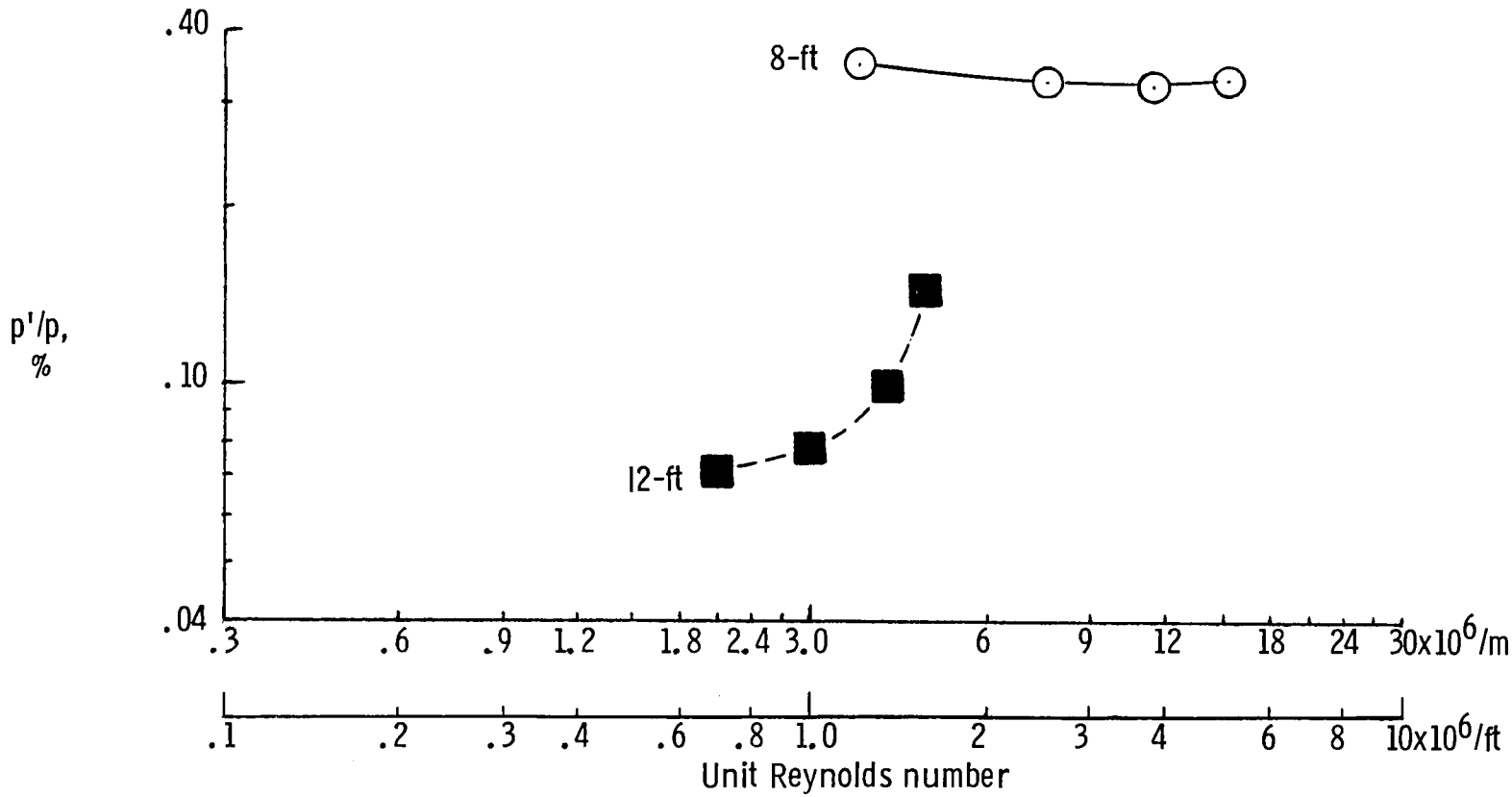


Figure 3.- Comparison of static-pressure fluctuations in Langley 8-Foot Transonic Pressure Tunnel and Ames 12-Foot Pressure Tunnel. M = 0.80.

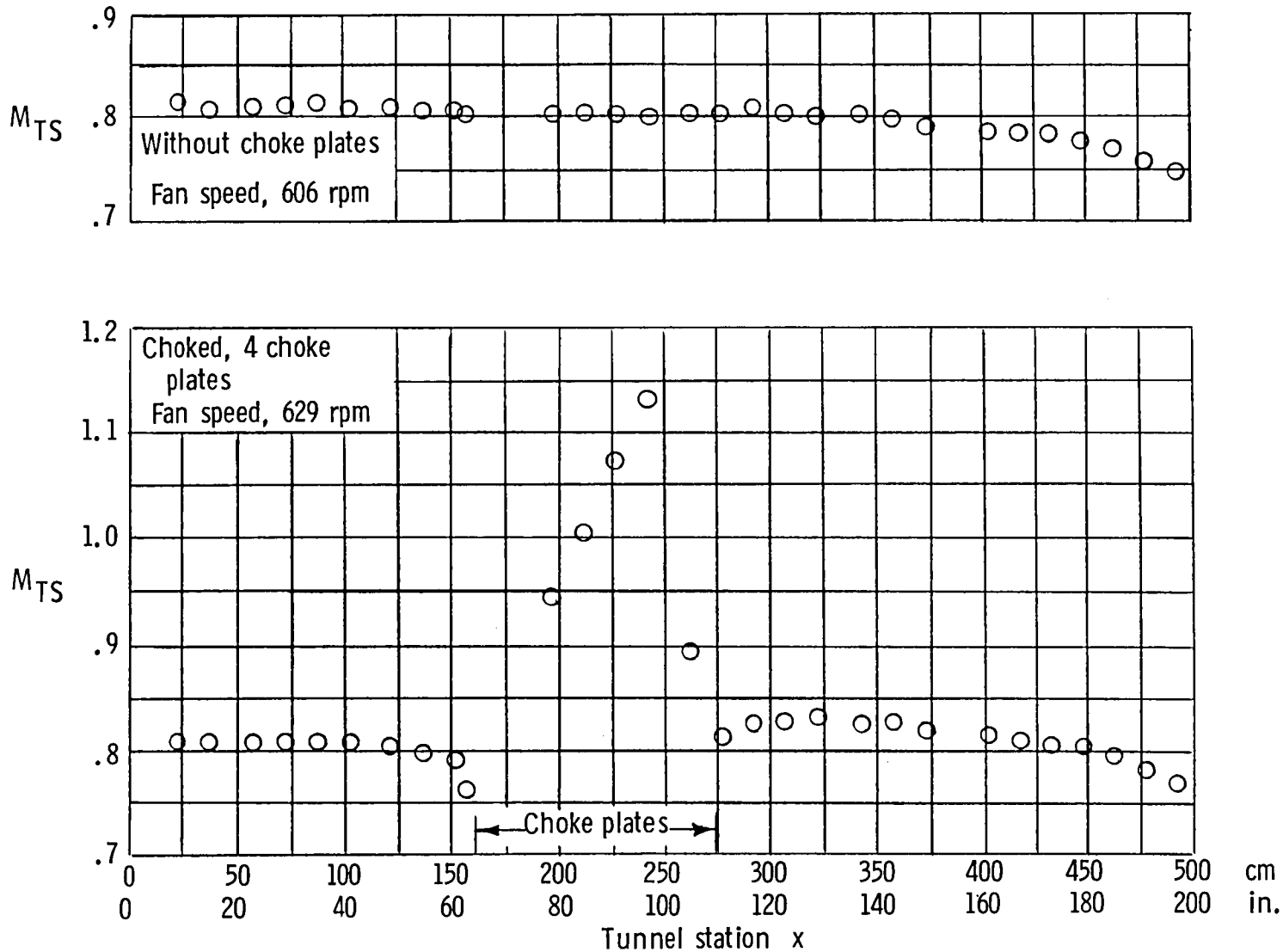


Figure 4.- Mach number distribution of Langley 8-Foot Transonic Pressure Tunnel with and without choke plates. Slats covered; M = 0.81.

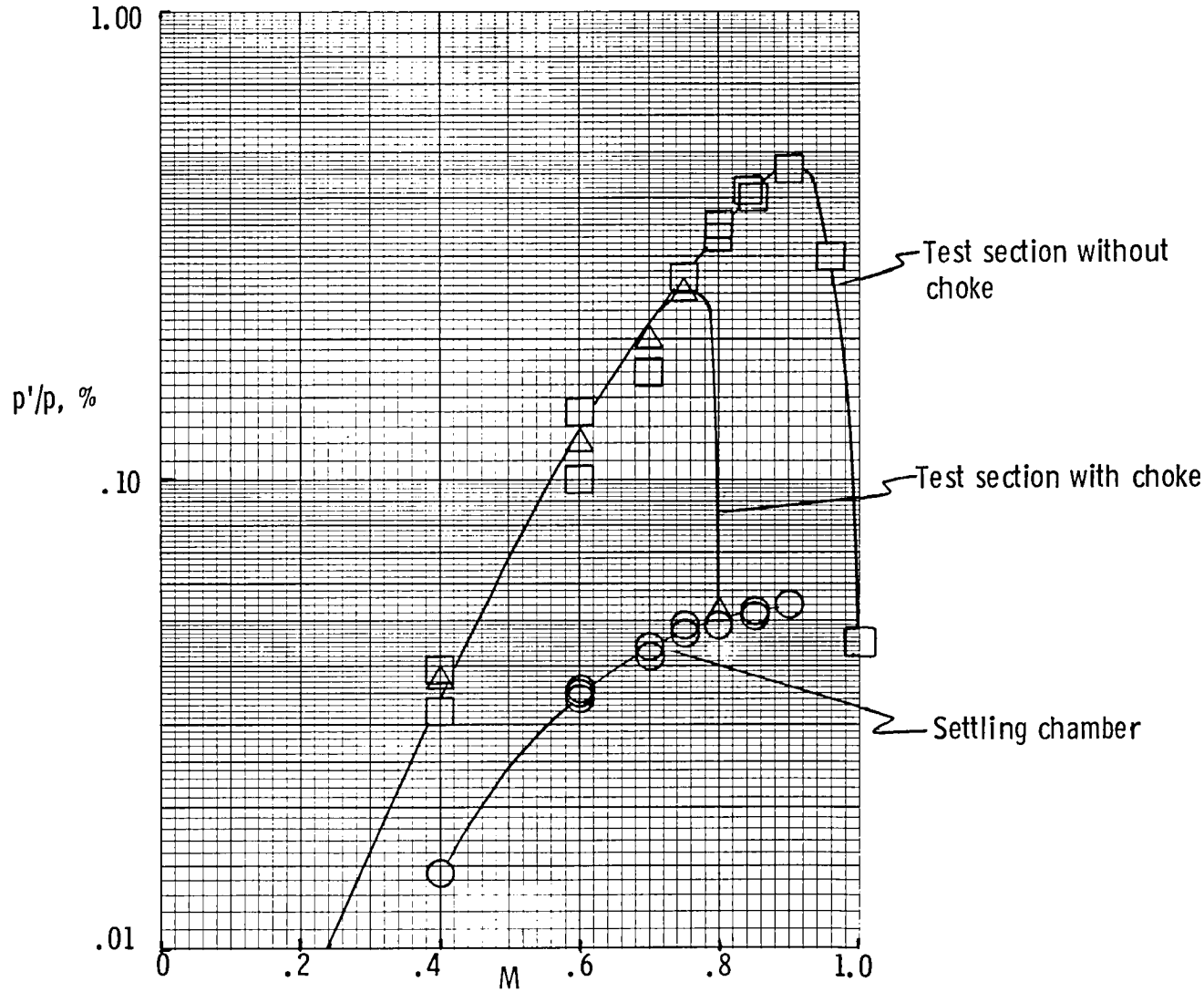


Figure 5.- Effect of choke on static-pressure fluctuations in Langley 8-Foot Transonic Pressure Tunnel.

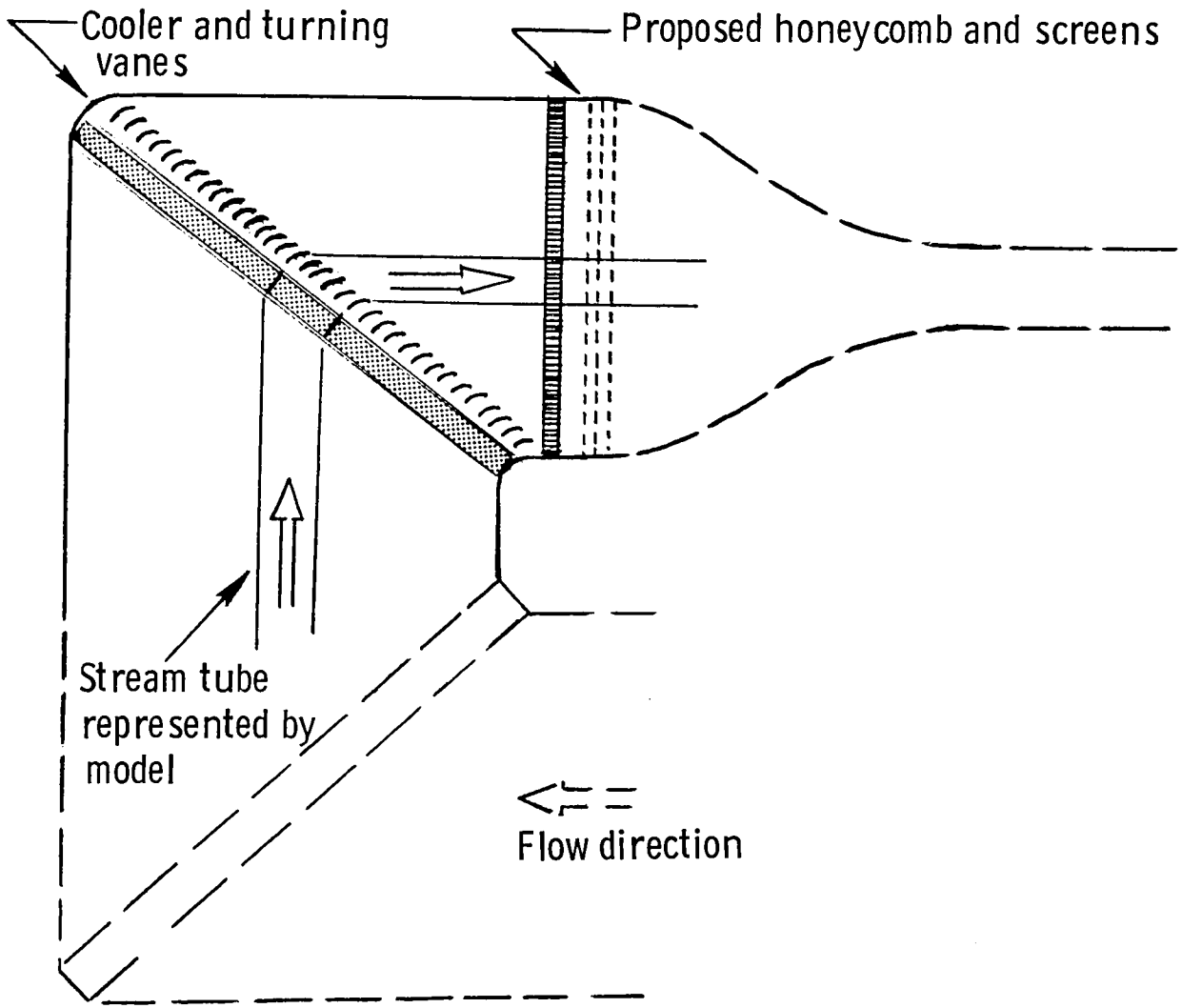


Figure 6.- Section of Langley 8-Foot Transonic Pressure Tunnel represented by model.

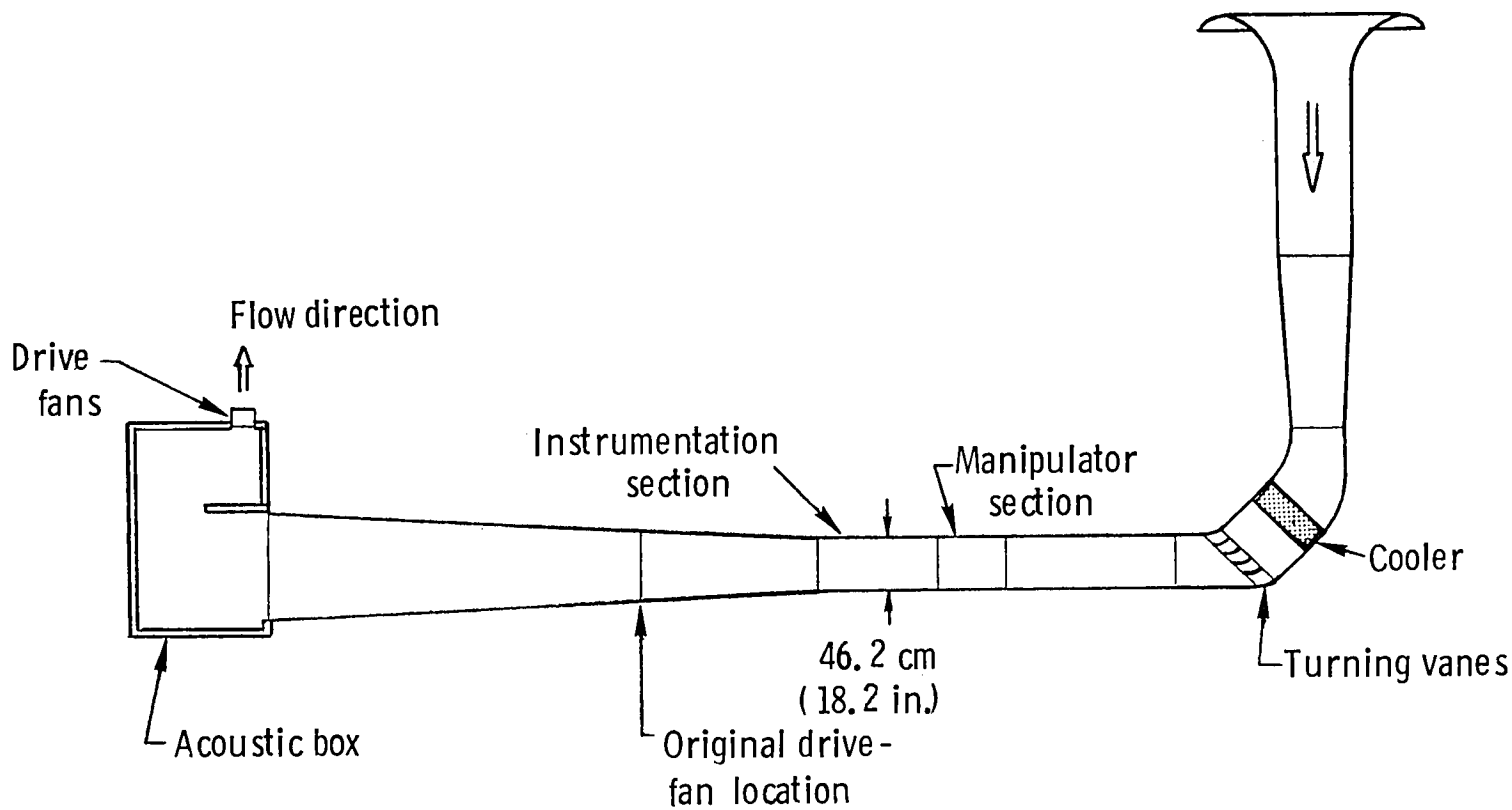


Figure 7.- Test apparatus.

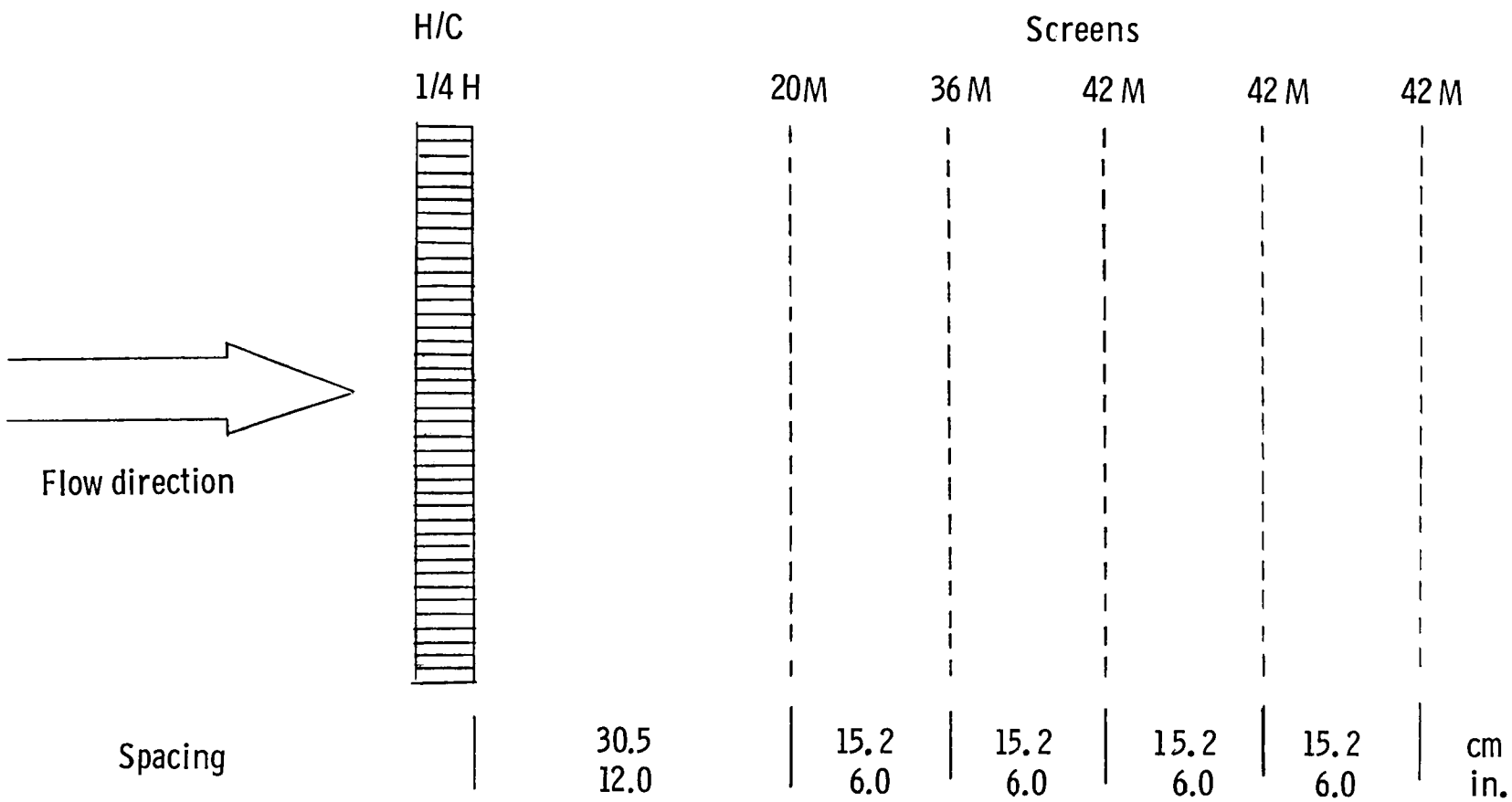


Figure 8.- Honeycomb-plus-screen configuration for initial tests.

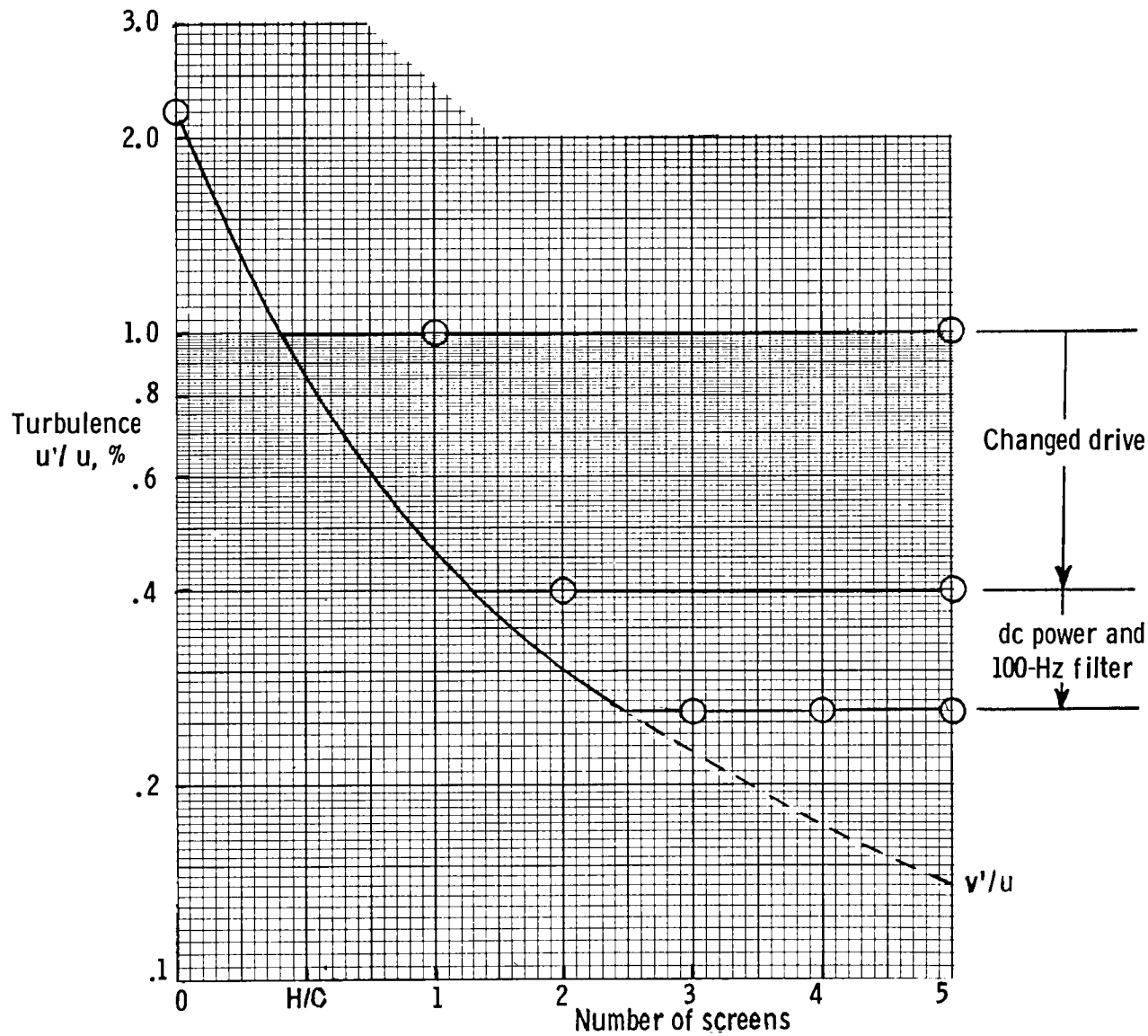
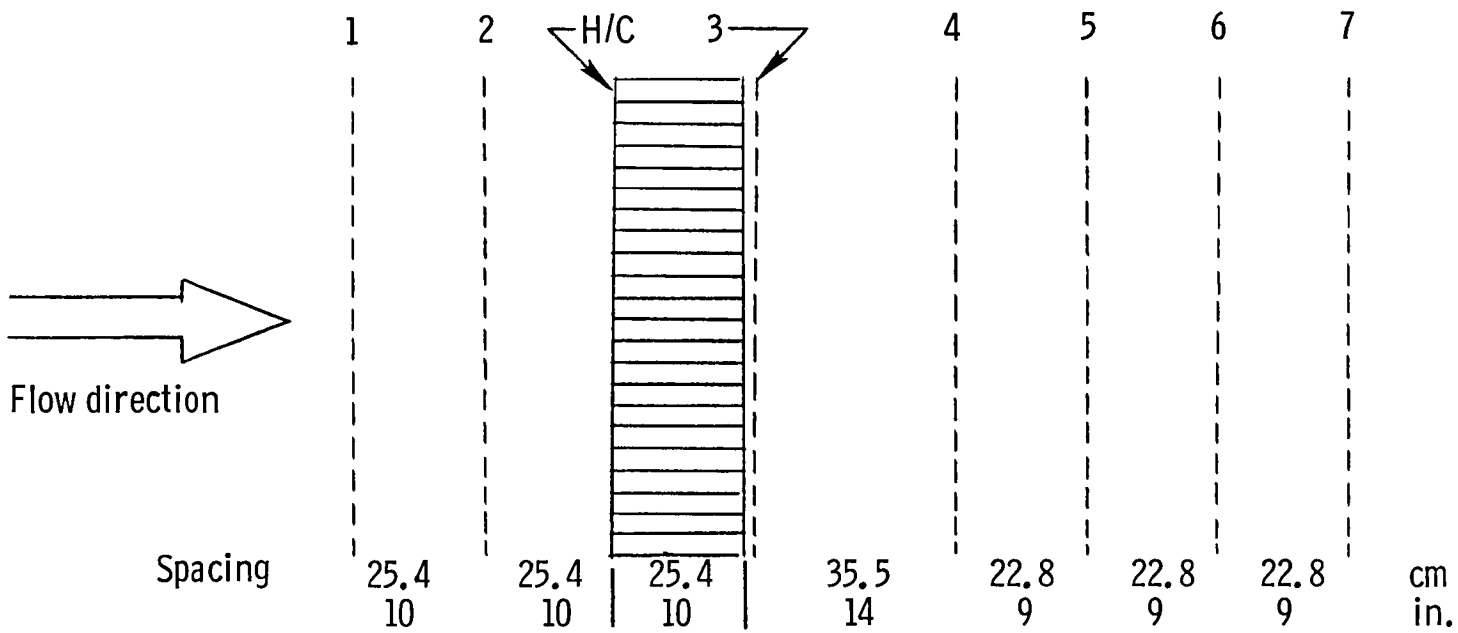


Figure 9.- Illustration of contamination of experiment (or "floor") on u'/u.



		Mesh/cm	Mesh/in.	Open area, %
Honeycomb	H/C	0.79	2	——
Screen	1	1.57	4	41 to 44
	2	3.15	8	41 to 44
	3	6.30	16	70 to 72
	4	11.81	30	↓
	5	15.75	40	
	6	19.68	50	
	7	19.68	50	

Figure 10.- Honeycomb-plus-screen configuration recommended by consultant.

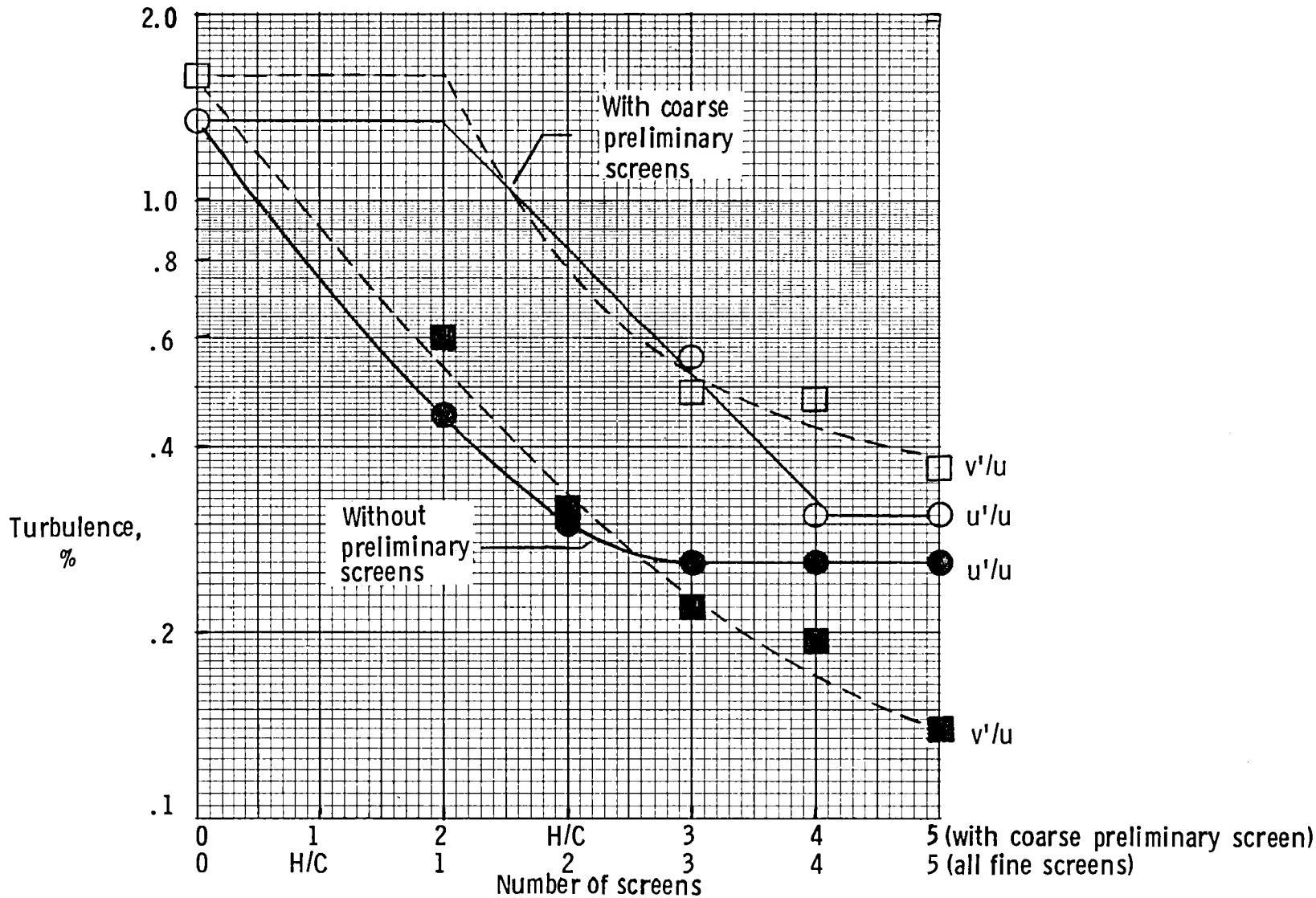


Figure 11.- Reduction of turbulence with honeycomb-plus-screen combinations. 100-Hz high-pass filter.

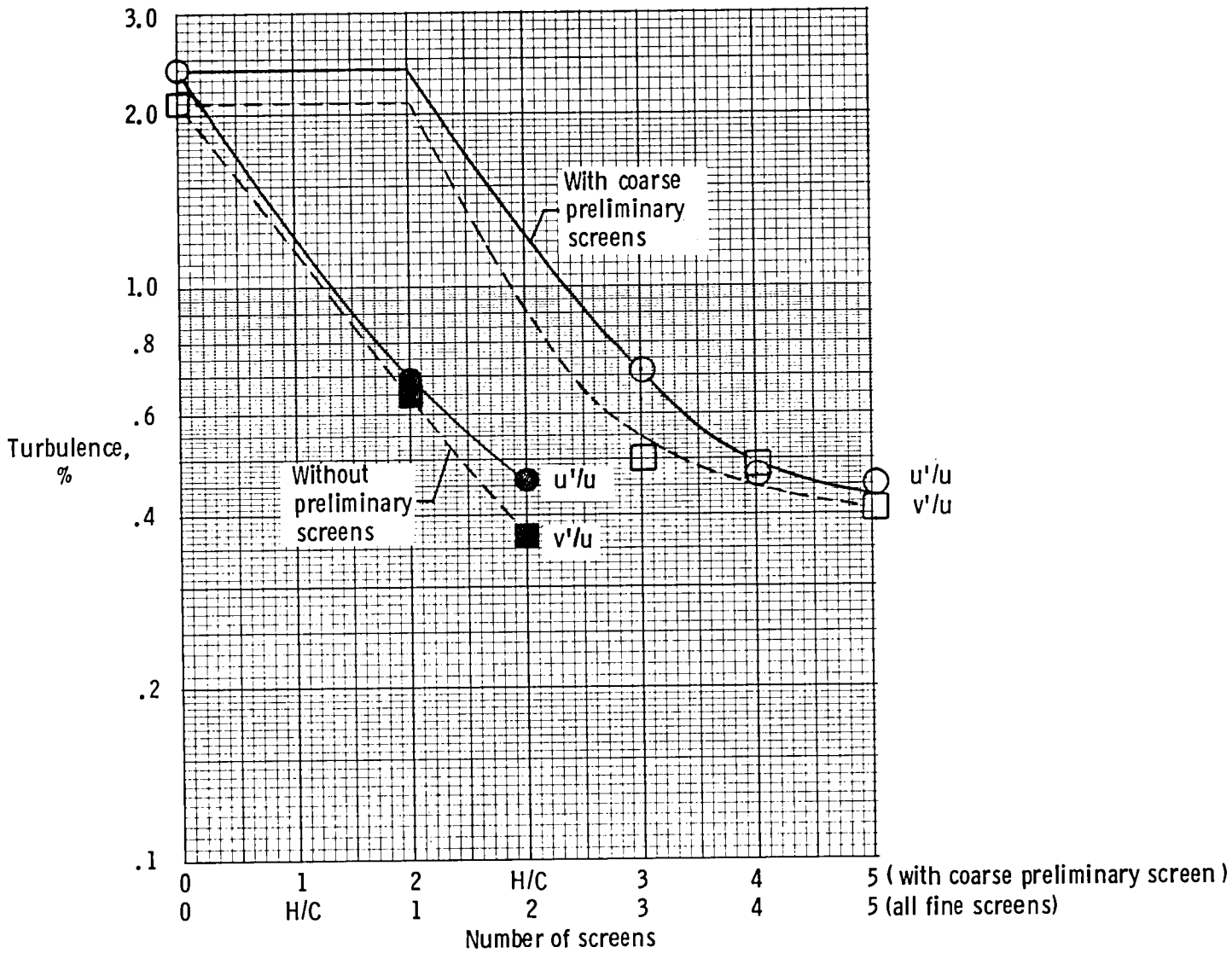


Figure 12.- Reduction of turbulence with honeycomb-plus-screens combinations. 2-Hz high-pass filter.

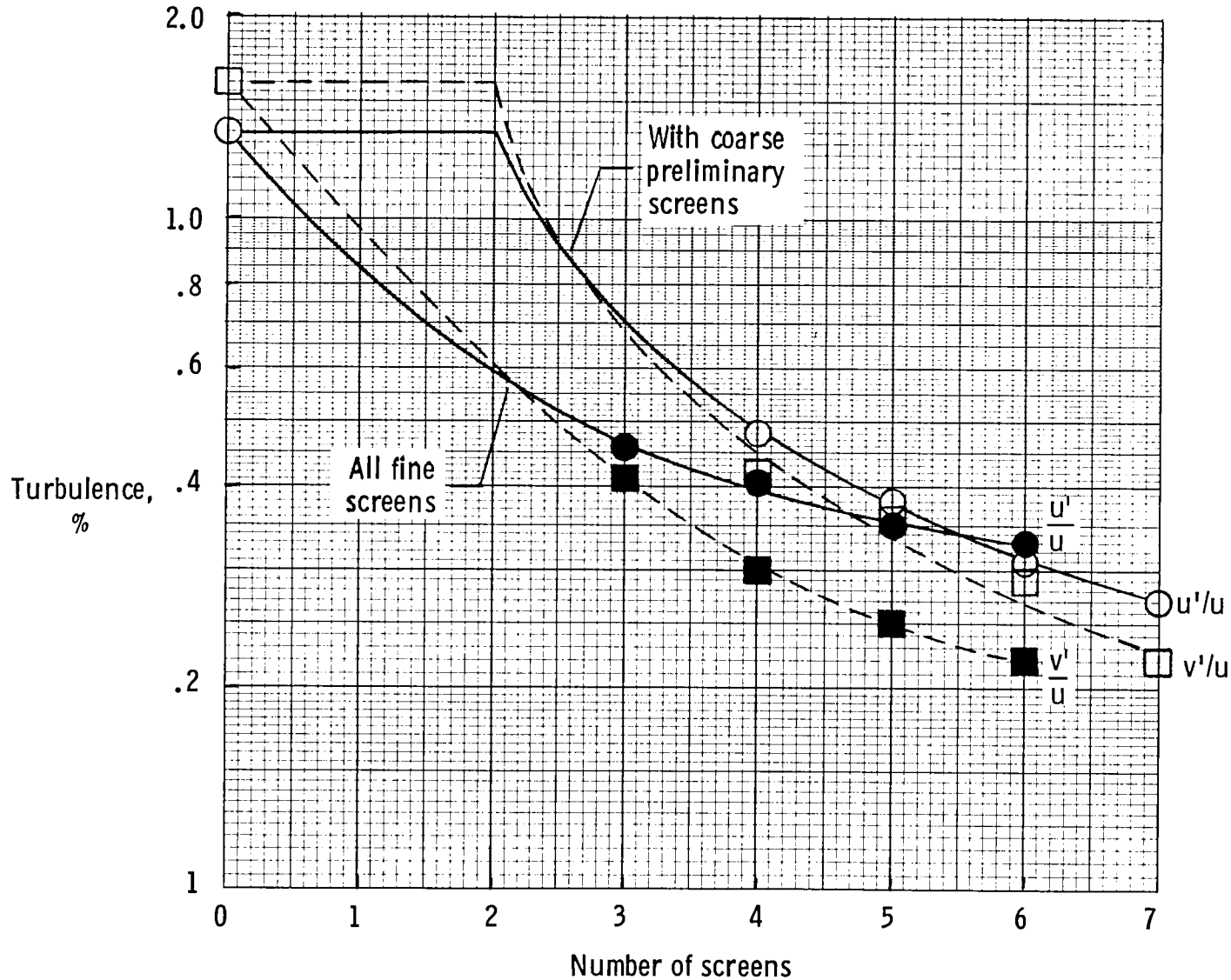


Figure 13.- Reduction of turbulence with screens alone. 100-Hz high-pass filter.

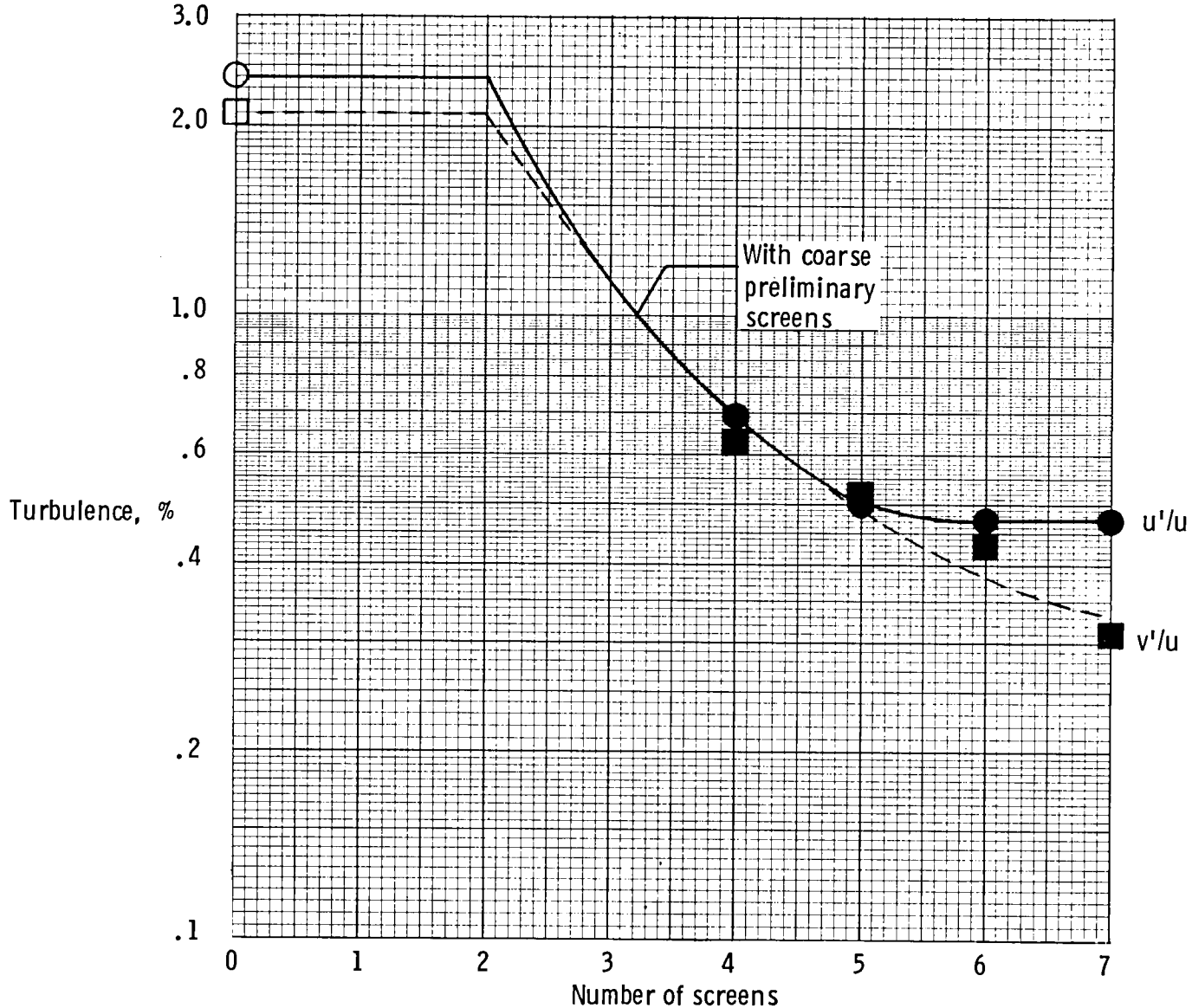


Figure 14.- Reduction of turbulence with screens alone. 2-Hz high-pass filter.

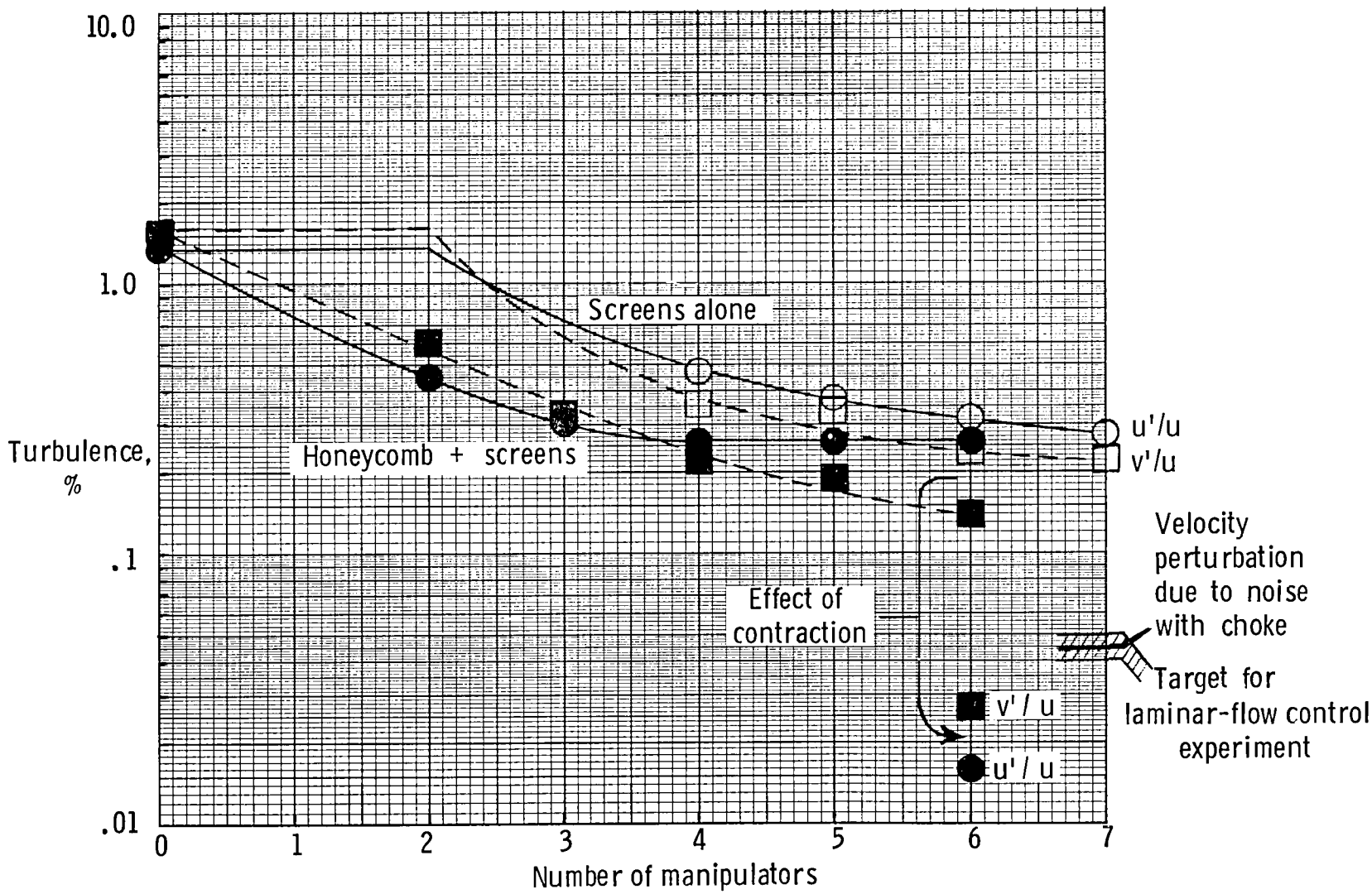


Figure 15.- Comparison of effectiveness of screens-alone and honeycomb-plus-screens combinations. 100-Hz high-pass filter.

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
NASA TM-81792		

4. Title and Subtitle	5. Report Date
EVALUATION OF TURBULENCE REDUCTION DEVICES FOR THE LANGLEY 8-FOOT TRANSONIC PRESSURE TUNNEL	June 1981
	6. Performing Organization Code 505-31-43-02
7. Author(s) Marion O. McKinney and James Scheiman	8. Performing Organization Report No. L-14108
9. Performing Organization Name and Address NASA Langley Research Center Hampton, VA 23665	10. Work Unit No.
	11. Contract or Grant No.
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, DC 20546	13. Type of Report and Period Covered Technical Memorandum
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

Model tests were made of devices for reducing turbulence in the Langley 8-Foot Transonic Pressure Tunnel to permit laminar flow airfoil tests. The test model consisted of a cooler, turning vanes, and settling chamber (immediately upstream of the contraction) in which various combinations of screens and honeycomb were tested. Conventional hot wires were used to measure the axial and lateral turbulence reduction for the different turbulence reduction devices. The final configuration chosen consisted of a honeycomb followed by five screens. Results are presented herein to document this selection.

17. Key Words (Suggested by Author(s))	18. Distribution Statement
Wind tunnel Laminar flow Turbulence reduction	Unclassified - Unlimited Subject Category 09

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	30	A03

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