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The Construction of Airfoil Pressure Models by the Bonded Plate Method: Achievements, Current Research, Technology Development and Potential Applications

Pierce L. Lawing

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National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23665

INTRODUCTION

As noted in references 1 and 2, the 0.3-m Transonic Cryogenic Tunnel (0.3-m TCT) introduced for the first time the capability to test transonically two-dimensional airfoils at flight Reynolds numbers. To utilize this new capability required airfoil models that were constructed of cryogenically compatible materials which were unfamiliar to the model maker. Also, in order to fulfill the potential of the new tunnel to advance the state of the art in experimental transonic fluid dynamics, the models had to be unusually accurate in contour and possess a high degree of dimensional stability during large swings in temperature and force levels. In addition, in order to acquire the "flight" free transition data offered by the high Reynolds number capability, the surface finish of the model had to be very good, particularly in the leading edge region. Altogether, the new and more stringent requirements led to high model costs, and even worse, models that were found to be unfit for testing after construction. Much of the early model experience is documented in references 3 and 4.

A broad effort was mounted at the Langley Research Center to improve the technology for constructing both two and three dimensional models for cryogenic wind tunnels. This effort is documented in references 5, 6, and 7. Of the difficulties encountered during the early model making effort, many had a common source in the plumbing required to access the surface pressure orifices. It was decided that an independent effort to better integrate the plumbing into the model structure would eliminate many of the problems. Reference 3 contains a record of various schemes that were tried, including the concept of grooving the pressure channels into the face of a plate and then bonding on a second plate to form pressure channels, and finally contouring the resulting plate sandwich into an airfoil. It is this concept that appeared most promising, and its continuing development and future potentials are the subject of this paper.

CONSTRUCTION METHODS

Previous Method

A typical airfoil construction procedure in the past has been to rough cut the contour of the airfoil and then mill out relatively large channels in the surface leading to locations where pressure taps were desired. Steel tubing was then laid into the channels to provide access to the taps and the channel filled with a suitable potting compound. Finally, the contour was brought to the final design specifications. In an environment of large temperature changes, differential thermal expansion of the metal model and the potting compound leads to unacceptable changes in the model surface.

In an attempt to circumvent this problem for cryogenic application, a single piece metal cover plate was used to cover a scooped out lower model half. The tubing was brazed to the cover plate to provide connection to the pressure taps. When machining the cover plate to final contour, it was found that the cover "oil-canned", leading to deviations in contour which were too large for transonic work.

The next evolution was to cut channels only along rows of pressure taps, and machine a strong cover plate to fit as shown in figure 1. The cover was then electron-beam welded and the surface finish machined. Although successful models have been constructed by this method, it has proven to be labor intensive, and the method is intolerant of mistakes in the fabrication process. The combination of new requirements, new materials, and the complicated solutions to these problems, led to models that were nearly complete before

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problems were discovered that made the model unfit to test. A common denominator to many of these problems was the bundle of tubing which provided connection to the pressure taps. Several efforts were initiated to improve the technique; one such effort was the inclusion of the plumbing as an integral part of the model.

Construction of Samples

Many small samples were constructed to investigate the bonding technology necessary to seal the integral pressure channels. Results from some of the sample construction programs are contained in references 8 through 11. A typical example of the bonding investigation is shown in figure 2, where a sample has been sectioned to show a bond obtained using brazing foil and a vacuum brazing oven. Also of interest in this figure are the triangular pressure channels, several of which have been cut in the face of each plate. Since the sandwich of plates was laid flat in the brazing oven this becomes a test of gravitational effects. If gravity is a factor in the flow of metal during the braze foil melt, then the channels on the bottom plate would be expected to fill with molten metal. As may be seen, this does not happen and the dominant force is thought to be capillary attraction from the narrow gap between the plates. This speculation is further reinforced when it is realized that the brazing foil was a single thin sheet which also covered the grooves. Close examination shows that during the melt, the portion of the foil covering the grooves partially melted and was drawn away into the adjacent narrow gap.

Construction of Airfoil Model

After a successful bonding technique had been identified, the decision was made to construct an airfoil model suitable for testing in the 0.3-m TCT. The airfoil design chosen was a symmetrical supercritical shape, which was consistent with the flat bond plane bonding and channeling technology which had been developed with the samples. A prime reason for constructing a test article was to learn of unanticipated problems. A very ambitious pressure orifice layout was proposed which not only duplicated the normal practice, but also fully exercised the new capabilities offered by this construction method.

Figure 3 is a photograph of the two halves of the model showing the surfaces to be bonded. The channel layout shown is for 94 orifices. Most of the orifices have been pre-drilled at the proper angle and depth to erupt the model surface during contour machining. At the ends of the model, where the channels are parallel, alternate channels terminate in a "down hole" which is drilled normal to the mating surface. The other half of the channels will mate with down holes drilled in the mating plate. These down holes are intercepted by a connector hole drilled from the end of the plate. These connector holes are to have tubes brazed in to form a connection with the wind tunnel pressure instrumentation system. This method was used to avoid overcrowding, since the larger connector holes would be too closely spaced if drilled side-by-side in the bond plane.

Figure 3 also shows the plates arranged with the channels at the trailing edge matching; in this case trailing edge orifices will be formed by the match of the two channels. There are 8 trailing edge orifice locations shown. The left- and right-hand edges of the plates will become the model leading edge. The fan shaped channel configurations are the top and bottom leading edge pressure tap rows. The right-hand edge is the upper model surface, and the second, smaller fan is a row of orifices to be one-half the diameter of the normal orifices to check for the effect of orifice size near the leading edge. Also visible on the lower right-hand corner are 4 orifice locations, which will be in the model/tunnel wall juncture region. Note that room is provided at the leading and trailing edge for an offcut after brazing. Thus, the dowel holes at the trailing edge will be removed; the smaller dowel holes near mid-chord will have the dowel pins brazed in and will remain in the model. The larger holes near the ends of the plate at mid-chord will remain open and will be used to secure the model during testing.

Figure 4 is a photograph of the model halves and two of the four sheets of brazing foil which were used, as well as two of the alignment dowels and all of the connector tubes. Figure 5 shows the model in the vacuum brazing oven. The cylindrical weights on top of the model are to provide a moderate pressure to force the two pieces together as the brazing foil melts. Figure 6 is a photograph of the model after brazing and rough machining to cut off the excess material from the leading and trailing edges and to form the mounting tangs. At this point it is possible to check the integrity of much of the internal plumbing before the relatively more expensive contour work is performed. Figure 7 shows the model as completed and ready for test.

RESULTS

At this writing, the model has been successfully machined to contour, validation measurements taken, tests run in the 0.3-m TCT, and preliminary data analysis begun. The next two sections will provide a list of the new capabilities demonstrated by this model, a discussion of the problems encountered, and a sample of the aerodynamic data.

New Research Capabilities

Capabilities offered by this new model construction technology and not routinely available on other 2-D airfoil models are as follows:

1. Trailing-edge pressure orifices are easy to install, and installation of a spanwise row of trailing edge orifices may now be routine. The fabrication of even a single trailing-edge orifice was very difficult with previous methods and impossible on thin airfoils.

2. An orifice row at the wing stagnation line-test section wall juncture may now be provided. This capability is extremely difficult to provide with normal methods.

3. There are no appreciable voids in the model to promote structural irregularities during mechanical or thermal stress. The new method uses less than one percent of the model volume for pressure passages.

4. The bonds of near parent metal strength and toughness offer an enhanced margin of safety since the bond line now acts as a crack stopper, and a failure in one half of the model will not easily propagate to the other half.

5. The models inherently have higher strength and may be subjected to larger loads.

6. The expense of building models should be reduced since provision may be made to check all of the pressure channels for leaks and blockage before the relatively more expensive contour machining operations.

7. Model construction costs themselves may be greatly reduced by the reduction of man-hours necessary to install pressure orifices and the related internal pressure tubing.

Problems Encountered

Warpage. The first problem encountered in the construction of this model was warpage of the plates during the vacuum brazing process. This was unexpected since there had been no detectable warpage during the extensive sample construction program. However, the samples were typically 25 percent of the model size, and warpage may be a nonlinear function of size. The warpage was primarily spanwise and resulted in a dip in the bond plane at mid-span of 0.0017 in terms of chord length (or about 0.010 inches). Although small, this deflection was sufficient to prevent the eruption of some of the upper surface pressure orifices, which ultimately had to be located and drilled externally. This was accomplished by taking an x-ray photograph with the film in contact with the model surface. After development, the film was taped to the surface and the orifices were drilled directly through the film. This technique was successful about 80 percent of the time on the first try. It was necessary to drill a second time on the remaining orifices, and all orifices were eventually recovered.

Cross leaks. Due either to imperfect bonding or porosity of the bond itself, cross leaks were detected in approximately 30 channels. Since some of the leaks were on groups of 3 channels, this meant that there were approximately a dozen cases of cross leak. Any detectable leak was ruled a cross leak case, but at the present stage of data analysis, there have been no anomalies in the data directly attributable to cross leaks.

Blocked channels. There were 30 channels through which no flow could be detected. The cause of the blockage is suspected to be from the use of "stop-off" compound during the brazing process. This is standard practice when there is a portion of the work that is not to be brazed. There was no indication that the stop-off was required based on the results of the sample program; but in a spate of over-conservatism, it was used to ensure that the brazing metal did not run onto the channels. The stop-off compound is suspect primarily because it was possible to free some channels of blockage with liquid Freon, which would not have been possible had they been blocked with the brazing alloy.

Aerodynamic Data

Drag rise Mach number. This airfoil is a Langley-developed design and is intended to serve in transonic applications such as vertical control surfaces. The prime objectives of the testing were to determine the suitability of a model constructed using the new technique under cryogenic conditions and to determine the improvement in the drag rise Mach number as compared to a standard airfoil used for similar purposes, in this case the NACA 0012. The tests were conducted in the 0.3-m TCT (the operation of the facility is described in references 1, 2, and 12).

Figure 8 shows preliminary zero lift drag data for the supercritical airfoil and matching data from the NACA 0012, as a function of Mach number. Additional data for the NACA 0012 may be found in reference 13. Both airfoils were tested in the 0.3-m TCT. The test Reynolds number for both data sets is 30 million based on model chord. The data in both cases is uncorrected for changes in angle of attack and Mach number due to wall interference effects. The newer airfoil exhibits a definite improvement in drag rise Mach number. It should be noted that this data comes from a drag survey rake and was not dependent on the new pressure orifices built into the model using the new model construction technique.

Pressure distributions. Figure 9 presents pressure coefficient data at transonic conditions and a moderate lift coefficient. This data shows the presence of a shock wave on the upper surface between 30 and 38 percent chord. Part (a) of this figure is for the model at an angle of attack of 2 degrees, corresponding to a lift coefficient of 0.31. Part (b) is the data of part (a) with the data for -2 degrees, lift coefficient of -0.31, superimposed. The circle symbols are for the upper surface pressure taps and the square symbols are for the lower surface. Since this is a symmetrical airfoil, the pressure signatures at positive and negative angle of attack should match with the upper and lower symbols changing places. As may be observed from part b, the pressures are very nearly the same. This demonstrates good top and bottom symmetry of model construction, good testing technique, and also indicates that the cross leaks between channels mentioned earlier do not contribute significant errors.

NEW RESEARCH

The previous sections have demonstrated the success of the bonded plate technology in producing a useful airfoil model to test. However, the plate warpage problem is not understood, materials having better dimensional stability need to be investigated, the efficiency of the fabrication process obviously could be increased, and there are only a limited number of interesting airfoils which can be produced with flat bond planes. Research efforts by contractors have been funded to remove the deficiencies in the present technology and to promote further advanced technology for the future. The remainder of this section will deal with the progress to date. The effort is slanted somewhat by a desire to produce a "thin" airfoil model not possible with current methods. A thin airfoil is roughly defined in terms of the maximum thickness to chord ratio, where, in terms of fabrication difficulty, any airfoil with a ratio of less than 10 percent is considered thin. However, there are aircraft in service with wings and other components much thinner, and so a goal of 6 percent has been tentatively set. Obviously, a small absolute value of chord length is more difficult to construct than a larger one, and the thinness ratio used here must be accepted as only a loose criteria of fabrication difficulty.

New Bonding Technology

A persistent handicap encountered during this program has been the lack of reliable vacuum brazing methods. This problem has many facets; but for the current application, a principal problem is control over the gap between the two plates being brazed. An obvious solution is brute force loading to suppress any relative movement between the two plates during the thermal cycle of the brazing process. However, use of low stress, wire cut machining may eliminate relative movements, which are due to relaxing mechanical stresses imposed primarily by the various machining processes.

Photoetched Channels

To quote a conclusion of reference 14, "This has been shown to be a highly cost-effective technique for creating a complex network of channels in the surface of 300 series stainless steels and Vascomax 200. It has also proved possible to create matched pairs of channels on both the concave and convex surfaces of profiled bond planes. A particular advantage is the ability to carry out corrective work at the intermediate stages." The work referred to here is an extension of the printed circuit board process where the art work, in this case the channel layout, can be carried out on conveniently large drawings and then photographically reduced to the necessary size. Figure 10a shows the chemically etched channels on a surface. Figure 10b is a magnified view of the same channels and shows the orifice holes drilled at the end of the channel; note the dimples that were etched in at the end of the channel to facilitate the location of the drill bit.

Curved Bond Planes

Figure 11 shows the results of applying the photoetching technology to curved surfaces, in this case one convex and one concave. Figure 12 is a photograph of the same surfaces face-to face but translated to illustrate the curvature. Figure 13 shows a magnified view of the plates after brazing to illustrate the formation of circular channels. This also indicates the precision in location of the top and bottom channel halves. The matching surfaces in these figures were cut with an electrical discharge milling machine using a small wire as the electrode, somewhat in the fashion of the common kitchen cheese slicer.

This process has become known as wire cutting. After the matching surfaces had been brazed together, the wire cut process was once again employed to cut upper and lower contours, in this case the aft section of a 6 percent supercritical airfoil. This piece, along with the superimposed matching offcuts, is shown in figure 14, where the edge of the curved bond plane and the upper and lower surface contours are clearly evident.

The left side of figure 15 shows the exposure of various size orifices as wire cut, as well as a trailing edge orifice. The right side of figure 15 presents magnified views of 1.0, 0.5, and 0.32 mm (0.040, 0.020 and 0.013 inch) diameter orfices to illustrate the quality of the orifice after being machined by the wire cut machine. All of the figures in this section were taken from reference 14, and the reader may find much more detailed information in this source.

Thin Sections

Although the 6 percent airfoil has been a goal of the present efforts at technology advancement, there are applications of thin airfoil technology even when the airfoil is thick such as occurs when the application calls for a sharp, or thin, leading or trailing edge. Historically such geometries have been very difficult to instrument in sufficient detail. This occurs not only because the interior volume is limited, but frequently the local pressure gradients are intense requiring very closely spaced pressure orifices to enable the fluid dynamicist to understand the flow processes taking place. In the present technology, using curved bond planes, the pressure orifice density is limited only by the minimum size hole that can be drilled in the surface, since the pressure channels can be very small.

POTENTIAL APPLICATIONS

Three-Dimensional Models

In the general case, application of the bonded plate method to three-dimensional wings will involve bond planes that cannot be generated by a straight wire in a wire cut machine, and the matching halves of the bonding surface will have to be formed by a process capable of accurately producing a contoured surface. One such process currently in use is the numerically controlled milling machine. If the accuracy and the dimensional stability requirements can be met for the bonding process, then photoetching can be used to create pressure channels, and an arbitrary 3-D airfoil can be fabricated. This scheme has not been tried, but it appears to be a much more difficult task than attempted to date. There is, however, a special class of wings, called conical wings, that can be generated by a straight line and these should be more easily fabricated. Also, there are wing components such as vortex flaps, slats, and other controls that may be essentially two dimensional, or at least conical, so that the bond plane may be generated by a straight line. In addition, pressure instrumented fabrication of components with very small dimensions such as canards, vertical and horizontal tails, and tip fins would be much easier with the bonded plate method.

The multilayer concept sketched in figure 16 is one means of providing more room for pressure channels. This concept may be particularly useful in applications such as a high aspect ratio wing where a row of orifices must be served at many spanwise stations. In this concept each bond line would serve one spanwise orifice row.

Ambient Temperature Tunnels

Thus far the discussion has centered around problems peculiar to cryogenic tunnels, which are primarily differential thermal expansion encountered when dissimilar materials are used, and fabricating the often unfamiliar materials required to meet the combined strength and fracture toughness criteria demanded by the cryogenic environment. The requirement for high fidelity of surface contour is typical of transonic tunnels and the requirements for high strength is characteristic of high Reynolds number tunnels. The constraint of limited instrumentation volume is a function of model configuration and tunnel size. Therefore, the bonded plate method should find application in ambient temperature transonic and supersonic tunnels.

Hypersonic Tunnels

Hypersonic configurations that are designed for efficient cruise performance tend to have thin, highly swept wings and control surfaces with nearly sharp leading edges. These components are uncambered, and when pressure distributions are required, they present an ideal opportunity for application of the bonded plate method. Due to its high strength and excellent dimensional stability during the thermal cycling that accompanies hypersonic testing, 17-4 ph stainless steel is one of the metals of choice for hypersonic models. Even though its very low fracture toughness at cryogenic temperatures prevents its applications in cryogenic tunnels, it was used in the early stages of the bonded plates program because of its good dimensional stability in the brazing oven and the familiarity of the shop personnel with its fabrication characteristics. Using electroplated copper between the plates as an assist, parent metal strength bonding was easily obtained. The process is particularly interesting because the resulting bond was partially brazed and partially diffusion bonded. Figure 17 shows a sample airfoil constructed of 17-4 ph, and figure 18 is a drawing generated by ultrasonic scanning which shows the interior channels and also voids in the bond plane. Since it had no cryogenic application, further development of the technique using 17-4 ph was discontinued, and the research was directed to other metals. The data accumulated using 17-4 ph stainless steel is documented in reference 11.

Thin Airfoils

The present method offers a reasonable solution to one of the major problems in the wind tunnel testing of thin airfoils, which is the inability to provide sufficient instrumentation coverage for airfoil surface pressure measurements. This problem is especially acute for airfoils as thin as 6 percent of chord. Conventional construction techniques have proven too demanding on the volume of material available within thin models to allow a sufficiently dense distribution of pressure orifices to ensure meaningful aerodynamic data. This problem is especially difficult to overcome near the trailing edge of the model. Additional difficulties in terms of the suitability of conventional materials and fabrication techniques have arisen with the introduction of cryogenic operating temperatures in pressurized wind tunnels, such as the U.S. National Transonic Facility (NTF) and the Langley 0.3-m Transonic Cryogenic Tunnel. The ability to properly take advantage of the high Reynolds number capability of these new cryogenic wind tunnels is seriously compromised when adequately instrumented pressure models cannot be readily and routinely produced.

The means of constructing airfoil models of a type not heretofore possible is of obvious value to aeronautics researchers, both experimental and theoretical, since it directly impacts both fighter wing design and advanced turboprops, as well as provides fluid mechanics input to the trailing edge strong interaction problem. In addition, the maturation of this technology will allow full experimental investigation of promising new "sharp leading edge concepts" including the vortex flap, transonic maneuvering supersonic fighters, high L/D hypersonic aircraft, hypersonic missiles, and variable geometry wings.

Cost Reduction

The construction methods being used in this program, although somewhat exotic, are inherently less labor intensive than conventional methods and promise to reduce fabrication costs of 2-D models by at least a factor of two. Since the current cost of a typical 2-D model is $50,000, and the costs of 3-D models are more than an order of magnitude higher, this could result in considerable savings to NASA, as well as to the rest of the aeronautical research community. Also, the sequence of steps in the construction process tends to minimize wasted investment in a given model should failure occur during some critical phase of construction.

TECHNOLOGY SPINOFF

New Materials

The introduction of new materials into the vacuum brazing program is a continuing process. For instance, the stainless steel alloy A-286 is being phased into the advanced part of the program. This alloy has great promise as a material for the construction of cryogenic models, but has been underutilized due to the extreme difficulty of conventional machining, such as ball end mill, for this material. Also the lack of dimensional stability during the machining process, probably due in part to the high stresses of conventional machining, has greatly increased the time in the shop. Since the machining techniques proposed in reference 14 erase the difficulties with cutting A-286, and the techniques demonstrated in references 15, 16, and 17 may be used to control the deflections, this material now has renewed potential.

Artificial Fracture Toughness

The concept of bonding several high strength metals together with a ductile bond has been shown experimentally by both the present author, reference 10, and in reference 18 to produce an end product with a fracture toughness considerably higher than the equivalent single piece of metal in the direction normal to the bonding plane. Traditionally, it has been accepted that a loss in strength is always necessary to accomplish a gain in fracture toughness. A reversal of this trend, even if only along one axis, is an encouraging development; and extensions of this technique may find usage in space and cryogenic technology, as well as the aerospace industry. Concepts such as the one shown earlier in figure 16 would take high advantage of the artificial fracture toughness effect.

Metal Bonding Technology

The type of parent metal strength, high fracture toughness, bonding being developed for use with models to be tested in cryogenic tunnels may also be the type of bond that will be of use in future satellites, spacecraft, and space construction, which must face similar problems in the deep cold of outer space and the severe thermal cycles upon being re-exposed to the sun. The principal advantage lies in the vacuum brazing process. Since it occurs at constant temperature and, therefore in the absence of thermal stresses, it is a joining process having the potential for providing parent metal strength bonding with no distortion of the parent metal. Sufficient insight into the chemistry and physics of the brazing melt layer and/or diffusion process, coupled with multilayered metal-metal composites, may allow development of a new material science leading to ultra-high strength materials that retain their fracture toughness. Also there is an opportunity to extend this technology to the construction of other high strength, high fracture toughness hardware with fluid passages; e.g., cooled turbine blades, scramjet fuel injectors, nuclear reactor heat exchangers, transpiration cooled nose cones, and space radiators and collectors.

CONCLUSIONS

A research and development program to build wind tunnel pressure models centered around the concept of bonding together two plates with the pressure channels cut into the bond plane has been described. Specific conclusions are:

1. The bonded plate method has been used to construct a sophisticated airfoil model which was successfully tested in an advanced cryogenic transonic wind tunnel.

2. Photographic "masking" combined with chemical milling is a very reliable and cost effective method of providing pressure channels suitable for high density pressure instrumentation with minimum demand on parent model material. This technique offers greatly increased flexibility in orifice and pressure channel layout compared to conventional model construction methods.

3. The wire-cut process (electro-discharge-machining) for producing bond planes and airfoil contours works with metals fully compatible for use in models to be tested in cryogenic wind tunnels.

4. Small diameter high quality pressure orifices (i.e., round holes with smooth edges) can be economically produced when pre-drilled blind holes are cut at the model surface by the wire-cut process.

5. With care in the choice of materials and technique, vacuum brazing can be used to produce strong bonds without clogging pressure channels and without degradation of the parent metal strength and toughness.

REFERENCES

1. Kilgore, R. A., and Dress, D. A.: The Application of Cryogenics to High Reynolds Number Testing in Wind Tunnels. Part 1: Evolution, Theory, and Advantages. Cryogenics, pp. 395-402, August, 1984.

2. Kilgore, R. A., and Dress, D. A.: The Application of Cryogenics to High Reynolds Number Testing in Wind Tunnels. Part 2: Development and Application of the Cryogenic Wind Tunnel Concept. Cryogenics, pp. 484-493, September, 1984.

3. Kilgore, Robert A.: Model Design and Instrumentation Experience with Continuous-Flow Cryogenic Tunnels. Paper 9, AGARD/VKI LS-111, May 1980.

4. Lawing, P. L.; and Kilgore, R. A.: Model Experience in the Langley 0.3-m Transonic Cryogenic Tunnel. Presented at the Workshop on High Reynolds Number Research, NASA CP-2183, December 1980.

5. Young, C. P.; Bradshaw, J. F.; Rush, H. F., Jr.; Wallace, J. W.; and Watkins, V. E., Jr.: Cryogenic Wind Tunnel Model Technology Development Activities at the NASA Langley Research Center. Paper No. AIAA 84-0586, 1984.

6. Young, Clarence P., Jr.: Design and Construction of Models for the National Transonic Facility-I. Paper 4, AGARD R-722, 1985.

7. Young, Clarence P., Jr.: Design and Construction of Models for the National Transonic Facility-II. Paper 5, AGARD R-722, 1985.

8. Lawing, P. L.; Sandefur, P. G., Jr.; and Wood, W. H.: A Construction Technique for Wind-Tunnel Models. Tech Brief, LAR-12710, Fall 1980.

9. Wigley, D. A.; Sandefur, P. G., Jr.; and Lawing, P. L.: Preliminary Results on the Development of Vacuum Brazed Joints for Cryogenic Wind Tunnel Aerofoil Models. ICMC preprint, San Diego, CA, August 10-14, 1981.

10. Lawing, P. L.; Wood, W. H.; and Sandefur, P. G., Jr.: Method for Increasing Fracture Toughness of Metals. NASA Tech Brief LAR-12805, Spring 1982.

11. Wigley, D. A.: The Structure and Properties of Diffusion Assisted Bonded Joints in 17-4PH, TYPE 347, 15-5PH and Nitronic 40 Stainless Steel. NASA CR 165745, July 1981.

12. Ray, E. J.; Ladson, C. L.; Adcock, J. B.; Lawing, P. L.; and Hall, R. M.: Review of Design and Operational Characteristics of the 0.3-Meter Transonic Cryogenic Tunnel. NASA TM-80123, September 1979.

13. Ladson, C. L.: Status of Advanced Airfoil Tests in the Langley 0.3-Meter Transonic Cryogenic Tunnel. Paper Presented at the Fifth Annual Status Review of the NASA ACEE Transport Program Held at Dryden Flight Research Center, Edwards, California. NASA CP-2208, September 14-15, 1981.

14. Wigley, D. A.: Technology For Pressure-Instrumented Thin Airfoil Models. NASA CR 3891, Contract NAS1-17571, May 1985. (Phase I SBIR)

15. Wigley, D. A.: The Dimensional Stability Analysis of Seventeen Stepped Specimens of 18 Nickel 200 Grade Maraging Steel, PH13-8Mo, and A286, NASA CR-172168, 1983.

16. Wigley, D. A.: The Problem of Dimensional Instability in Airfoil Models for Cryogenic Wind Tunnels. NASA CR-16603, 1982.

17. Wigley, D. A.: Machining-Induced Deformation in Stepped Specimens of PH13-8M., 18 Nickel Maraging Steel Grade 200Ti and Grain-Refined HP 9-4-20. NASA CR-172450, 1984.

18. Wigley, D. A.: The Metallurgical Structure and Mechanical Properties at Low Temperature of Nitronic 40, with Particular Reference to its Use In the Construction of Models for Cryogenic Wind Tunnels. NASA-CR-165097, 1982.

BIBLIOGRAPHY

1. Tuttle, Marie H.; Kilgore, Robert A.; and McGuire, Peggy D.: Cryogenic Wind Tunnels - A Selected, Annotated Bibliography. NASA TM-86346, April 1985.

2. Schachterle, G.; Ludewig, K. H.; Stanewsky, E.; and Ray, E. J.: Design and Construction of Two Transonic Airfoils for Tests in the NASA Langley 0.3-m TCT. Paper presented at the ETW Cryogenic Technology Review Meeting, Amsterdam, September 15-17, 1982.

3. Kilgore, R. A.; Dress, D. A.; and Lawing, P. L.: Some of the Capabilities and Desirable Features of an "Ideal" Transonic Wind Tunnel. NASA TM-85484, November 1983.

4. Lawing, P. L.; Adcock, J. B.; and Ladson, C. L.: A Fan Pressure Ratio Correlation in Terms of Mach Number and Reynolds Number for the Langley 0.3-Meter Transonic Cryogenic Tunnel. NASA TP-1752, November 1980.

5. Ladson, C. L.; and Kilgore, R. A.: Instrumentation for Calibration and Control of a Continuous-Flow Cryogenic Tunnel. NASA TM-81825, May 1980.

6. Johnson, C. B.: A Study of Non-Adiabatic Boundary-Layer Stabilization Times in a Cryogenic Tunnel for Typical Wing and Fuselage Models. Presented at the AIAA 11th Aerodynamic Testing Conference, Colorado Springs, Colorado, March 18-20, 1980.

7. Adcock, J. B.; and Johnson, C. B.: A Theoretical Analysis of Simulated Transonic Boundary Layers in Cryogenic-Nitrogen Wind Tunnels. NASA TP-1631, March 1980.

8. Stainback, P. C.; and Johnson, C. B.: "A Probe and Data Reduction Technique for Obtaining Hot Wire Data at Transonic Speeds" in the Flow Quality Measurements in Transonic Wind Tunnels and Planned Calibration of the National Transonic Facility Appendix. NASA CP-2183, pp. 113-121, High Reynolds Number Research - 1980, December 1980.

9. Johnson, C. B.; and Adcock, J. B.: Measurement of Recovery Temperature on an Airfoil in the Langley 0.3-m Transonic Cryogenic Tunnel. Presented at the AIAA 16th Thermophysics Conference, Palo Alto, California, June 23-25, 1981.

10. Boyden, R. P.; and Johnson, W. G., Jr.: Results of Buffet Tests in a Cryogenic Wind Tunnel. NASA TM-84520, September 1982.

11. Johnson, W. G., Jr.; Hill, A. S.; Ray, E. J.; Rozendaal, R. A.; and Butler, T. W.: High Reynolds Number Tests of a Boeing BAC I Airfoil in the Langley 0.3-Meter Transonic Cryogenic Tunnel. NASA TM-81922, April 1982.

12. Dress, D. A.; Johnson, C. B.; McGuire, P. D.; Stanewsky, E.; and Ray, E. J.: High Reynolds Number Tests of the CAST 10-2/DOA 2 Airfoil in the Langley 0.3-Meter Transonic Cryogenic Tunnel - Phase I. NASA TM-84620, May 1983.

13. Murthy, A. V.; Johnson, C. B.; Ray, E. J.; Lawing, P. L.; and Thibodeaux, J. J.: Studies of Sidewall Boundary Layer in the Langley 0.3-Meter Transonic Cryogenic Tunnel With and Without Suction. NASA TP-2096, March 1983.

14. Stanewsky, E.; Demurie, F.; Ray, E. J.; and Johnson, C. B.: High Reynolds Number Test of the CAST 10-2/DOA 2 Transonic Airfoil at Ambient and Cryogenic Temperature Conditions. AGARD-CP-348, AGARD Fluid Dynamics Panel Symposium on Wind Tunnels and Testing Techniques, Cesme, Turkey, September 26-29, 1983.

15. Johnson, C. B.: CAST 10-2 Airfoil Studies With Sidewall Boundary Layer Removal. Research and Technology, 1983 Annual Report of the Langley Research Center, pp. 6-7, NASA TM-85702, December 1983.

16. Jenkins, R. V.: Reynolds Number Tests of an NPL 9510 Airfoil in the Langley 0.3-Meter Transonic Cryogenic Tunnel. NASA TM-85663, November 1983.

17. Boyden, R. P.; Johnson, W. G., Jr.; and Ferris, A. T.: Aerodynamic Force Measurement With a Strain-Gage Balance in a Cryogenic Wind Tunnel. NASA TP-2251, December 1983.

18. Wigley, David A.: Basic Cryogenics and Materials. NASA CR 177932, June 1985.

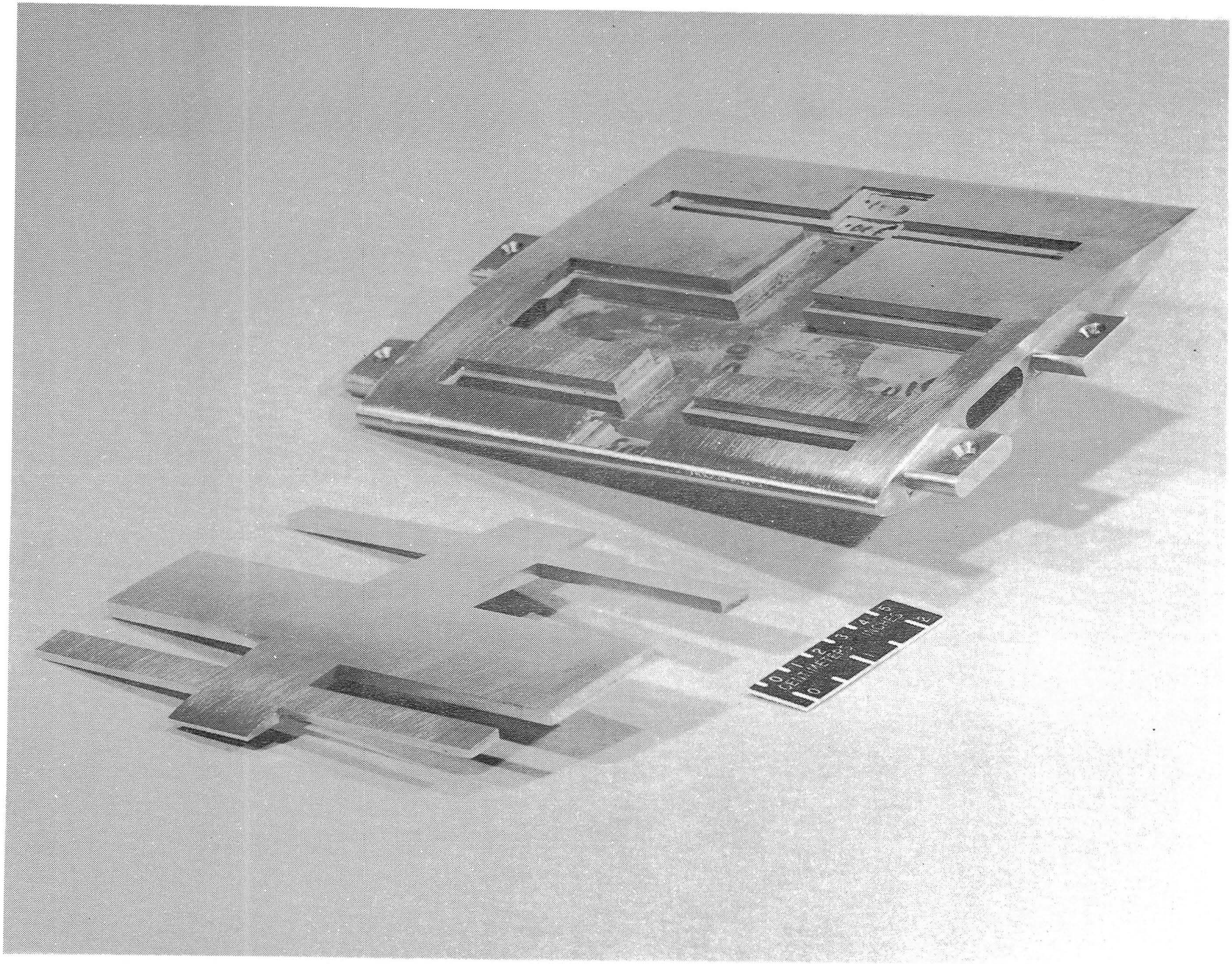


Figure 1.- Photograph of two dimensional airfoil body and cover showing complex void for pressure orifice tubing.

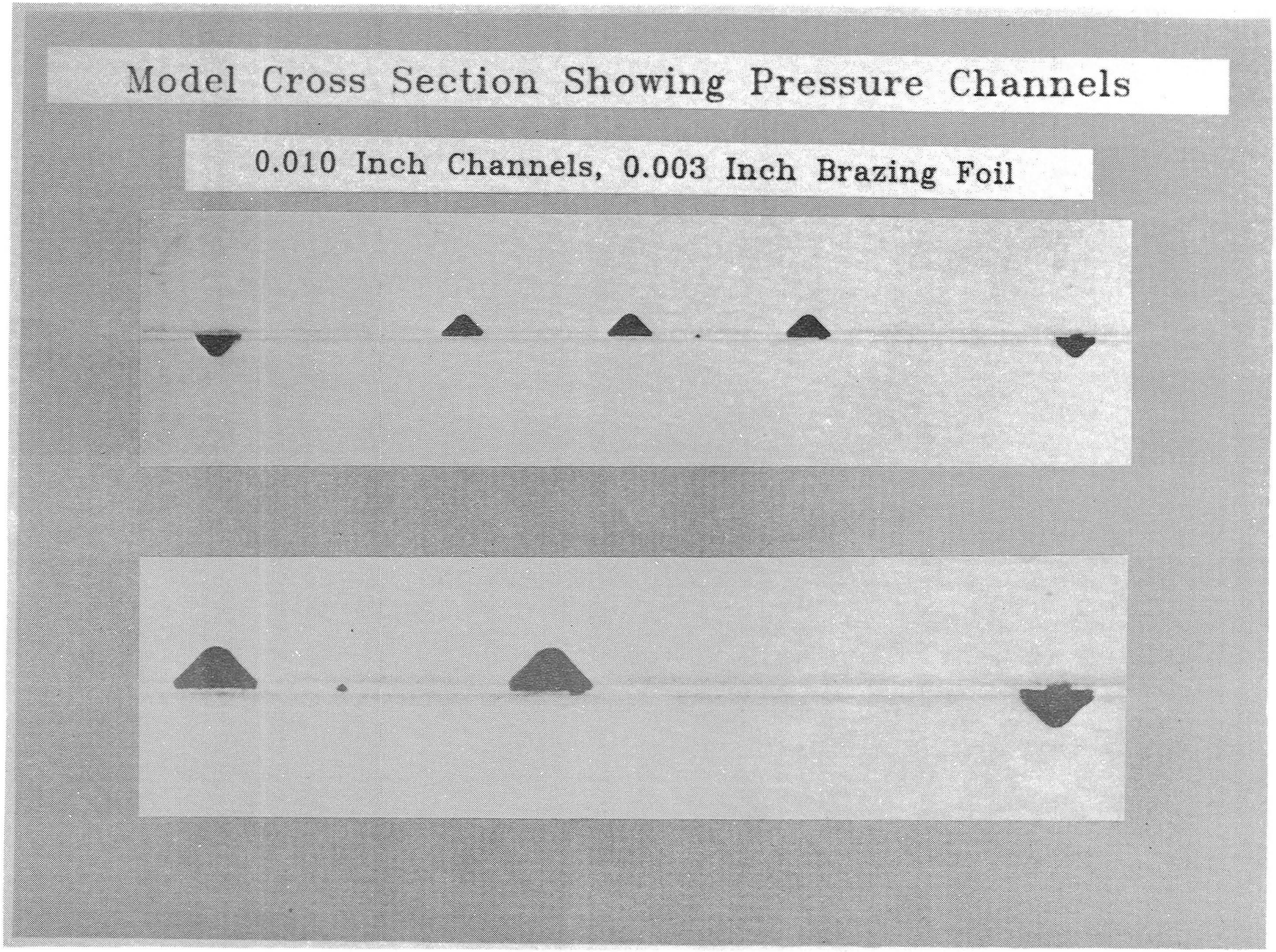


Figure 2.- Cross section through sample showing brazed joint and pressure channels.

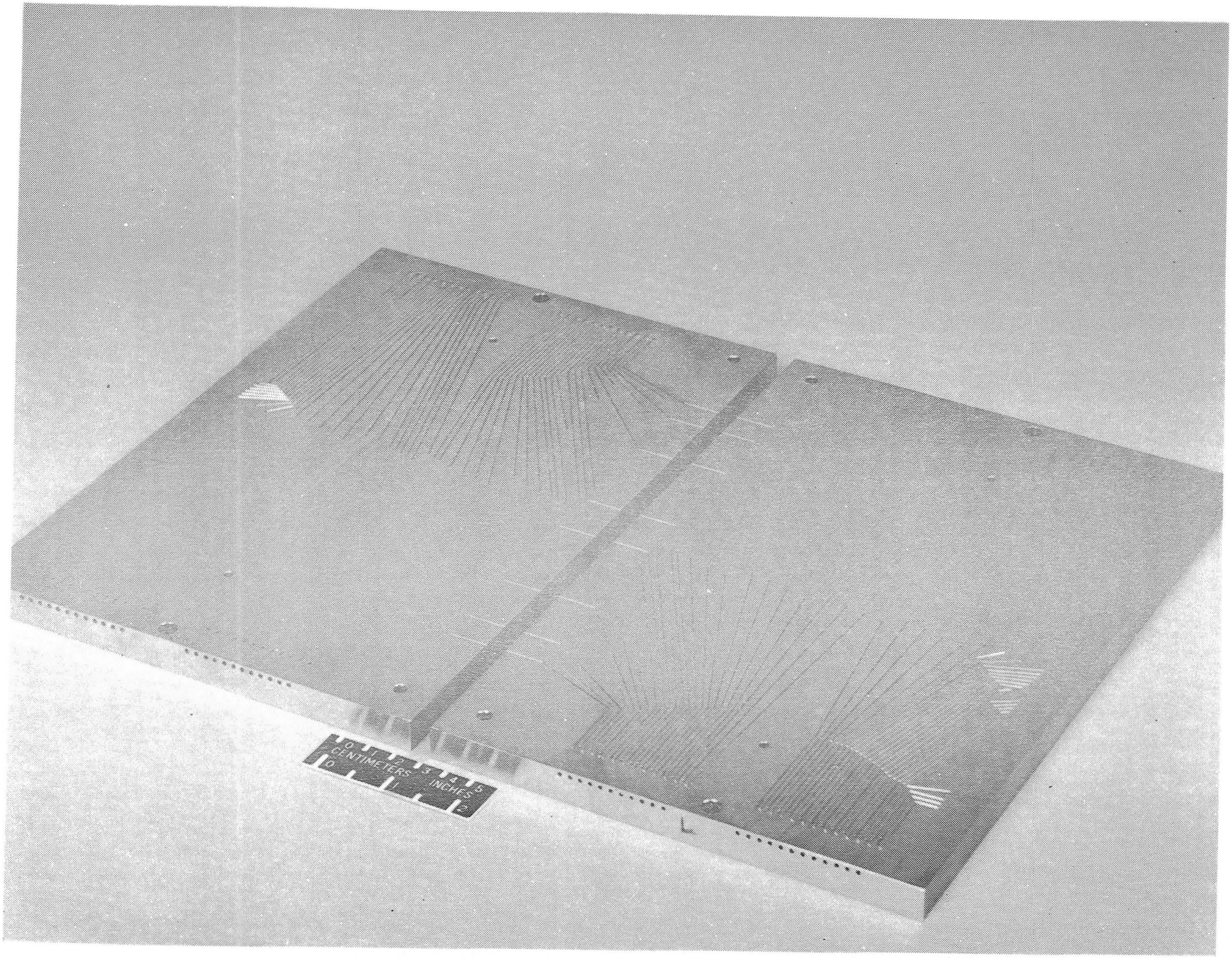


Figure 3.- Plates for symmetrical airfoil model shown prior to brazing to illustrate pressure channel layout.

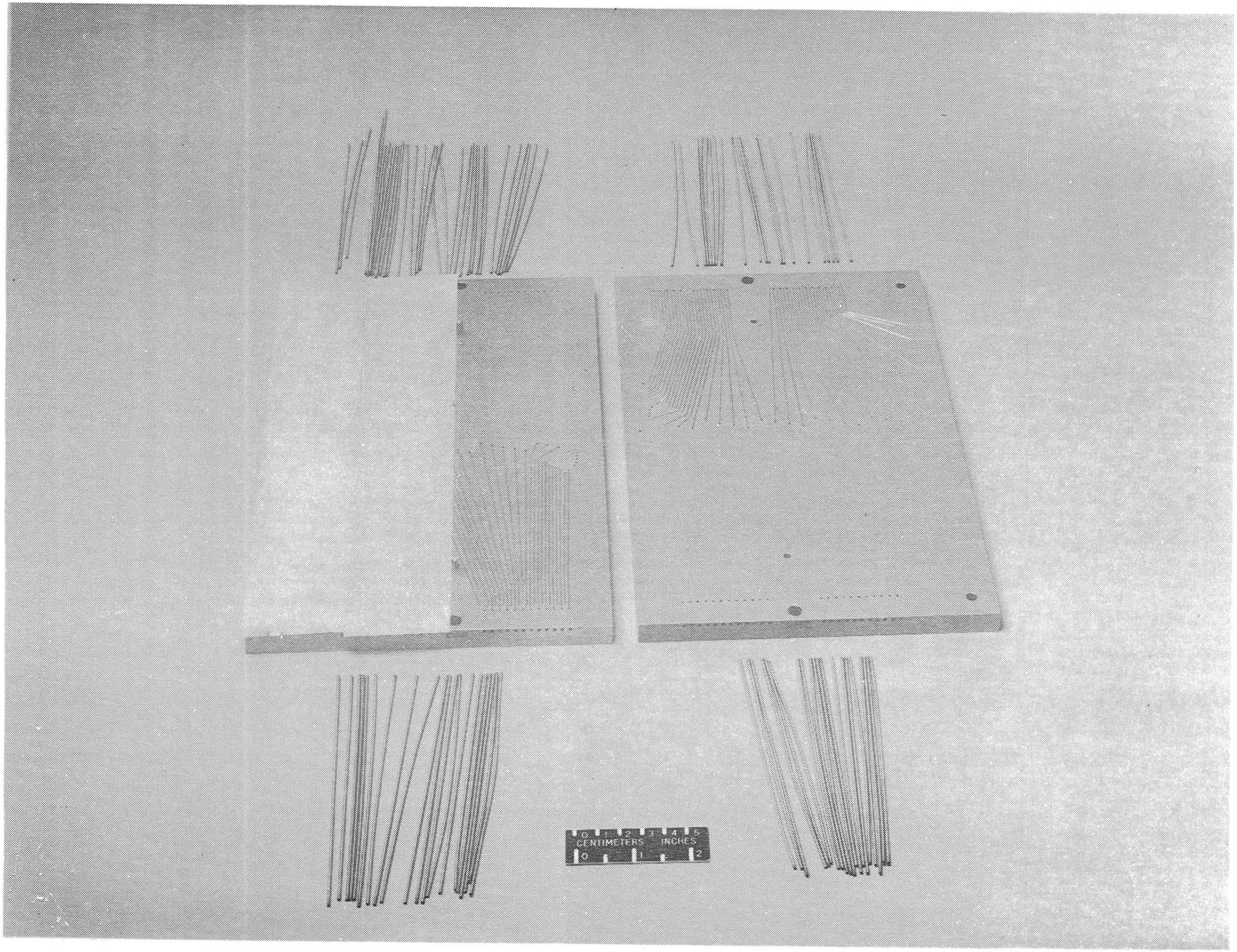


Figure 4.- Plates, connector tubing, and 2 of 4 pieces of brazing foil for symmetrical airfoil model.

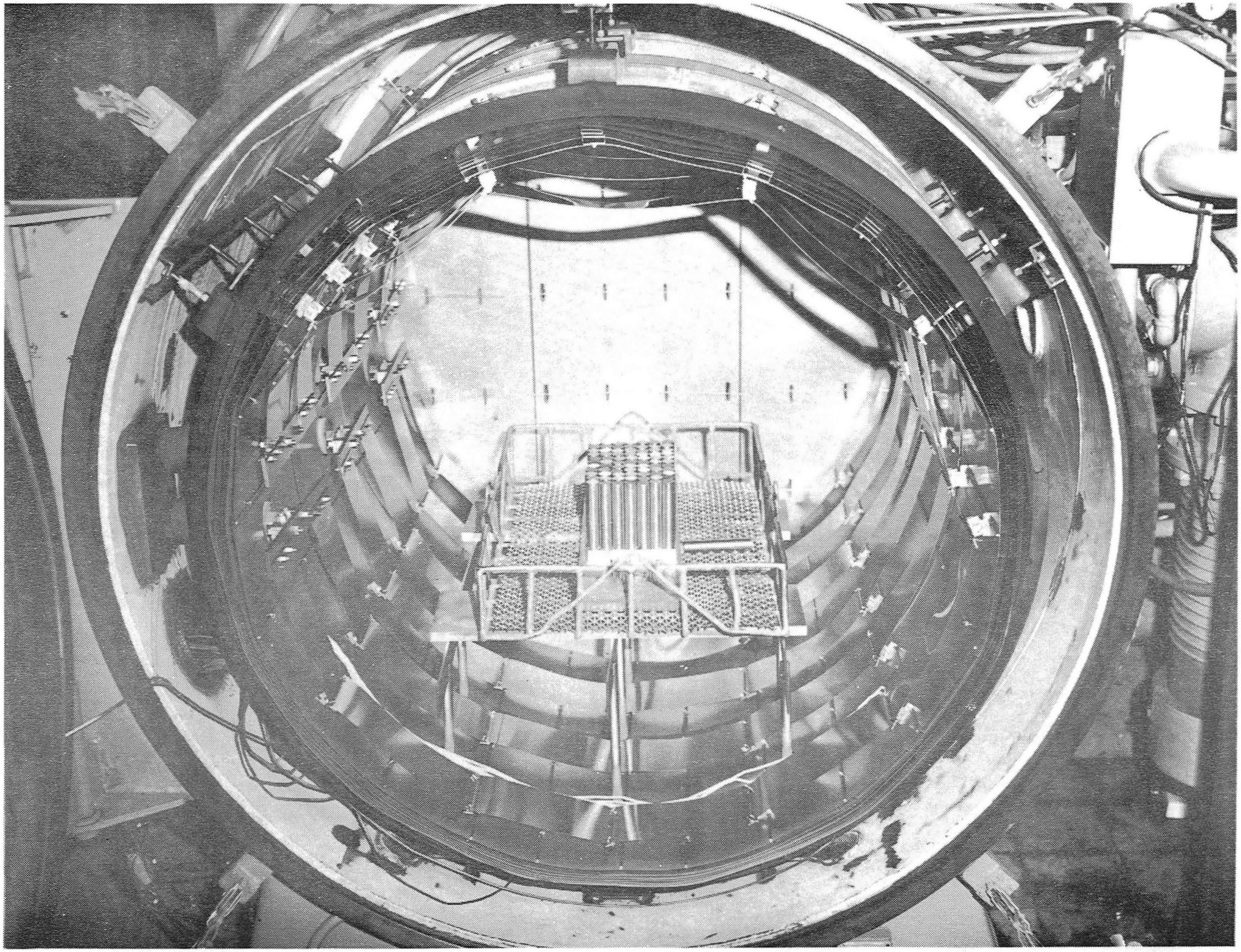


Figure 5.- Symmetrical airfoil model positioned in vacuum brazing furnace, with cylindrical weights in place.

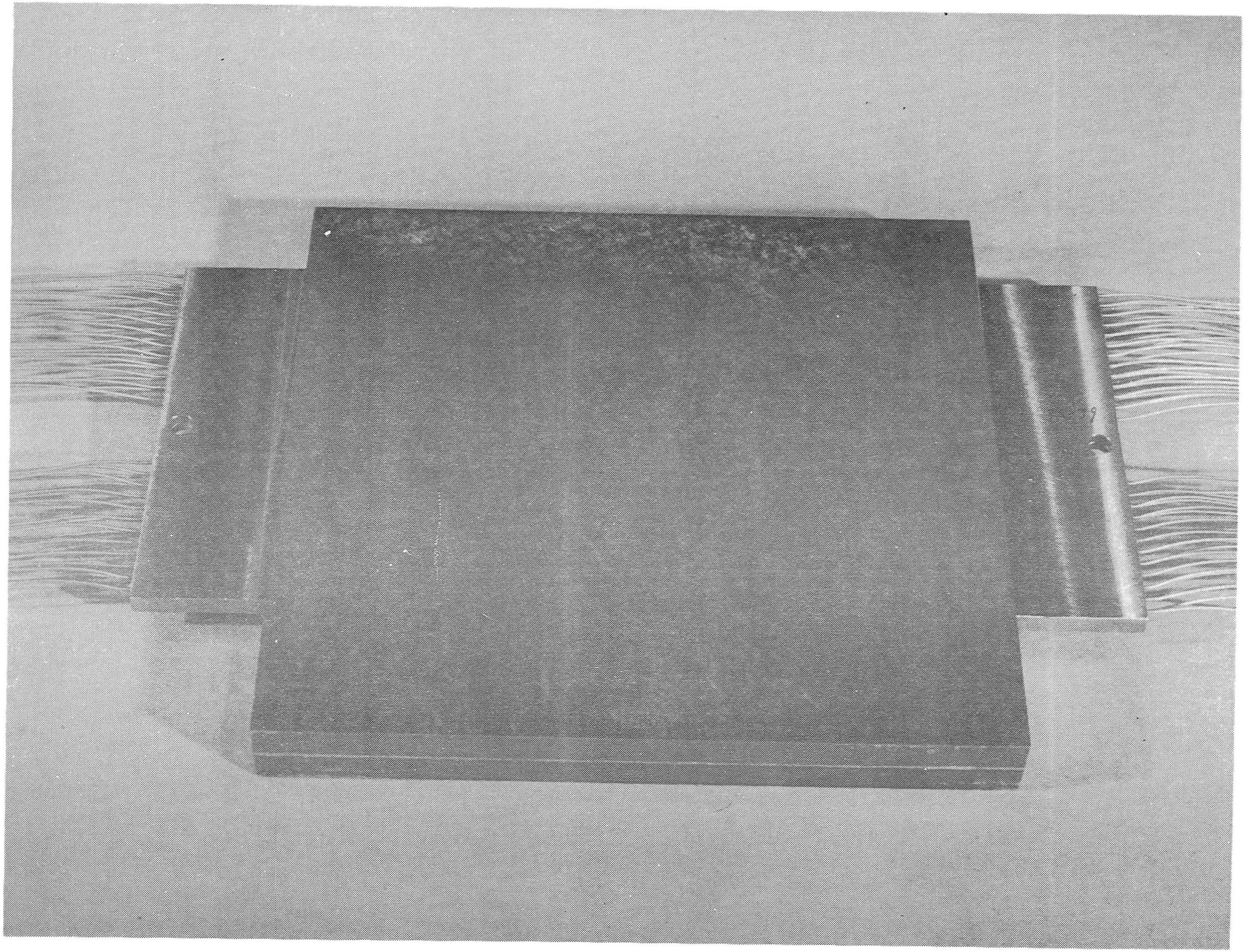


Figure 6.- Symmetrical airfoil model after vacuum brazing; model now ready for leak check.

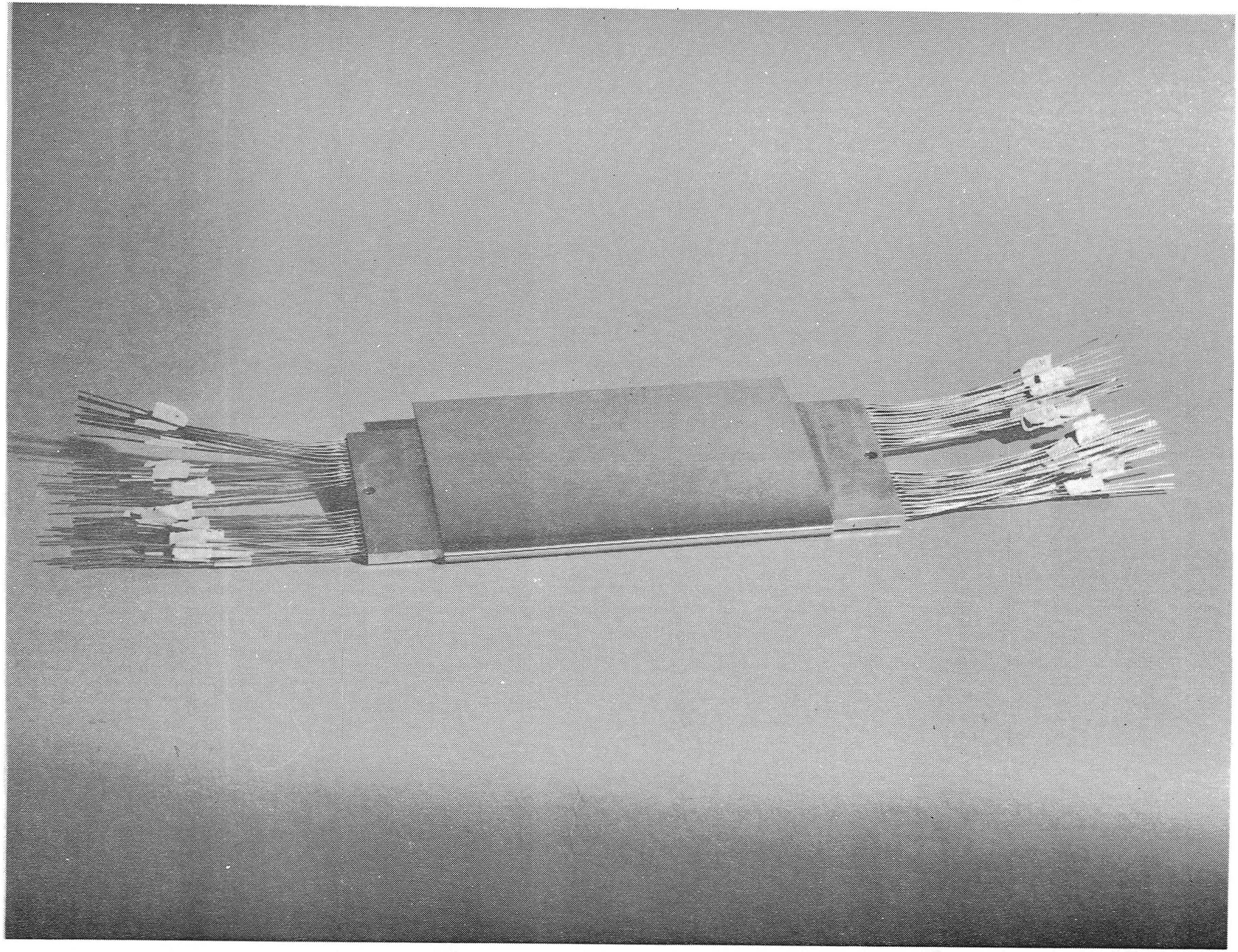


Figure 7.- Ready for test symmetrical airfoil model fabricated by the bonded plate method.

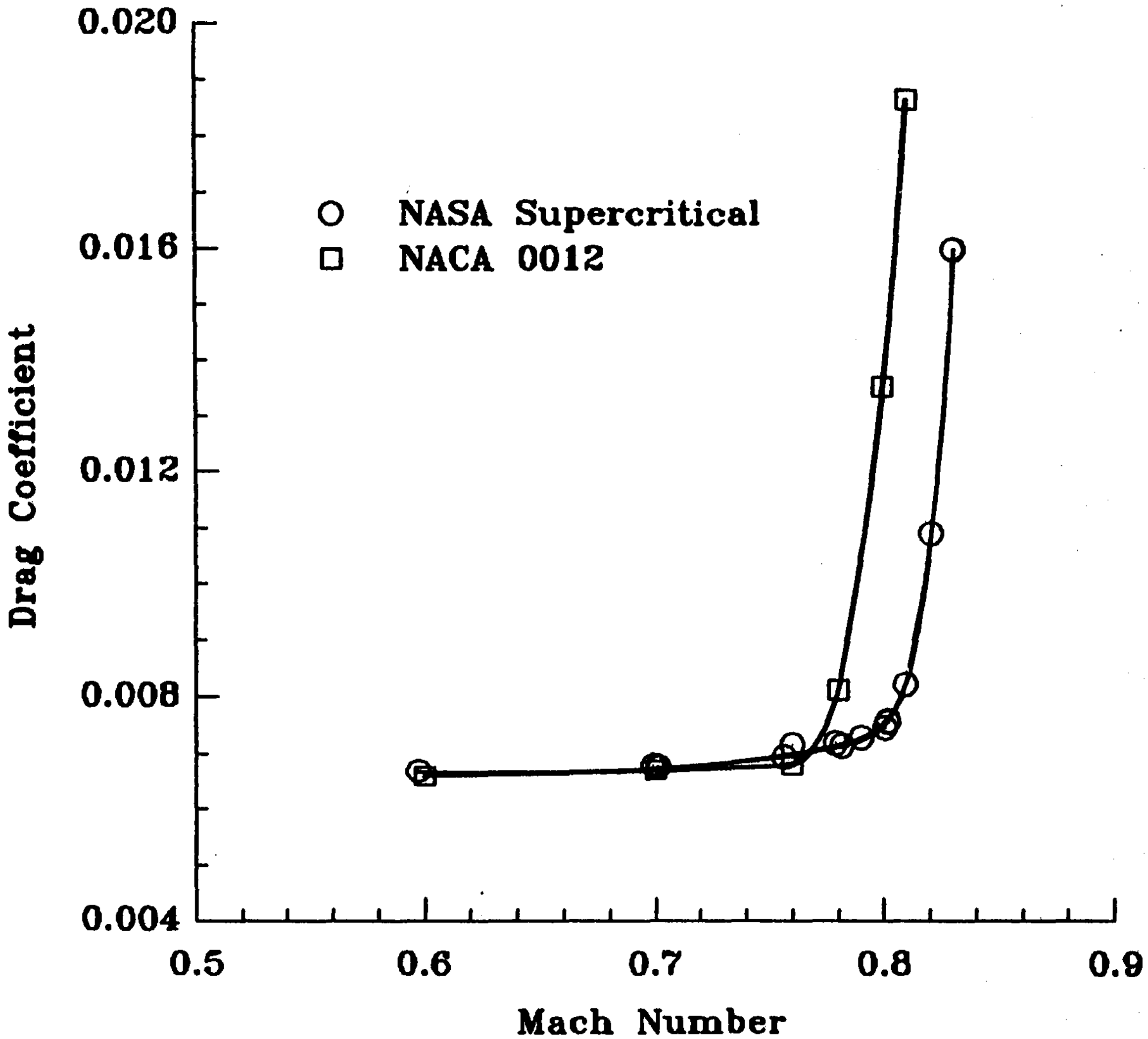
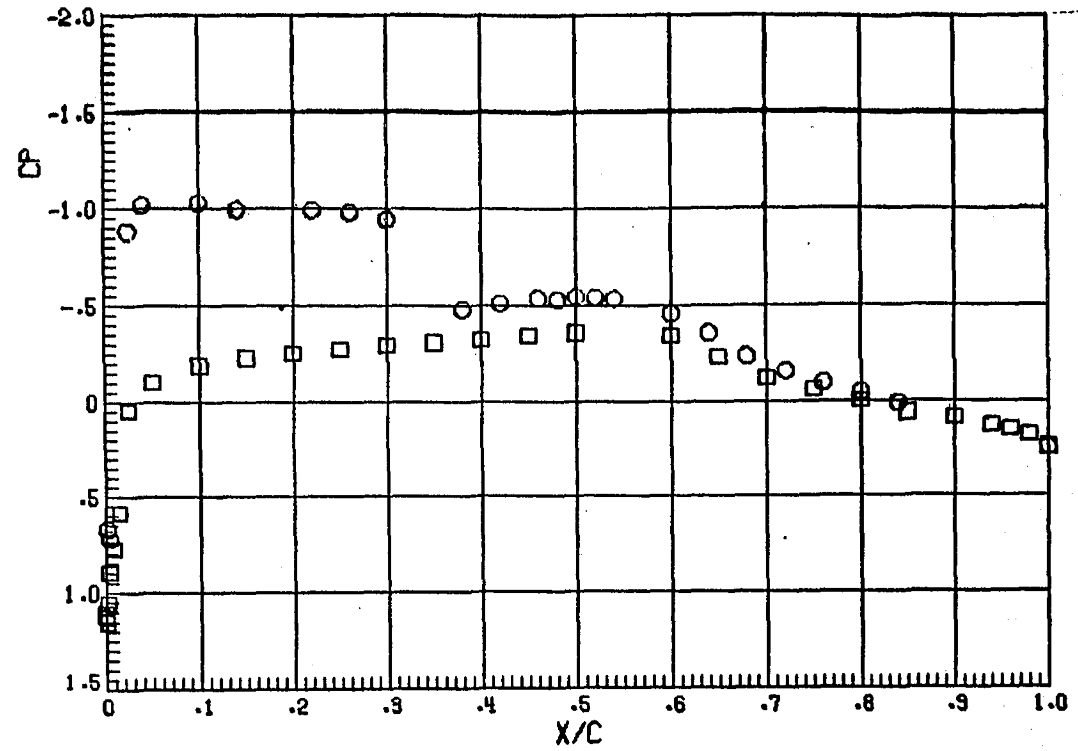
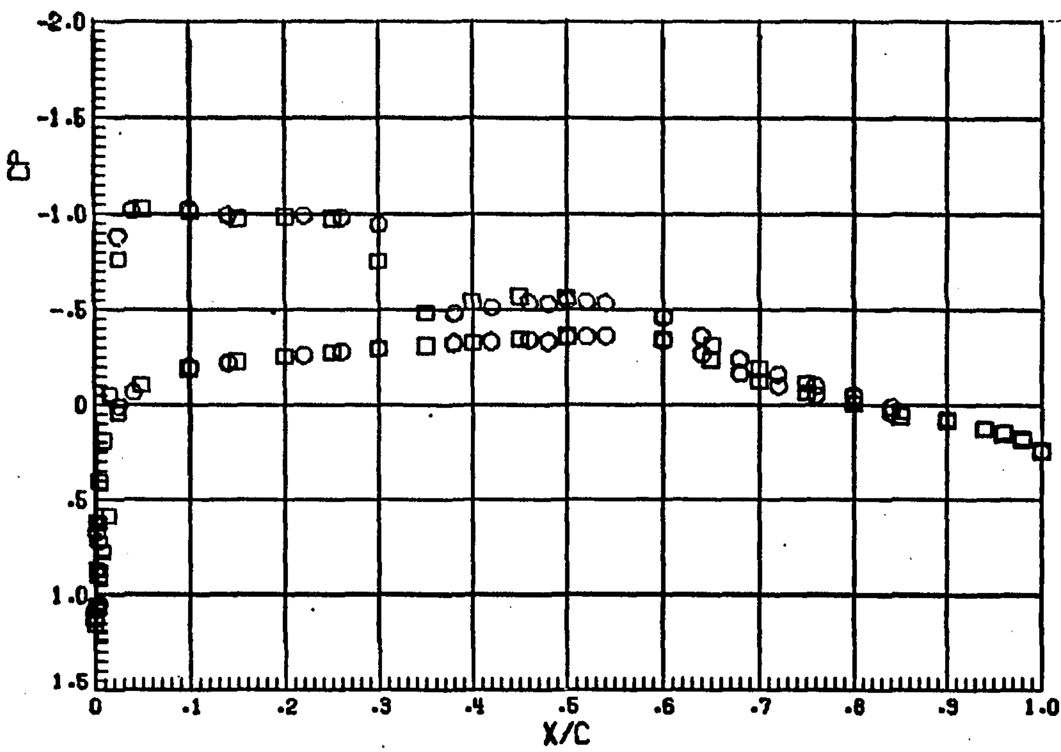


Figure 8.- Drag coefficient as a function of Mach number for the NACA 0012 airfoil and the symmetrical airfoil. Tests conducted at a chord Reynolds number of 30 million.

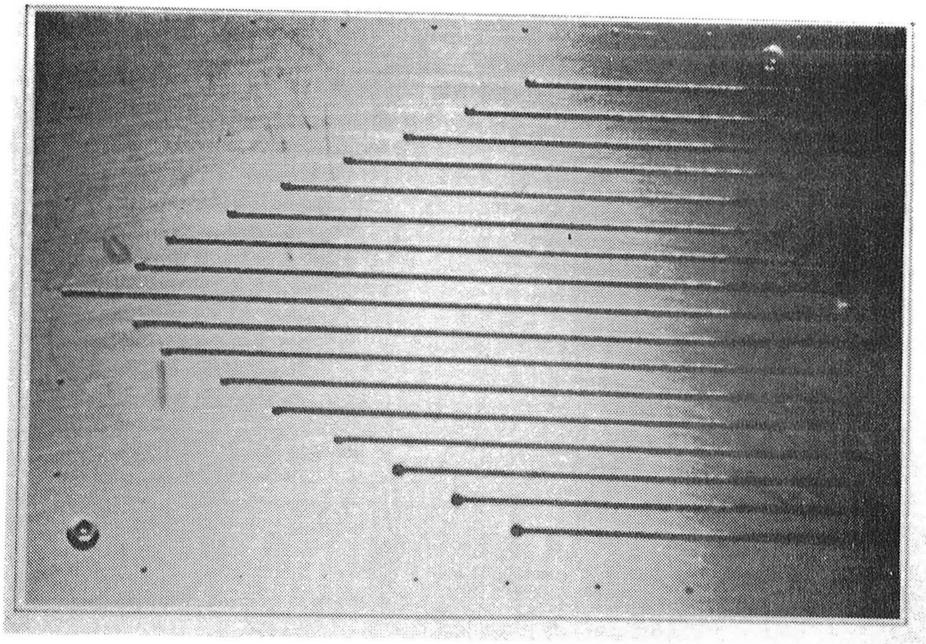


(a) Lift coefficient of 0.31.

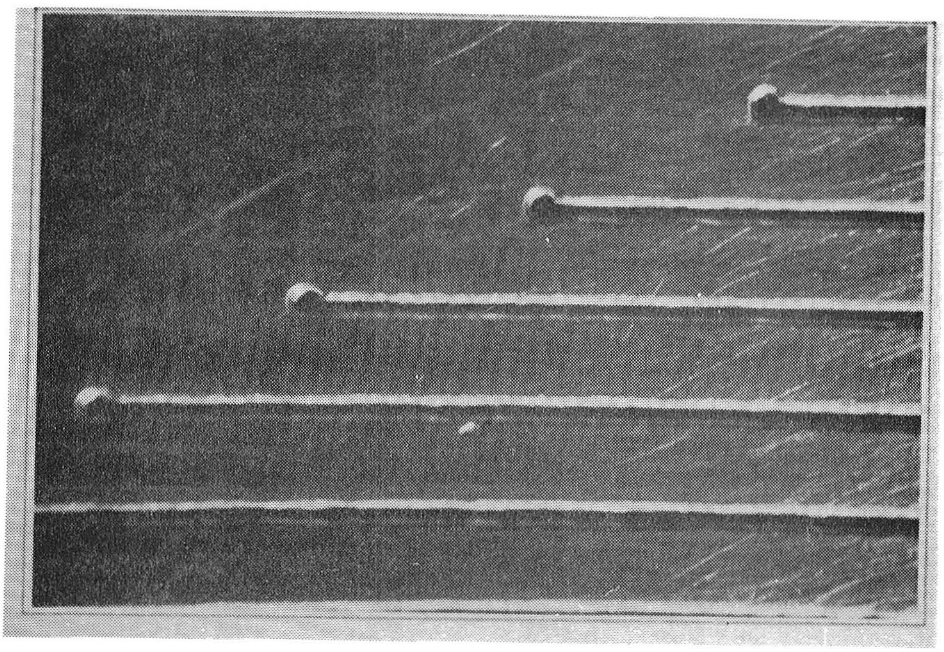


(b) Lift coefficient of +0.31 and -0.31.

Figure 9.- Symmetrical airfoil pressure distribution for Mach number of 0.76, Reynolds number of 30 million. Plotted in terms of pressure coefficient as a function of normalized distance from the leading edge.



(a) Sample channel layout.



(b) Magnified portion to show quality of channels and dimple at the channel end with drilled orifice holes.

Figure 10.- Photoetched pressure channels.

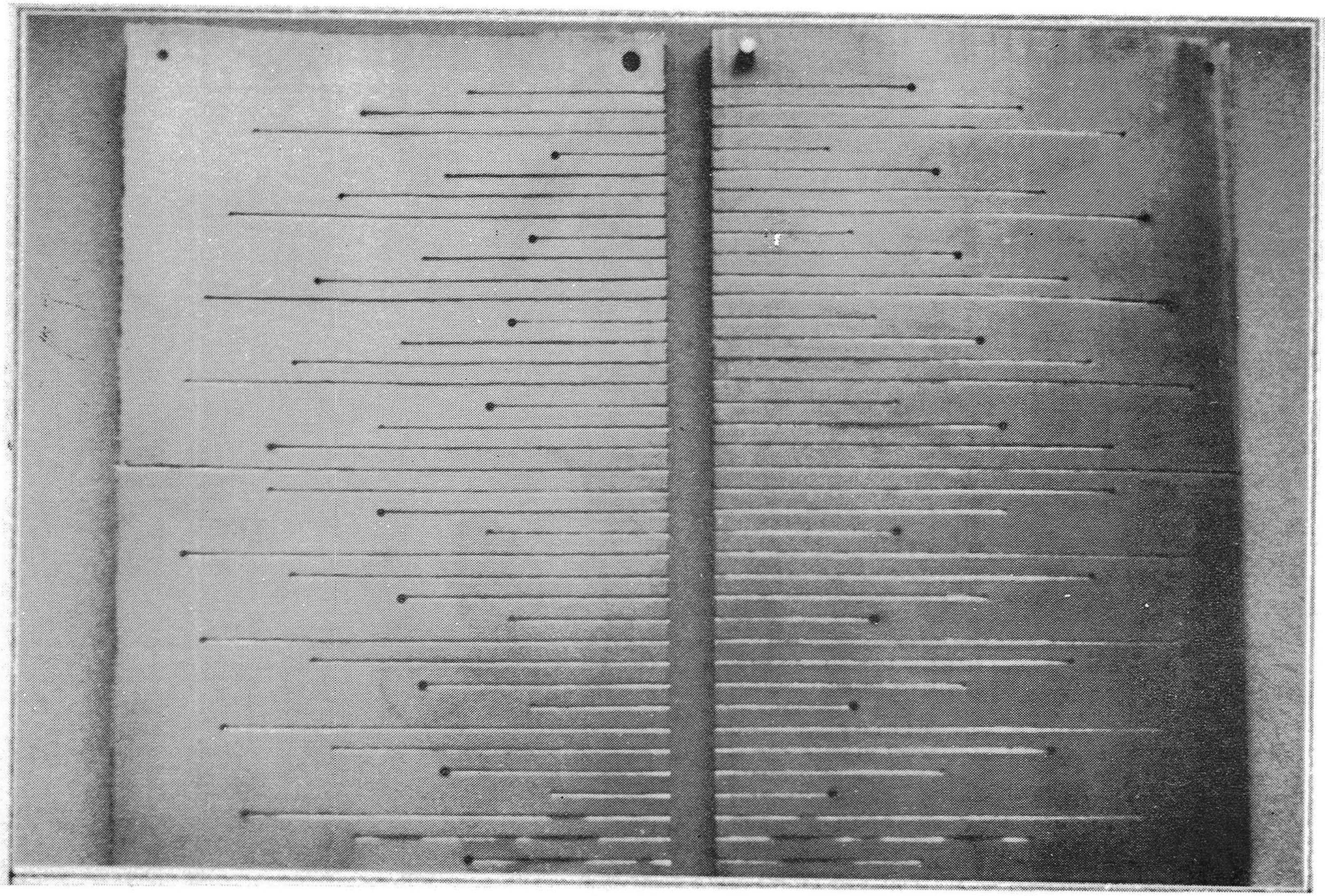


Figure 11.- Pressure channels etched on curved surfaces, concave to the left and convex to the right.

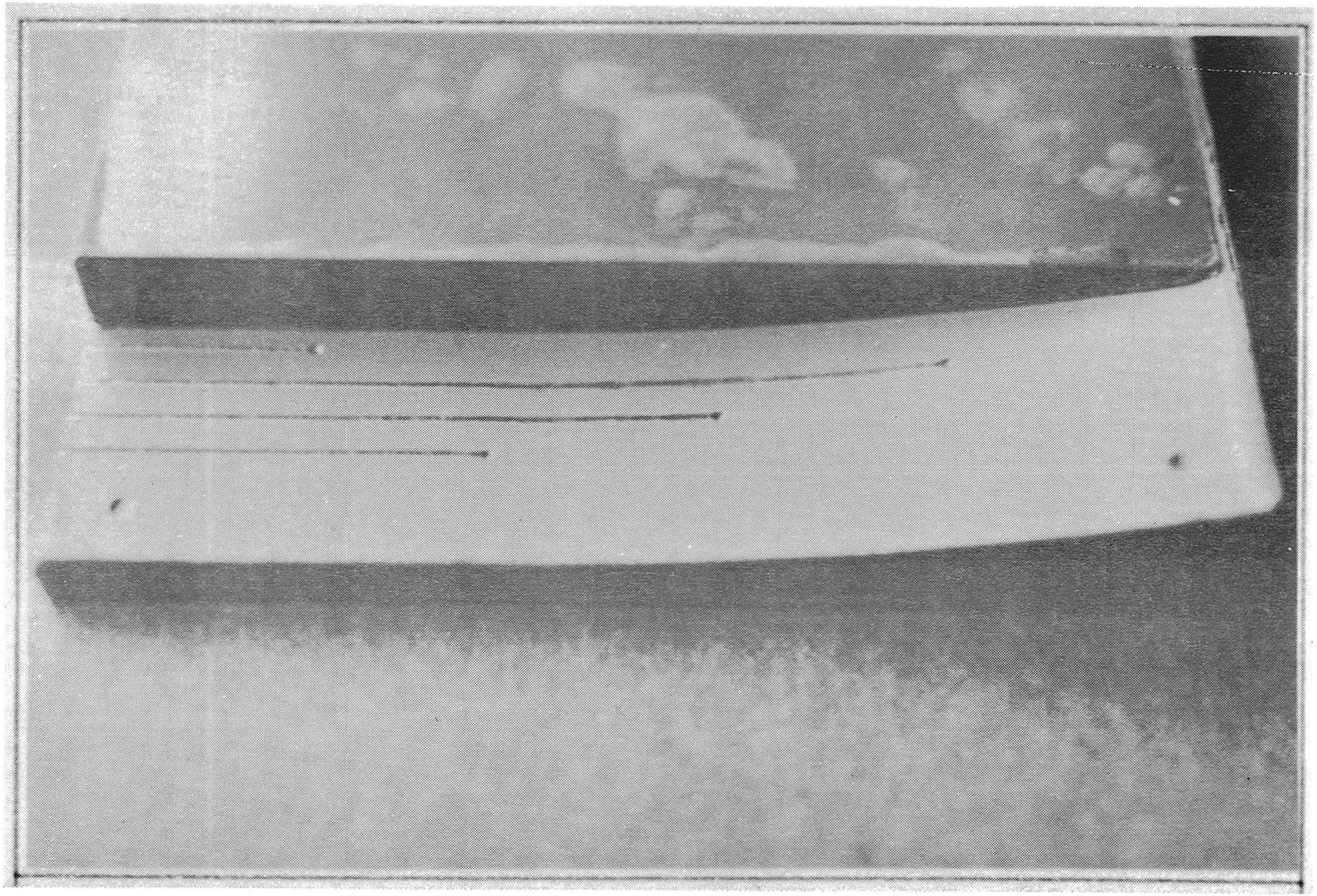


Figure 12.- Plates for curved bond line sample with top plate translated spanwise to illustrate curvature.

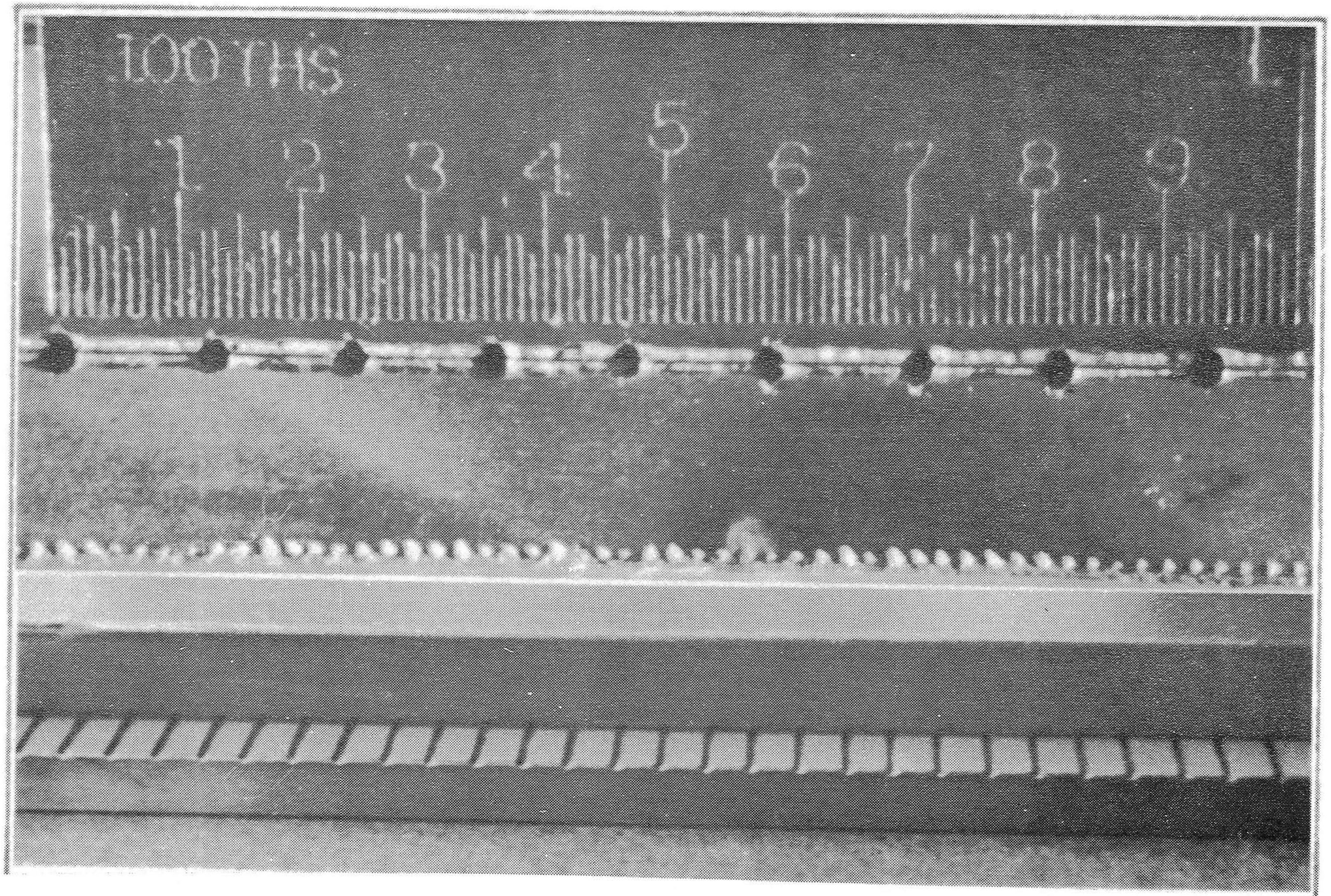


Figure 13.- Plates shown after bonding to indicate quality of match between upper and lower channels.

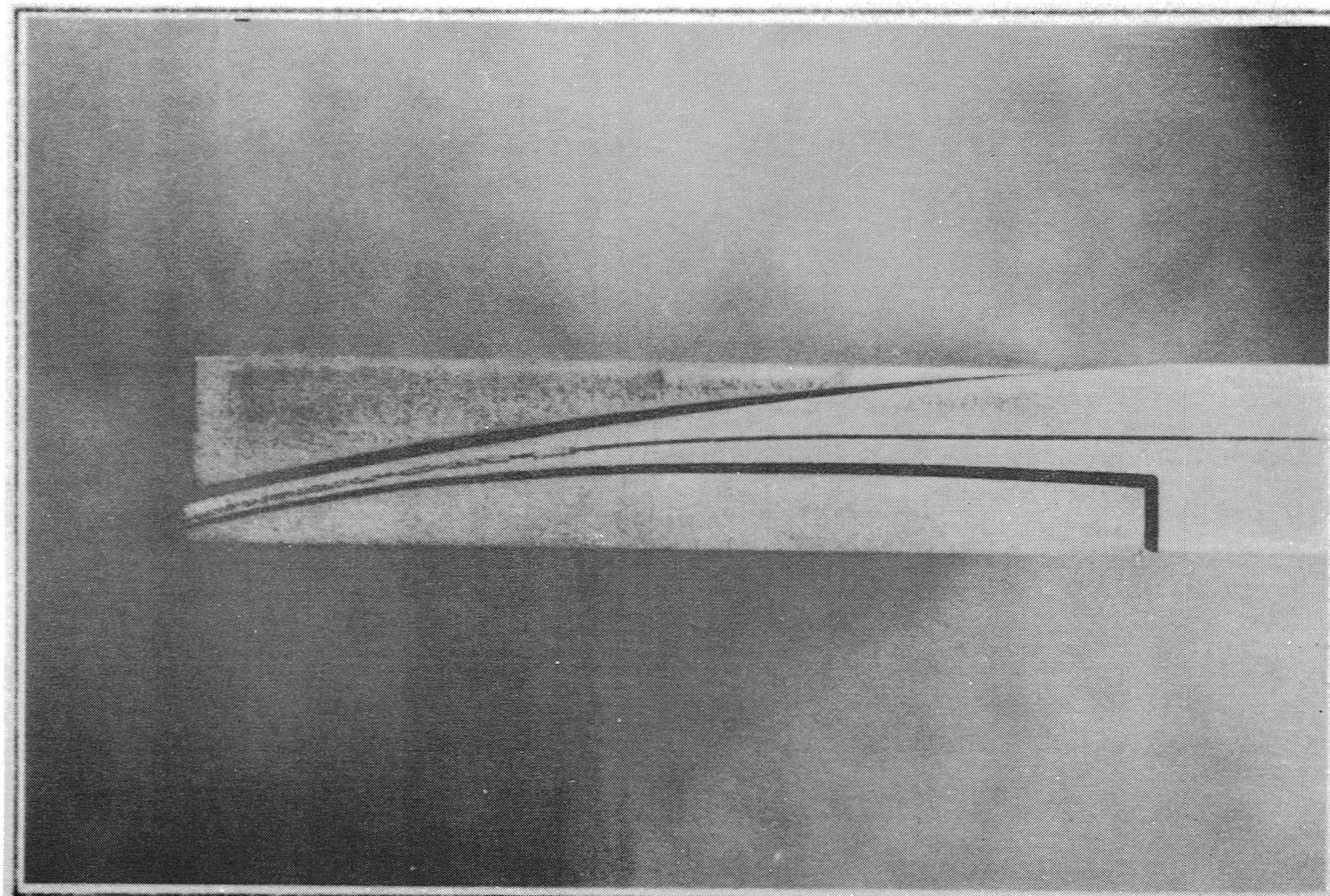


Figure 14.- Sample of a cusped, thin, wirecut airfoil trailing edge model together with cutoffs.

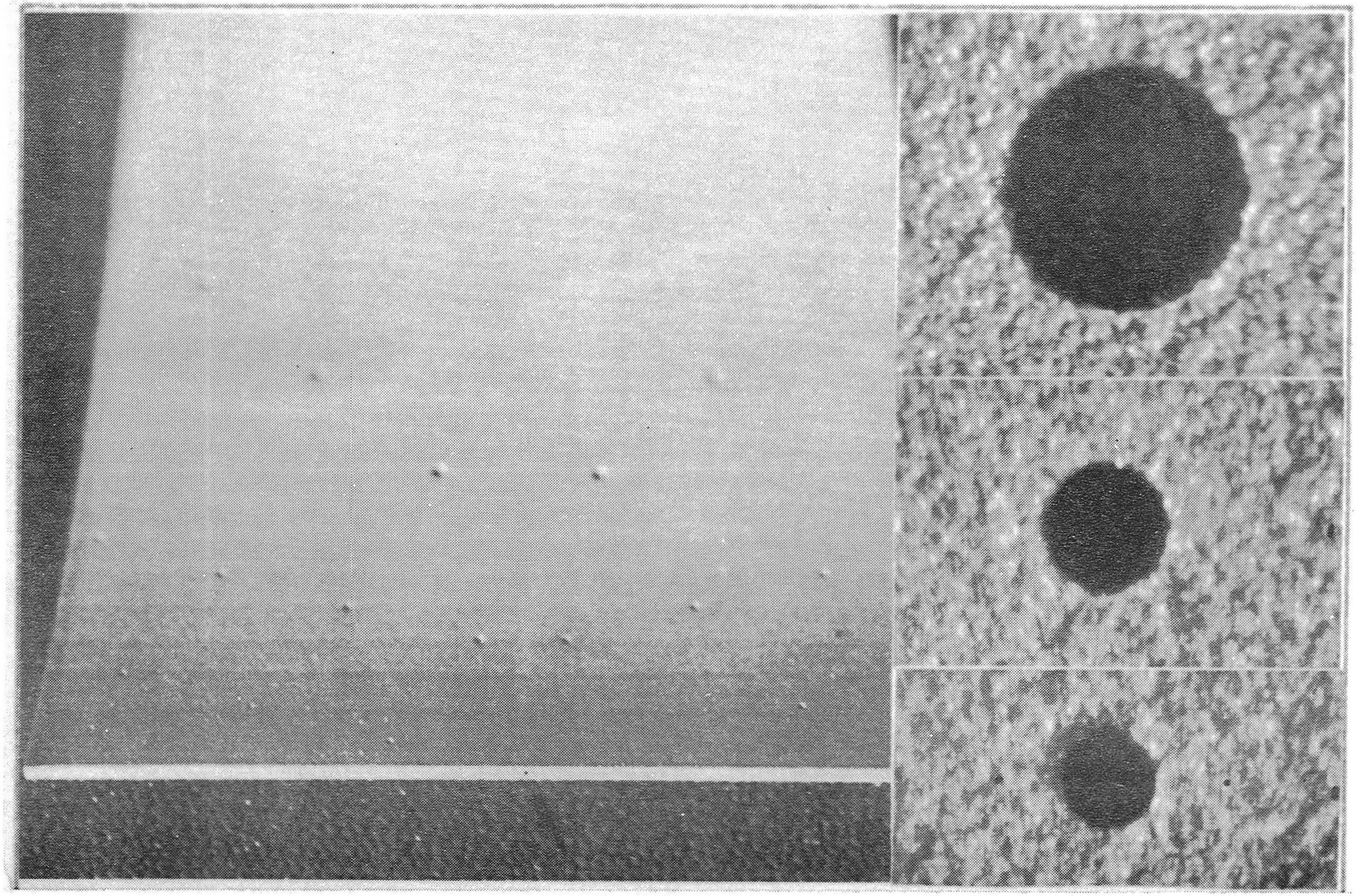


Figure 15.- Sample of cusped, thin, wirecut airfoil trailing edge model; arrow at left points to trailing edge orifice, inset at right shows orifice quality for 1.0, 0.5, and 0.32 mm (0.040, 0.020, and 0.013 inch) orifices.

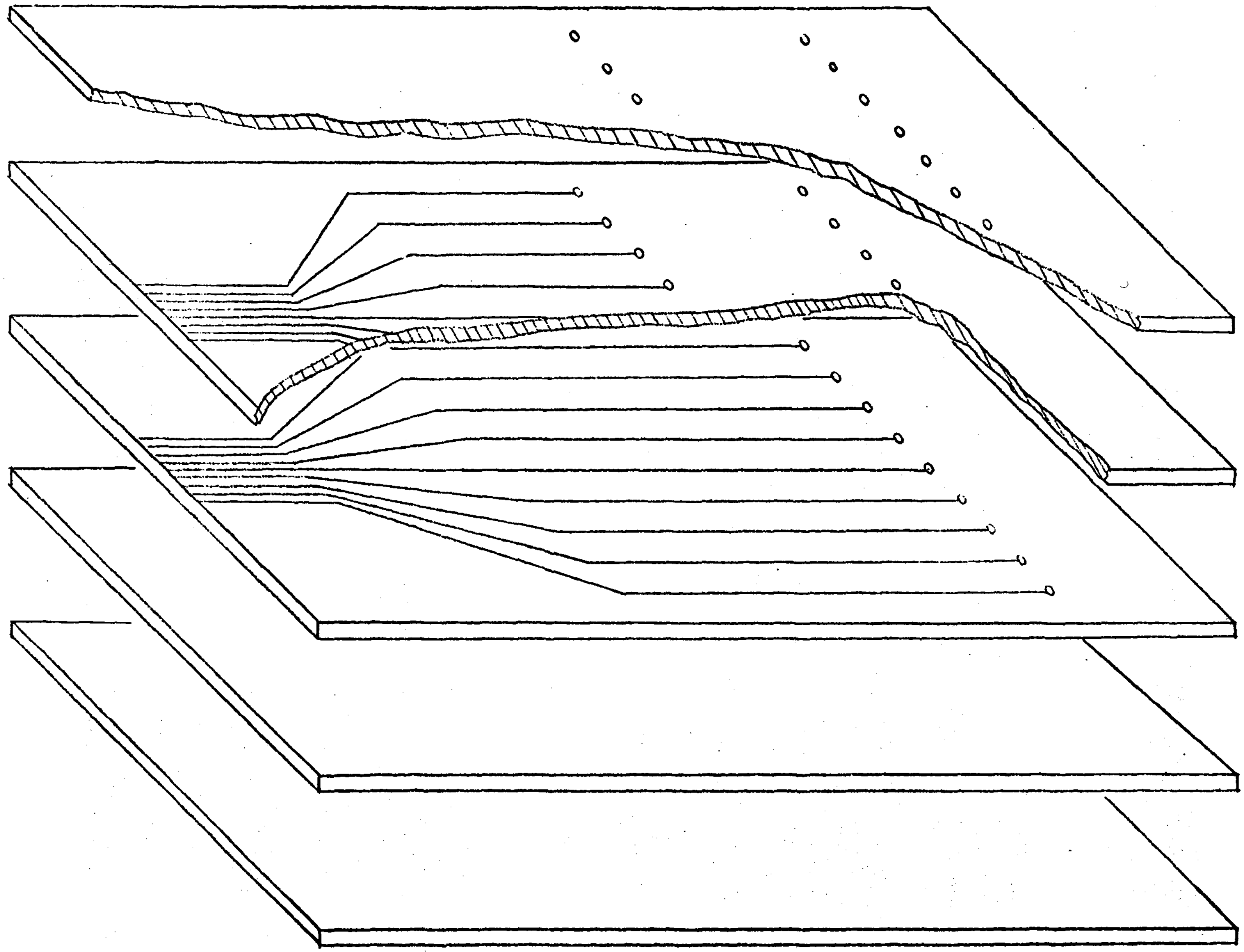


Figure 16.- Multi-layer bonded plate concept proposed for high aspect wings to provide additional pressure channels.

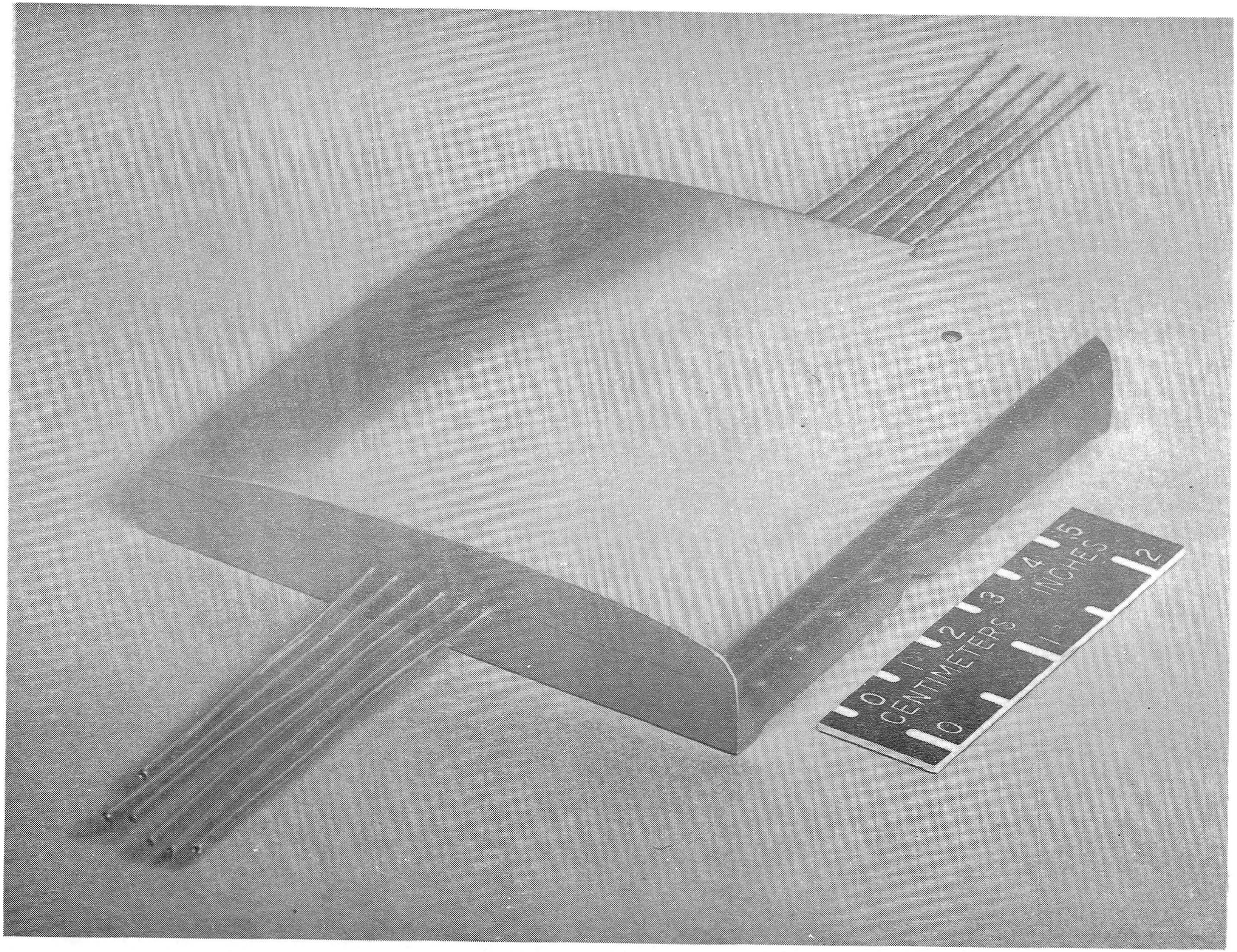


Figure 17.- Sample airfoil model constructed by the bonded plate method using 17-4 ph steel.

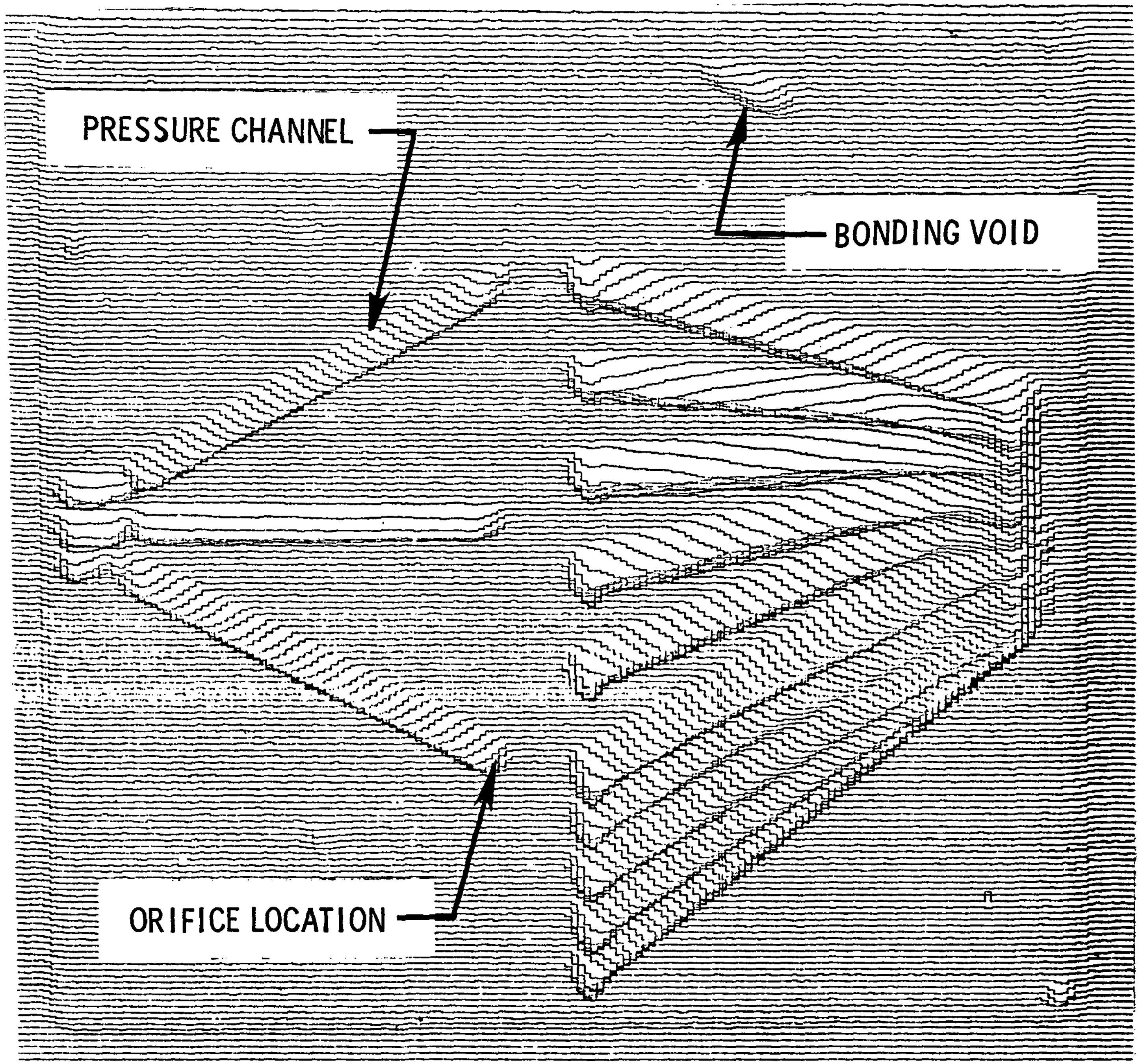


Figure 18.- Location of internal pressure channels and bonding voids generated by ultrasonic scanning.

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16. Abstract

A method of constructing airfoils by inscribing pressure channels on the face of opposing plates, bonding them together to form one plate with integral channels, and contour machining this plate to form an airfoil model is described. The research and development program to develop the bonding technology is described as well as the construction and testing of an airfoil model. Sample aerodynamic data sets are presented and discussed. Also, work currently under way to produce thin airfoils with camber is presented. Samples of the aft section of a 6 percent airfoil with complete pressure instrumentation including the trailing edge are pictured and described. This technique is particularly useful in fabricating models for transonic cryogenic testing, but it should find application in a wide range of model construction projects, as well as the fabrication of fuel injectors, space hardware, and other applications requiring advanced bonding technology and intricate fluid passages.

17. Key Words (Suggested by Author(s))
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