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Technology for Pressure-Instrumented Thin Airfoil Models

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Summary

Aims and Achievements of the Program

Models used for experimental aerodynamic studies are usually equipped with rows of orifices in their surfaces to enable measurement of the static pressures. In conventional model construction techniques each orifice is individually fixed to a small diameter tube which connects to a pressure-measuring transducer mounted either within the model or outside the tunnel walls. Locating an orifice at the trailing edge is difficult and, for thin airfoils, providing the necessary array of orifices is nearly impossible.

The technology developed during Phase I of this program (Ref 1.) centered around the formation of channels in the surfaces of plates which were subsequently vacuum brazed together to create a network of internal pressure passages which replace the individual tubes. This overcame the limitations of the conventional techniques.

However, application of this technology was restricted by the limitations imposed by a single bond plane and difficulties in ensuring that the bond surfaces remained flat and parallel during brazing. The major achievement of Phase II has been the development of the "Laminated Sheet" technique. This overcame many of the problems with bond plane distortion and also greatly increased the number of channels that could be placed inside a thin airfoil.

In order to provide a focus for the program, it was decided to build a thin airfoil, the canard of the X29A experimental aircraft. This NACA 64a-105 airfoil has a maximum thickness of only 5% of the chord. At a 6.25% scale, the maximum root chord thickness is less than 7.4 mm [0.3 inches] on the actual model. In the final version, a total of 56 pressure orfices were placed on three rows on the upper surface. Of these, 24 were located at about 30% span, 19 at about 60% span and 13 at about 90% span. A total of 37 orifices were placed in three similar rows on the lower surface, 14 on the inner row, 14 in the middle row and 9 in the outer row. In addition 3 orifices were placed the tip itself to give a grand total of 96 orifices.

The model was tested successfully in the 0.3 m TCT at NASA Langley over the full range of temperatures, Reynolds numbers, subsonic and supersonic Mach numbers and dynamic pressures achievable in this cryogenic wind tunnel. This included data at 0.9 Mach at and beyond flight Reynolds numbers. The concept of the laminated sheet technique was thus fully validated and a large amount of unique aerodynamic data was obtained.

Fabrication of larger sized airfoils was also investigated and a NACA 65a-105 airfoil section was chosen for development. This thin airfoil has a direct application to the wing of a modern fighter aircraft. Only limited success was achieved in scaling up the concept to the larger laminate needed, size 275 x 425 mm [11 x 17 inches] and thickness 13 mm [0.510 in.]. This simultaneous increase by factors of x 3.25 in area and x 1.5 in thickness turned out to be too large an excursion beyond the 'known envelope' of brazing variables. Fixturing problems were encountered that created warpage of the wing reference plane.

Furthermore, it appeared that the laminate was being heated non-uniformly. Some or all of these problems led to localised regions of distortion and some areas of voidage in the bond planes. This caused cross-leaks between some passages. In many respects it would appear that this model was too large to be brazable in the available furnace.

Nevertheless, one of the two large laminates that had been vacuum brazed was EDM wire-cut to form a 2D airfoil that could be tested in the 0.3 m TCT. This airfoil had a chord of 230 mm [9 in], a clear span of 330 mm [13 in.] and an overall span of 406 mm [16 in.]. However, a 400 mm cut is at, or near, the extreme limit of the wire-EDM machines capabilities and many problems had to be overcome by the sub-contractor in order to get the initial rough-cut airfoil shape from the laminated stack.

Thus, scale up to the larger size airfoil stretched the technique to, or beyond, the limits of two essential technologies, the vacuum brazing and EDM wire-cutting. With the experience now available, it should be possible to solve the outstanding problems, if this were considered technically desirable and if adequate resources were made available.

The technique has also been evaluated to the proof-of-concept stage for the construction of airfoils with twisted sections and cusped leading and trailing edges. Considerable success has also been achieved with small-scale samples of exotic configurations such as gull-wing airfoil sections, typical of some designs for supersonic transports. At this stage in the development of the technique, further effort in fabricating small models of these more advanced configurations could produce results unachievable by any other technique.

The technology of using embedded passages could also be applied to areas of aerodynamic research other than pressure measurements. Possiblities include, boundry layer control by ducting flow through internal passages, seeding devices for flow visualisation studies, wake survey probes, optical position indicators using fibre optics, manifolded cooling passages, fuel injectors, etc.

Finally, there is good reason to believe that the laminated thin sheet technology could be applied in a number of non-aerodynamic applications, for example in building miniature heat-exchangers, fluid control devices and other devices that need the formation of complex channel geometries within a confined space.

Vacuum brazing is ideally suited to routine production as, once the brazing conditions and variables have been defined, it is a highly reproducable process. If the required configuration falls within the 'known envelope' of the brazing parameters, it is reasonably easy to define the necessary variables. However, as this research program has demonstrated, expansion of the envelope can be a time-consuming and frustrating experience.

1. Introduction and Overview.

1.1 Background

Models used for experimental aerodynamic studies are usually equipped with rows of orifices in their surfaces to enable measurement of the static pressures. The more orifices that can be provided, the richer the aerodynamic data that can be obtained when the model is tested.

In conventional airfoils each orifice is individually fixed to a small diameter tube which connects to a pressure-measuring transducer mounted either within the model or outside the tunnel walls. Instrumentation of thin airfoils is a difficult problem, especially at the thin leading and trailing edges.

1.2 Lawing's Work on Brazing Thick Plates

The initial work on the concept of forming embedded passages within a brazed block was carried out by Lawing and his co-workers at NASA LaRC and is described fully in Ref. 2. This work culminated in the fabrication of a model of an NASA 12% symmetrical supercritical 2D airfoil with a 150 mm [6 inch] chord and a free span of 200 mm [8 in.] suitable for testing in the slotted wall test section of the 0.3 m TCT.

It had over 70 pressure orifices, 52 of which were distributed on the upper and lower surfaces along the central chord. It was tested over the transonic Mach number range and up to flight Reynolds number. The results are documented in Ref. 3.

1.3 Our Work During Phase 1, the PITACT Program.

The work carried out during Phase I of the SBIR program was directed towards the development of:
Pressure Instrumented Thin Airfoils for Cryogenic Tunnels,
the so-called PITACT program.

The technology developed during Phase I of this program (Ref. 1.) was a logical continuation of Lawing's work. Channels formed in the surfaces of thick plates created a network of internal pressure passages when the thick plates were subsequently vacuum brazed together. This thick plate technology was, however, limited in the number of channels that could be accommodated on a single bond plane.

AWS 4777 braze alloy was used for brazing stainless steels and the Pd-Ni alloy, MBF 1005, was used to braze maraging steel V200. It was necessary to use a lower melting-point alloy for maraging steels to avoid the grain-growth that otherwise occurs at temperatures above about 995 C [1820 F].

Note: The principal measurements and calculations for the work described in this report were carried out using customary units. They were then converted into SI units as required by exhibit A of the SBIR Phase II contract. Customary units have been inclused in [ ] brackets for the convenience of the reader. Other apects of the report are as laid down in the NASA Publications guide, NASA SP-7047.

The technique of chemical-milling was developed successfully to produce channels with good definition and surface finish. This proved to be a very cost-effective method of producing complex channel geometries and it permitted easy variations of channel width and depth.

Extensive use was made of wire Electro-Discharge Machining in a number of areas. It was used extensively for sample analysis, as it enabled clean cuts to be made through the bond planes and channels, without the metal smearing associated with conventional machining techniques. There was little further preparation required to obtain high quality surfaces, either for metallographic examination or surface finish of an airfoil.

It was also possible to prepare curved bond planes, and thus investigate the fabrication of cusped leading and trailing edges. It was shown that it was possible to chemically-mill channels on both the concave and convex wire-cut bond planes and thus to locate orifices in the leading or trailing edges of thin airfoils. This is illustrated in Fig. 1.

Thus, this Phase I work, which is detailed in Ref. 1, demonstrated the potential attractions of the basic process. It also allowed development of a number of the detailed techniques, such as chemical-milling of the channel networks, that were eventually incorporated successfully into Phase II. Other relevant development work is described in Refs. 4 to 6.

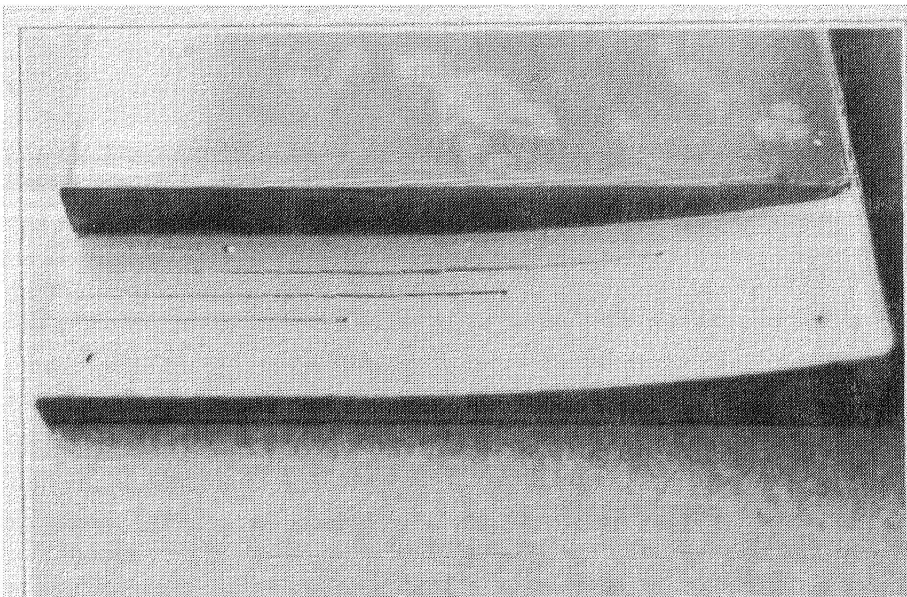


Fig. 11d Samples DS2 A(top) and B(bottom) put together after chemically milling channels

Fig. 1 Testpiece Developed During Phase 1 Showing Curved Bond Lines.

1.4 Initial Work in Phase II.

Although the Phase I work was considered to be highly successful in demonstrating the potential of the technique, it was realised that there would be significant problems to be overcome during Phase II. In particular, considerable difficulties were encountered in fixturing samples with a length greater than a few inches in such a way as to ensure that the bond surfaces remained flat and parallel to within a few thousandths of an inch during brazing.

Stresses had been induced in the surfaces of the plates during their machining and these were annealed during the brazing heat-treatment creating warpage and distortion. Furthermore, such distortion was proportional to the length of the sample, or possibly to a higher power of the length, thus creating more and more difficulty with the larger samples. The problem of machining-induced deformation is discussed at length in Refs. 7, 8 and 9. An alternative approach was, therefore, investigated.

2. Development of the Laminated Thin Sheet Technology.

The major achievement of Phase II has been the development of the "Laminated Sheet" technique. This overcame many of the problems with bond plane distortion in thick plates and it also greatly increased the number of channels that could be placed inside a thin airfoil.

A clear illustration of the principles involved was given in Ref. 2 and this is reproduced here as Fig. 2.

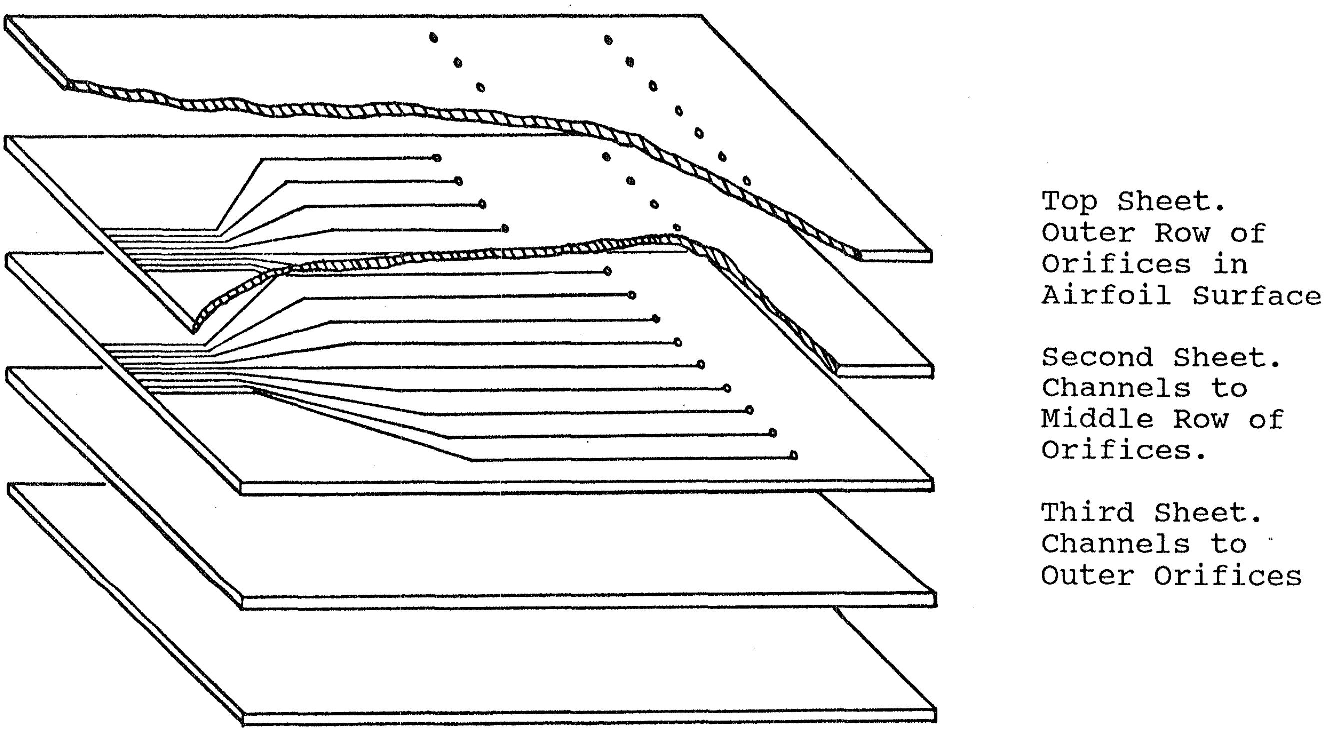


Fig. 2 Illustration of the Basic Principles of the Laminated Brazed Thin Sheet Concept of Airfoil Construction.

There were many areas of uncertainty that had to be resolved in developing this technique. Some of the major areas are detailed in the following sections.

2.1 Availability of Materials.

2.1.1 Thin Sheets of High-Strength Stainless Steels.

2.1.1.1 General Comments.

There is a very restricted range of available materials as there is very little call for high-strength stainless steels in the form of thin sheets. Furthermore, for model applications, the quantities needed are far too small for a producer to be prepared to roll special batches of a particular grade. Thus, is is necessary to work with whatever is commercially available.

2.1.1.2 17-7 PH

This was obtained in sheets 0.635 mm [0.025 in.] thick and 125 mm [5 in.] wide. There is thus an availability problem for all but the smallest models. Furthermore, the sample obtained had been coiled onto a small radius former and exhibited curvature in two directions, thus making sheet preparation difficult. However, from the specific interest of our program, it was its vey low toughness at cryogenic temperatures that eliminated 17-7 PH from further consideration once the basic brazing characteristics had been defined. These were found to be completely satisfactory and thus the material could still be considered for possible use for ambient and high temperature models.

2.1.1.3 A286

This was found to be readily available in 2438 x 1219 mm [8 x 4 ft] sheets x 0.813 mm [0.032 in.] thick, probably due to its widespread use in high temperature aerospace applications, such as in jet engines. However, the material is not normally used for precision applications and the sheets are often scratched or dented in storage and handling. Care has thus to be taken to select the best available and to ensure that it is packed correctly and not further degraded during transport.

The toughness of A286 at cryogenic temperatures is excellent and it has a good track record in the construction of models for the 0.3 m TCT and NTF cryogenic wind tunnels. However, it is not an easy material to machine, as it is easy to work harden. Furthermore, our earlier work [Refs. 7 - 9] showed that large compressive or tensile surface stresses are induced by milling and grinding, respectively, and this creates large machining-induced deformation.

2.1.2 Sheet Braze Foil.

The brazing alloy used in all the Phase II work was AWS 4777 and only Allied Chemicals produce this alloy in the required thin foil form. Their version of the alloy, Metglas MBF 20, is available in a maximum width of 100 mm [4 in.] and thicknesses of 0.038 and 0.051 mm [0.0015 and 0.002 inches]. Using foils singly or in combination this enabled effective available thicknesses of .038, .051, .076, .089, .102, .140 mm etc. [0.0015, .002, .003, .0035, .004, .0045 in.] to be evaluated for determination of optimum foil thicknesses for particular applications.

2.2 Basic Brazing Parameters

OBJECTIVE: to obtain the correct combination of the controlling parameters to achieve good brazed bonds across the 'land' between the channels, thus avoiding cross-leaks between channels, without blocking the channels themselves.

2.2.1 Capilliary Attraction and Gravity.

Early experiments using sets of channels on top of, and beneath, the bond plane showed that there was no preferential filling of the lower channels, thus indicating no strong gravitational effect. It would appear that the capilliary attraction of the molten metal in the small gaps betwen adjacent sheets is the dominant force involved.

2.2.2 Process Variables.

There are four basic, interrelated parameters that have to be optimised to realise this objective: foil thickness, brazing temperature, brazing time and applied load.

2.2.2.1 Foil Thickness

The required braze alloy thickness depends on the particular application. If the braze foil is too thin, there is too little molten metal available to be drawn by capilliary attraction into the gaps between the sheets. As a result, voids form in the bond line and this has at least three undesirable consequences:

-the mechanical integrety is lowered,
-cross-leaks can occur between adjacent channels,
-voids outcropping in the airfoil contour spoil the surface finish and have to be filled to allow measurement of good aerodynamic data.

On the other hand, too thick a braze foil causes the channels to be flooded by the excess molten metal. Under particularly adverse situations, molten braze alloy can be forced out from between the sheets, flow along the outside of the sample and bond it to the support structure in the brazing oven.

2.2.2.2 Brazing Temperature,

The Metglas MBF 20 foil can be brazed at temperatures between about 980 C and 1200 C [1800 F and 2200 F]. At the lower end of this temperature range, the material is relatively viscous, it does not flow easily and gaps can be formed if the alloy does not flow and wet the complete surface. At the highest temperatures it flows very easily and can flood channels or be forced out from between the sheets if the applied loads are too high. Thus, the appropriate brazing temperature will depend on the dominant consideration for each application.

The AWS 4777 family of braze alloys have boron and silicon additions which depress the melting point of the foil. However, once the foil has melted and wetted the bonding surface, these small, mobile atoms diffuse into the parent metal. Their concentration in the molten alloy thus decreases, causing its melting temperature to increase until it solidifies isothermally. It is, however, not possible to determine whether or not our samples did, in fact, solidify isothermally, or during subsequent cooling from the brazing temperature.

The mode of heat transfer in a stack of thin sheets in a vacuum furnace was one major area of concern in the period before the vacuum furnace was available to permit experimental verification of the different theoretical mechanisms. Heat transfer in vacuum at high temperatures takes place by radiation and conduction and, of these two mechanisms, only conduction would be available to get heat to the center of the stack. The critical question was, thus, would it be possible to get the material at the center of the stack hot enough to melt the braze foil?

It was found that the braze foil did, indeed, melt even at the center of the thickest stacks. The most probable sequence of events is that radiation heating of the outermost sheets caused them to be heated above the melting point of the outermost braze foil. Once this foil had melted, the temperature of the next sheet in would increase rapidly, thus allowing the next foil to melt, with a consequent increase in heat transfer to the next sheet. The foils would thus melt sequentially in cascade fashion, allowing the whole stack to braze.

On a few occasions where brazing had not taken place quite as expected, it was subsequently found that the furnace control thermocouples had been placed in positions where they received more, or less, radiation than the center of the stack of sheets being brazed, thus indicating a different temperature. Care has, therefore, to be taken to ensure that representative temperatures are used to control the furnace cycle.

2.2.2.3 Brazing Time

This has to be long enough to allow:
- -clean-up and outgassing of the the bonding surfaces,
- -annealing of any locallised distortion and restoration of the sheets to a flat condition,
- -deoxidation of the stainless steel so that the molten braze alloy can flow and wet completely the surfaces to be bonded.

On the other hand, excessive brazing periods favour grain growth in the parent metal and liquid metal attack [aggression] at the interface.

2.2.2.4 Loading and Fixturing

The applied load has to be high enough to hold the sheets flat and parallel and give a uniformly thick gap for the molten alloy to flow into. It must not be high enough to flood the bond plane and force molten alloy into the channels.

A wide variety of dead weight and clamping systems were used to fixture the various configurations evaluated during Phase II. In all cases it was necessary to allow for thermal expansion of the sheets as they heated to, and cooled from, the brazing temperature. In the more complex samples an additional, and important, requirement was to maintain an accurate register between the sheets in a stack.
The greatest challange of Phase II was to design the correct type of fixture to achieve the required combination of these factors. The majority of problems encountered could be ascribed to failure to meet this objective.

2.3 Evaluation of Material Properties.

One consequence of the laminated structure of a stack of brazed sheets is the anisotropic nature of their mechanical properties. In particular, the fracture toughness is much greater for crack propagation perpendicular to the bond plane than in the bond plane. This can be demonstrated by the variation in Charpy impact energies of samples having their notches placed in the bond plane and normal to it.

These are shown in Table 2.3 for both A286 and 17-7 PH. These results also show that, based on a required minimum Charpy energy of 34 joules [25 ft.lb.], 17-7 PH has an unaccepably low toughness at cryogenic temperatures, but that it is quite satisfactory for use at ambient.

Table 2.3 Charpy V Notch Impact Energies for A286 and 17-7 PH

Material	Condit'n.	Notch Orient'n.	Temp. K	Charpy Energies joules	Charpy Energies ft.lb
17-7	Ann.	Normal	300	58	43.0
17-7	Ann.	In Plane	300	36	26.7
17-7	Ann.	Normal	77	16	11.9
17-7	Ann.	In Plane	77	10	7.2
A286	Ann.	Normal	77	74	54.2
A286	Ann. (1)	In Plane	77	49	36.2
A286	Aged (2)	In Plane	77	40	29.2
A286	Ann.	In Plane	300	63	46.3
A286	Aged	In Plane	300	42	31.0

Notes: Diamond pyramid hardness (1) Hv (10g) = 118; (2) Hv (10g) = 313.

The effect of ageing heat-treatments on the toughness of A286 is also shown in Table 2.3 for specimens tested at both ambient and cryogenic temperatures. In the aged condition, the Charpy energy of brazed and laminated A286 sheet is about 33% lower than that of the annealed condition at room temperature. At liquid nitrogen temperature, the corresponding reduction is about 20% and, even in the less-tough direction, the brazed laminate is still above the minimum requirement.

In a typical airfoil, the sheets are essentially parallel to the airfoil surface and the most probable failure mode is due to bending. In this mode a crack would have to propagate normal to the bond plane and would probably become blunted when it reached it due to delamination at the weaker interface. A significant advantage of the laminated sheet technique is the ability to design-in 'blind' channels at critical locations that could be monitored for sudden pressure changes that would indicate the onset of disbonding. Such a system was incorporated in the test on the X29A model in the 0.3 m TCT, but no changes were found as the model showed no signs of disbonding.

2.4 Chemically-Milled Channels.

Earlier work in Phase I had shown that it was possible to chemically mill channels in the 300 series stainless steels and also the V200 grades of maraging steel. It was rapidly established that it was also possible to chemically-mill channels in both A286 and 17-7 PH, indeed the surface finish was better than that obtained in 300 series stainless steels, probably because of the finer grain sizes of the higher strength steels.

It was found that a minimum initial line thicknesses of about 0.5 mm [0.020 in.] was required to give a well defined image on the screen-printed lacquer used to define the areas to be removed during chemical-milling; thinner lines gave blurred images. This in turn defined the subsequent width-to-depth ratio of the channels, the deeper they were cut, the wider the channels became due to under-cutting at the edges. The minimum spacing between channels was determined by the need to leave enough material between them to form a good brazed bond.

The final dimensions specified for the 12 series models were:
0.37 mm [0.015 in.] deep and about 0.7 mm [0.028 in.] wide

2.5 Machining

2.5.1 EDM wire-cut.

This technique was used extensively during the program. It was used to planform excess material from the edges of the brazed blocks, particularly at the inboard edge of the model where the ends of the pressure passages had to be drilled out to take the thin stainless steel tube for connection to the pressure transducers.

EDM wire-cutting was also used extensively for diagnostic work to take sections through the bond planes and channels to check for voids, blockages, etc. It was also used to make small proof-of-concept demonstration models of 2D and 3D airfoils and for shaping samples with twisted bond planes.

2.5.2 Ball-Ended Milling Cutters.

The airfoil surface contours on all canards from the 9th series onwards were formed by CNC milling using ball-ended cutters. This will be discussed in detail as appropriate in later sections. It should be noted that the A286 should be in the age-hardened condition before any machining is carried out.

2.6 Surface Finish

Due to the importance of being able to form a good finish on the surface of an airfoil model, it was essential that braze joint outcroppings should be smooth. This topic was evaluated in detail very early in the development of the laminated brazed sheet concept. Conventional metallurgical preparation techniques were used to to prepare surfaces, i.e. grinding using a succession of finer water-lubricated silicon carbide papers followed by polishing with diamond pastes. It was quickly and conclusively established that there was no differential polishing and that the hardness of the braze alloy was similar to that of the parent metal.

2.7 Orifice Drilling

State-of-the-art model shop practice routinely uses 0.325 mm [0.013 in.] twist drills for drilling orifices in airfoil surfaces. Considerable care, operator skill and good equipment is neccessary when drilling any stainless steel with such small diameter drills. A286 is particularly notorious for the ease with which it work-hardens and blunts a drill bit, thus neccessitating frequent bit replacement if breakages are to be avoided. These drills were, therefore, used to test drill orifices through the surfaces of small samples of brazed laminate down into the sub-surface passages beneath. This was done with the A286 in both annealed and heat-treated conditions and no unduely high loss rates were found in either condition. Furthermore, there were no particular problems with the drill bit binding as it broke through into the passages, as had at one stage been feared.

It is possible to drill holes with diameters down to about 0.125 mm [0.005 in.] using rotary EDM techniques. These were evaluated on small test pieces and found to be very successful in placing holes normally into flat sheets. More refined mounting and indexing techniques would, however, be needed before this technique could be applied to a curved airfoil surface and this approach was not pursued further.

2.8 Pressure Tube Connections.

A number of different approaches were tried to determine an effective method of making leak-tight connections between the ends of the embedded passages in the laminate and the 1 mm [0.040 in.] diameter stainless steel tube used to mate up to the flexible plastic tubing from the pressure transducers. It was found that the ends of the passages could be counter-drilled with a 1.025 mm [0.041 in.] twist drill to a depth of about 3 mm [0.12 in.] to take the 1 mm tubes. Considerable care was, however, needed to avoid blocking the adjacent passages with swarf.

LaRC experience with using soft solders at cryogenic temperatures indicated that a 50% Sn:49.5% Pb:0.5% Sb solder would be suitable for fixing the tubes in position. However, an agressive flux such as orthophosphoric acid, or a commercial equivalent [Eutector Flux 157], is needed to clean the surface of stainless steel and allow the molten solder to wet the metal and form a good bond. Much care had to be taken to ensure that all traces of such fluxes were removed from the passages to prevent subsequent corrosion or other problems.

In practice, the most difficult problem was in achieving a good joint around each tube, particularly where the space between adjacent tubes was sometimes as small as about 1.5 mm [0.060 in.]. It was found that a well-made joint would withstand many cycles between ambient and cryogenic temperatures and significant mechanical abuse without failure.

3. Development of the X29A Canard models up to Series 11.

In order to provide a focus for the program, it was decided to construct a 6.25% model of the canard on the X29A experimental aircraft made by Grumman. This is the same scale as the model being built for the NTF, but, due to the very limited amount of room in the canard pivot to lead the channels out into the body of the model, it would not be practicable to test a pressure-instrumented canard on the NTF model. Instead it was to be tested independantly, mounted on the sidewall of the 0.3 m TCT.

The X29A canard airfoil has a NACA 64a-105 section with a maximum thickness of 5% of the chord, which is 7.6 mm [0.3 in.] on a root chord of 145 mm [5.70 in.] This is shown at approximately full scale in Fig. 3 (a). The model span is 70 mm [2.76 in.] A target of 100 pressure orifices was set, 60 on the upper surface and 40 on the lower.

3.1 General Philosophy.

In developing the detailed configuration of the canard, a number of basic philosophies were adopted:

Firstly, all stages of development were intended to be part of a logical progression towards defining a technology that could eventually become acceptable as a standard shop-floor technique in state-of-the-art model shops such as that at LaRC, DEI, Microcraft, etc. It was not intended to be so obstruse as to be limited to the research laboratory and be carried out by PhD's.

Secondly, the technology was to be cost-effective and not to require a higher degree of precision than necessary. Nevertheless, in many areas, more ambitious objectives were set for the R & D program in order to obtain a feel for the 'extent of the envelope' and the ultimate limitations of the technique.

Thirdly, inspection and quality control were to be applicable at every stage, so that a part could either be re-worked or scrapped at an early, low-cost stage.

Forthly, wherever possible, a significant degree of redundancy was built into the design so that some losses could be tolerated without the need to scrap the whole part.

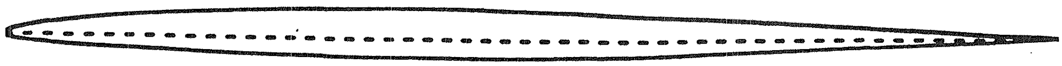


Fig. 3 (a) Approximately Full Scale Root Chord Section of the X29A Canard Model

3.2 Bond Plane Out-Crops and 'No-Go' Regions.

The first stage in the design process is to define the locations of the bond out-crops on the upper and lower surfaces. The thickness of braze foil needed between each layer will depend on the combination of the area and total thickness of laminated 0.8 mm [0.032 in.] sheets of A286. Let us assume that the earlier development work had shown that a total thickness of 0.1 mm [0.004 in.] of MBF 20 braze foil gave the required combination of brazed lands and unblocked channels.

Starting from the central wing reference plane and moving outwards, the upper surface of the model would thus be divided into 0.8 + 0.1 = 0.9 mm [0.032 + 0.004 = 0.036 in.] layers. Such a division is shown schematically in Fig. 3 (b) for a representative airfoil surface and a brazed laminate with three sheets of A286 above the zero bond plane.

The positions of the bond outcrops on the airfoil surface are shown in the schematic of Fig. 3 (b) by the labelled arrows, OC1, OC2 and OC3 for the three layers.

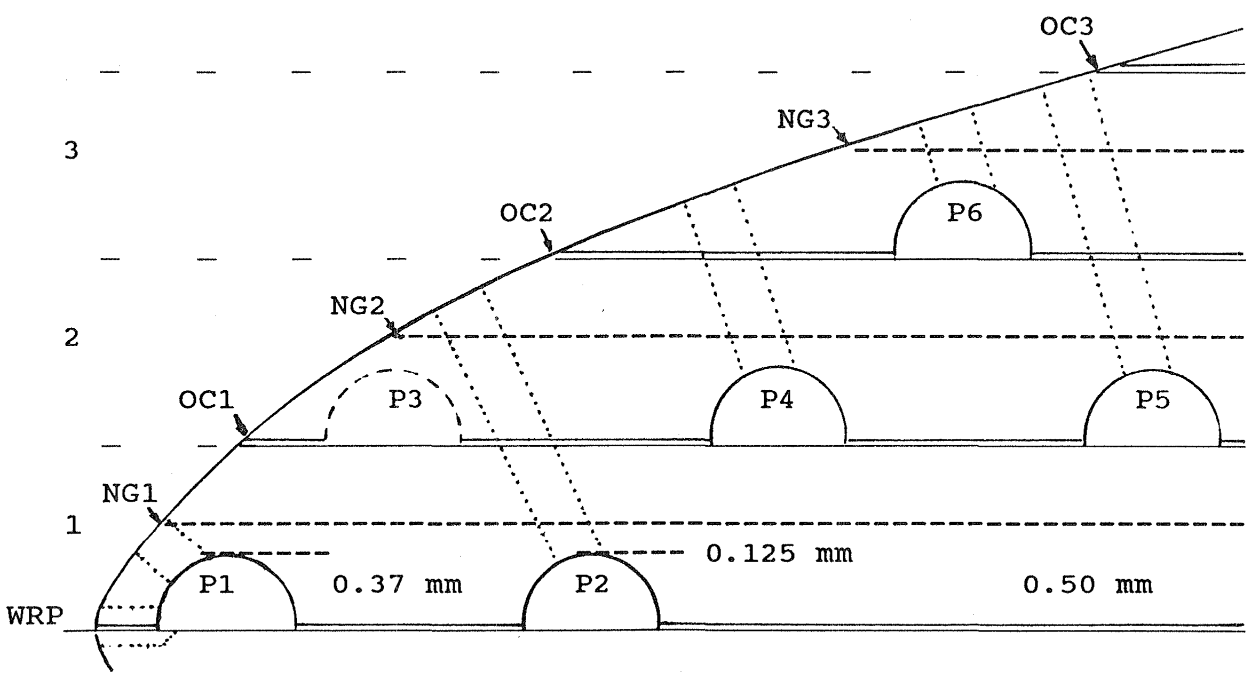


Fig. 3 (b) Schematic Representation of the Locations of Outcropping Bond Planes and 'No-Go' Zones in a Three Layer Brazed Laminate.

The locations of the outcropping bond planes is also shown by the solid lines in Fig. 3 (c) for the upper surface of an early development configuration of the X29A canard.

The earlier work on forming brazed bonds had indicated that, due to the dominant effect of capilliary attraction, the channels could be placed in either the upper or lower surface of a thick plate. Initial proof-of-concept work on the laminated brazed sheet technique confirmed that channels could, indeed, be placed on either surface of the sheet. The advantages and disadvantages to each orientation depend on the particular model configuration under consideration.

For the schematic representation of Fig. 3 (b) and the development configuration illustrated in Figs. 3 (c) and (d), the channels were placed on the under surface of each sheet in the stack to be laminated. Typically, the depth of the chemically-milled channels is about 0.37 mm [0.015 in.]. Allowing for a degree of uncertainty in their actual depth and a minimum of 0.125 mm [0.005 in.] of metal between the channel and the airfoil surface, a 'no-go' region 0.5 mm [0.020 in.] thick has to be created within the perimeter of the bond out-crop positions. The locations of the 'no-go' zones are shown arrowed in Fig. 3(b) and labelled NG1, NG2 and NG3 for the three different sheets of A286.

No channels can be placed in these areas, although it is sometimes possible to locate orfices here if they can be serviced by a passage on a lower bond plane. Thus, consider, for example, the schematic section of Fig. 3 (b). The orifice in the leading edge, or that nearest the leading edge, can be served from the foremost passage, P1, on the first layer as this lies to the rear of the first no-go zone, NG1.

Experience has shown that channels are best located no closer than at 2.5 mm [0.1 in.] centers and that they should be staggered on adjacent layers. The next passage on the first layer, P2, has to serve the second orifice, as it is not possible to locate a passage at the position P3 shown by dashed lines on the second layer. It can be seen that P3 would lie within the no-go zone and there would be too large a risk of the passage being exposed during machining. They can, however, be located at P4 and P5 in the second layer and at P6 in the third.

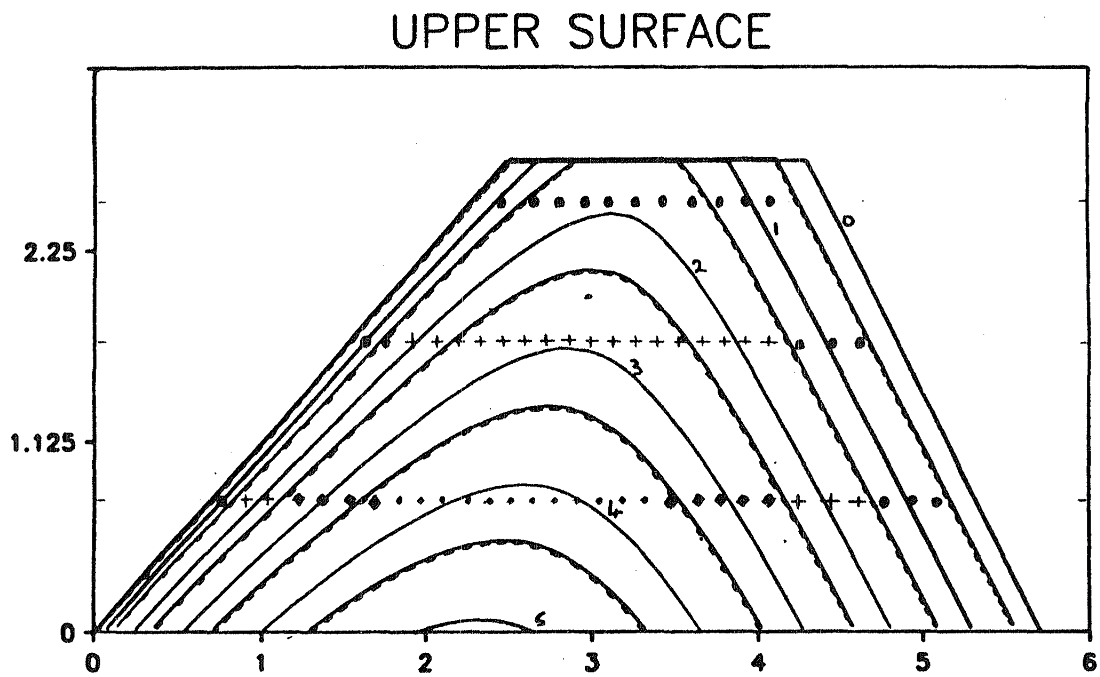
The 'no-go' zones are also shown in Figs. 3 (c) and (d) by the dashed contour lines between the solid contours of the bond out-crops.

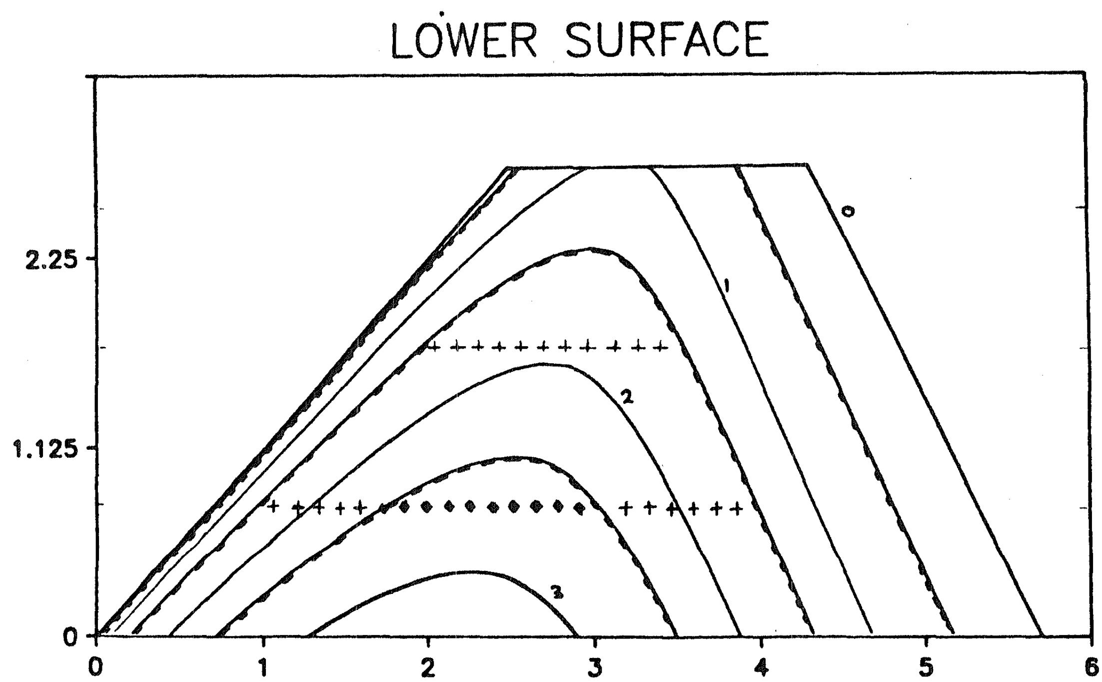
The lower surface is also divided into a similar series of layers, as shown in Fig. 3 (c). Here too the bond out-crops are shown by solid lines and the 'no-go' areas by dashed lines. On the lower surface their interpretation is, however, somewhat different. Viewed from the lower airfoil surface, the channels appear to be in the <u>top</u> surface of a sheet and they thus need a further layer over them to prevent them appearing on the airfoil surface.

The wing reference plane, or zero bond plane, is particularly demanding to design as its channels have to serve those orifices that are located in the thinnest sections of both the upper and lower airfoil surfaces.

3.3 Orifice Location.

For a real model, as apposed to a research and development prototype, location of the orifices is best carried out in collaboration with the researcher who will eventually be responsible for testing the airfoil model. In this way, the neccessary compromise between the desirable and the achievable can be made at this early stage.





Figs. 3. (c) Drawing of the Upper Surface Showing Bond Plane Outcrops [solid lines] and the 'No-Go' Zones [dashed lines].
(d) The Lower Surface Showing Bond Plane Outcrops and No-Go Zones.

If the model is being designed by someone without a good knowledge of what can be realistically expected from a 'state-of-the-art' model shop, or whatever organisation will be responsible for machining the model, it is also a good idea to have model shop input at this stage.

In the earlier series canard models, orifices were laid out in spanwise rows that were representative of locations likely to be required by a researcher.

The location of three possible chordwise sets of orifices on the upper surface of the development configuration is shown schematically in Fig 3 (c). Thus, in the outer row there are a total of 11 orifices, shown as solid circles, o , all of which are located in sheet Top 0. Also located in this sheet are two orifices near the leading edge and three near the trailing edge of the middle row of orifices, also shown by solid circles. Furthermore, there are also four orifices in the inner row located on sheet Top 0, one near the leading edge and three near the trailing edge.

Considering next the middle row, there are 17 orifice positions located on sheet Top 1, indicated by a + in Fig 3 (c). Also located on this sheet are five orifice positions on the inner row, two near the leading edge and three near the trailing edge, also indicated by + symbols. Of the remaining 21 orifices, 9 are located in sheet Top 2, indicated by diamond symbols, and 12 are on sheet Top 3 indicated by . symbols.

As noted above, the channels are located in the under surface of each sheet and thus fewer orifices can be located on the lower airfoil surface. It can be seen from Fig. 3 (d) that no orifices are located in the outer row and serviced from the bottom sheets. These orifices have to be fed from sheet Top 0. However, 11 orifices positioned in the middle row and indicated by + symbols are located on sheet Bottom 0. This sheet also serves 5 orifices near the leading edge of the inner row and 6 near its trailing edge. It is thus very crowded. Finally, 9 orifices, indicated by diamond symbols, are served from sheet Bottom 1.

3.4 Channel layouts

As part of the philosophies outlined above, wherever possible 2 channels were lead to each orifice position. This has a number of advantages. In particular:

-It allows initial checking for channel blockage and cross-leakage.

-It may be used subsequently for clearing obstructions by dirt, drilling swarf or other foreign objects.

-It prevents loss of use of a particular orifice due to blockage of one of the channels.

The penalty to be paid for this conservative approach is to halve the number of orifices that could potentially be serviced by single channels.

There are usually two restictions on the number of channels that can be lead to orifices in the airfoil surface:

-The spacing between adjacent channels must be adequate to prevent cross-leaks between them and to maintain mechanical integrity of the model.

-There must be adequate room at the root, or inner section of the airfoil, to allow attachment of the hypodermic tubing that connects to the ends of the brazed passages. As the tubing is 1 mm [0.040 in.] diameter, this can be a problem if the root is narrow or thin.

The implimentation of these guidelines can be seen in the series of channel lay-outs illustrated in Fig. 4 for the 9th series of canard model prototypes to be discussed in section 3.9.

It can be seen that all of the orifice positions in sheets Top 3 and Top 2 are fed by double channels and only 4 out of 13 on Bottom 1 have just a single channel to the orifice. Sheet Bottom 0 has 9 double channels and 12 single, while sheets Top 0 and Top 1 are so crowded that relatively few orifice positions are served by double channels.

Sheet Top 0 also illustrates another feature designed into this 9th series prototype. It can be seen that three of the channels are continued past the orifice positions in the outer row to emerge through the tip of the canard. These were intended to accomodate fiber optic filaments that could be used to track the position of the canard tip during testing. They also proved to be very useful in giving an early indication on a newly-brazed laminate of whether or not the channels had become blocked. They also served as useful reference points to locate the wing reference plane during set-up for machining.

3.5 Chemical Milling

The diagrams shown in Fig. 4 also illustrate other features found to be useful, including plate identification labels and a series of markers used to define the relative locations of the various sheets. They also serve to define the scaling factor used in reduction of the original drawings down to the photographic plates used to print the masks on the photo-sensitive lacquer that coats the A286 sheet.

3.6 The 8th Series of Canard Models.

The early proof-of-concept work was carried out on A286 sheets with straight channels that passed from one side to the other and could thus give an immediate indication of whether or not the channels were un-blocked after the brazing process.

The channel lay-outs whose design was discussed in sections 3.1 to 3.5 were first applied to the 8th series of test pieces. Initial results on this series were very disappointing as many channels were blocked with braze alloy. It appeared that the 'brazing recipe', i.e. the combination of foil thickness, load, temperature and time, that had proved successful in earlier tests no longer worked perfectly.

Nevertheless, two of the samples, 8C1 and 8C2 were used for initial investigation of the CNC ball-end mill machining conditions that would be required for later models. Another sample in this series was used to try out different methods of attaching the connecting tubes.

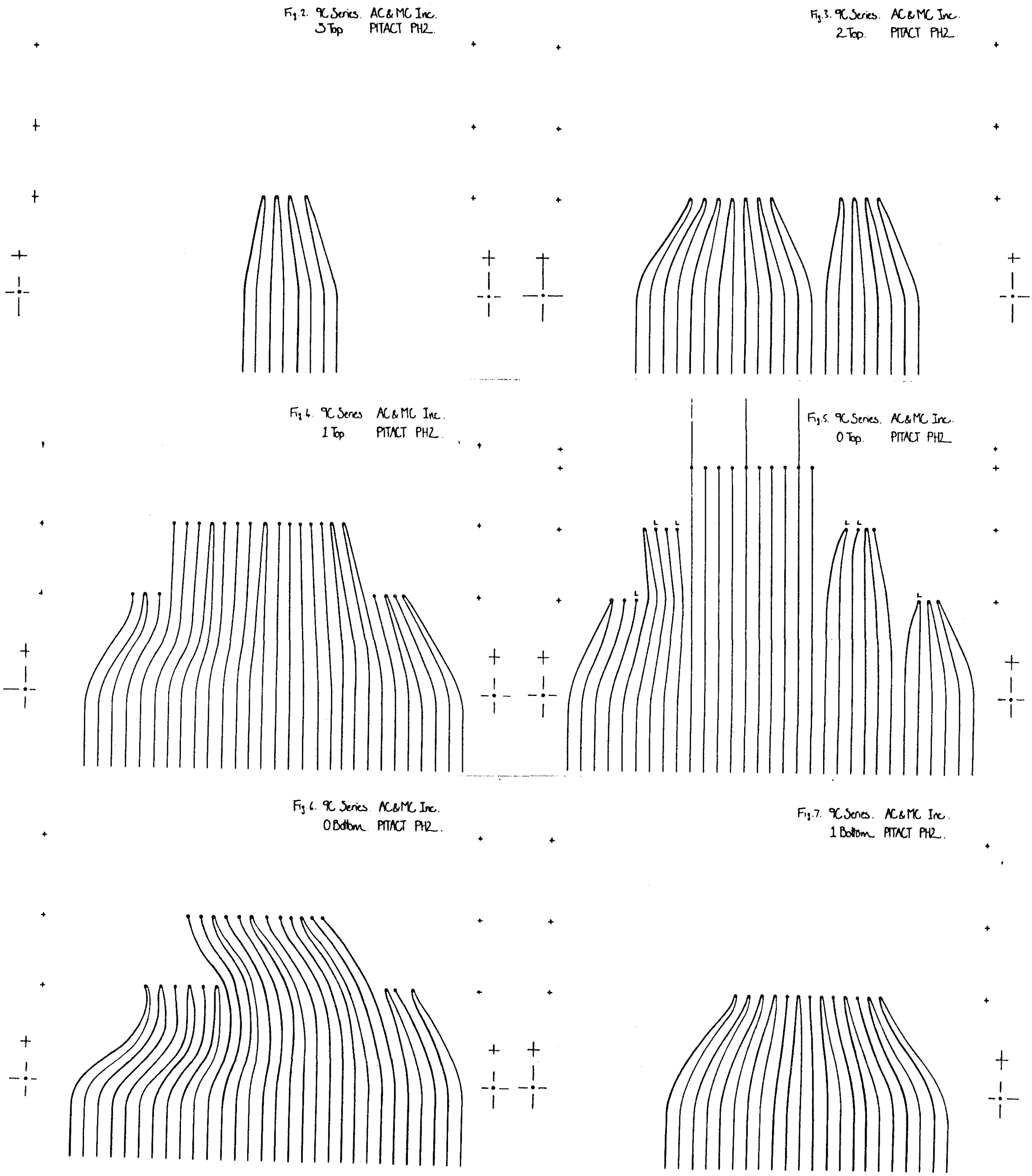


Fig. 4. The Channel Lay-Outs Used for the 9th Series of Canard Models.

3.7 The 9th Series of Canard Models.

This series of samples used essentially the same channel configurations as the 8 series and a number of modifications were made to the brazing variables to try to eliminate the channel blockage problem. Definite improvements were achieved, but not the 100% attained in the initial proof-of-concept tests.

Samples 9C1 and 9C2 were used for further machining tests which included rough and fine ball-end milling cuts, applying conventional tolerances in which the net contour is established at the bottom of the milled scallops. This enables the correct profile to be maintained during final hand finishing. The surface finish achieved on the upper surface was impressively good, there was no wavyness across the bond plane.

These prototype models proved that the good surface finishes obtained by laboratory techniques on small sized samples were also achievable on laminated brazed sheets by normal model shop practices.

The overall satisfaction was, however, spoilt by the fact that for both samples, operator error resulted in the cutter height being mis-set for machining the bottom surface. This surface was consequently undercut by 0.875 mm [0.035 in.]. Many of the channels were exposed, thereby giving an unitentional insight into their internal surface finish.

3.8 The 11th Series of Canard Models.

These samples also used the same channel lay-outs as the 8th and 9th series and further modifications were made to the brazing cycle parameters. Both samples brazed were 100% successful with no blocked channels and no cross-leaks. Sample 11C1 was sectioned at the three spanwise locations of the chordwise orifice rows to prove the quality of the brazed bond and the clarity of the channels. Sample 11C2 was retained as a fall-back that could be used as a last resort to enable one of this series to be machined if the slightly larger and more ambitious 12 series samples should fail to braze successfully.

4. Details of the 12 Series X29A Canard Models.

The success achieved in fabricating a perfectly brazed samples in the 11th series of samples focussed attention on the need to design a canard that would be of maximum use as a research tool. We were fortunate in having the help of L. Glaab, a GWU masters degree student, who assisted the technical monitor and contributed significantly to the program.

4.1 Wall Interference Effects, the 2D Inboard Section.

As noted earlier, it was not possible to adopt the actual mounting system used on the flight canard, due to the limitations on the space available in the support shaft. It was decided to test the model canard in a side-wall mounting, but this raised questions on how best to minimise interference effects from the tunnel sidewall. The configuration adopted was to locate a 2D section between the sidewall and the actual 3D canard. This can be seen clearly in Figs. 6 to 10.

This 2D section had a span of 37.5 mm [1.5 inches] and exactly the same section as the root chord of the canard. In order to exercise further control over the sidewall boundry layer, Glaab designed a 'glove' that fitted over the first 15 mm [0.375 in.] of the 2D section and directed the flow over the remainder of the 2D section.

4.2 Orifice Location.

The location and distribution of the orifices in the upper and lower surfaces were initially determined in conjunction with the technical monitor P.L.Lawing and L. Glaab. Slight modifications to some of their locations were subsequently necessary to accomodate the feed channels.

4.3 Bond Plane Out-Crops and No-Go Regions.

These were determined as described earlier and were essentially similar to those used in the earlier prototypes of the 8th, 9th and 11th Series.

4.4 Channel layouts

The inclusion of the 2D section as described above, meant that slightly larger sheets had to be used for the 12 series canards. These were size 225 x 275 mm [9 x 11 in.] and the channel layouts for the 12 series canards were modified to make the best use of the additional space available due to the inclusion of the 2D section. Fig 5 (a) to (d) shows photographs of the four chemically milled sheets, Top 1 to Top 4 used to make the upper surface of 12C3. The three through-channels on sheet Top 1 were for the orifices located in the canard tip. It can also be seen that, due to the need to fit as many orifices as possible into the thinnest sections of the airfoil, few of the orifices on this sheet are served by double channels. It was, however, possible to run double channels to many of the orifice locations on the other, less-crowded, sheets.

4.5 Chemical Milling

Three sets of the seven sheets needed to define the complete channel network were chemically milled. The channels were milled to a nominal depth of 0.37 mm [0.015 in.] and two complete sheets met this specification. However, on some sheets in the third set the channels were only about 0.012 in. deep. This was not originally considered to be a problem as they were intended as a back-up set.

However, in the event, this third set had to be used to braze the laminate that was eventually machined into 12C3, the testable model.

4.6 12C1

The fixtures, braze cycle, foil thickness and other parameters used for 12C1 were exactly the same as those for 11 series samples which had used the smaller, 175 x 225 mm [7 x 9 in.] sheets. The resultant brazed laminate gave an almost perfect sample, spoiled slightly by some small cross-leakage in one plane only, due probably to localised distortion of one sheet. This sample was held as a back-up that could have been used if neccessary.

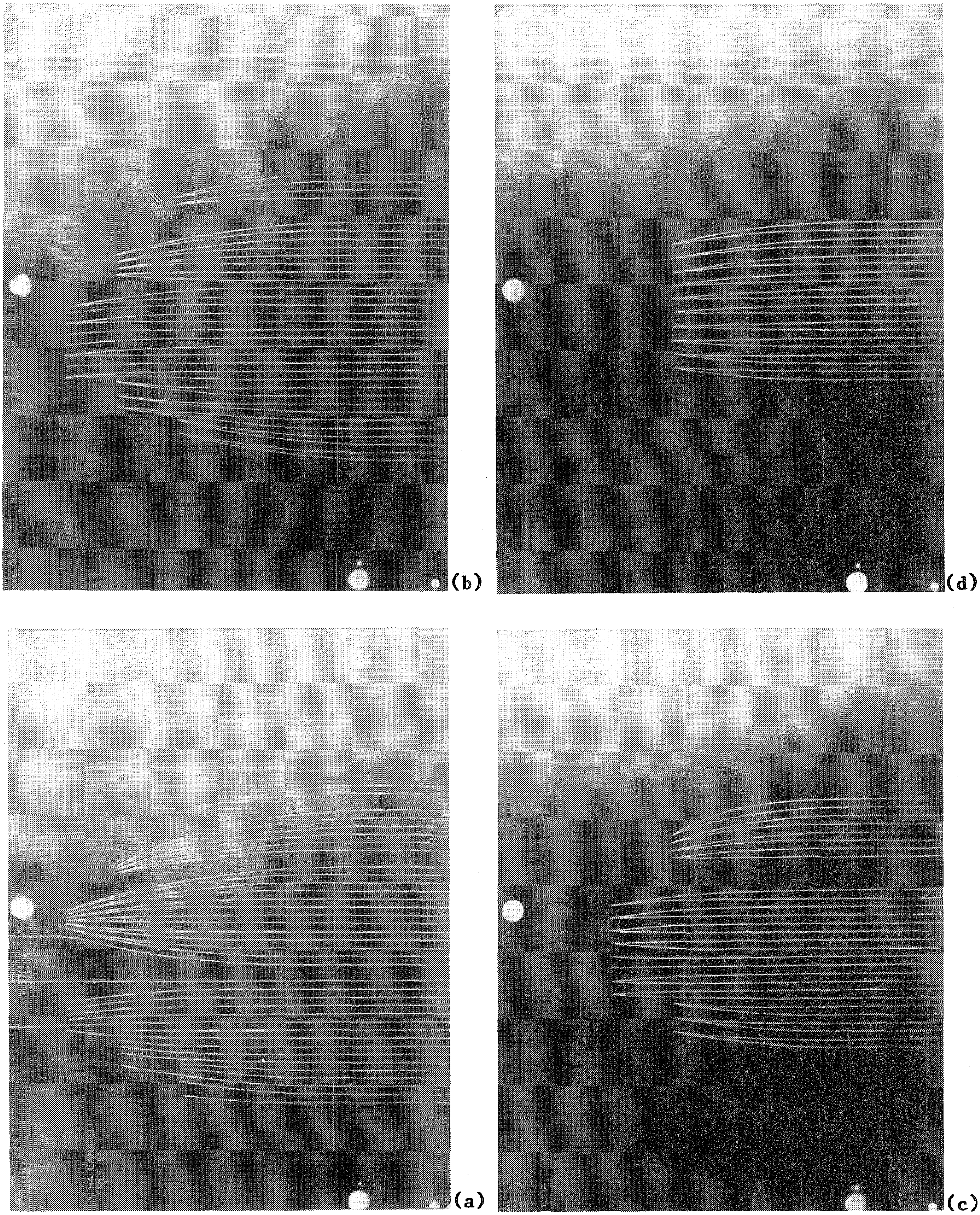


Fig 5 (a) to (d) Photographs of the Four Chemically-Milled Sheets, Top 1 to Top 4, Used to Form the Upper Surface of 12C3.

4.7 12C2

Small modifications were made to the brazing parameters and the second set of chemically-milled sheets were brazed into a laminate. The result was a perfect sample in all repects.

It was, therefore, sent to the sub-contractor for CNC milling, with the results shown in the two photographs, Figs. 6 (a) and (b). The large comet-shaped defect that can be seen in Fig. 6 (a) on the upper surface at the transition from the 2D to the 3D section was apparently caused by a rare error in the program tape. This, in isolation, would have caused the loss of, at most, one or two orifice positions and could have been accepted.

The problem shown in Fig. 6 (b) was, however, fatal. Due to some unexplained operator error, the model had been set up to the wrong height after it had been turned over to rough-cut the bottom surface. As a result, this surface was severely undercut and a number of the channels were exposed.

5. Brazing, Machining, Finishing and Orifice Drilling in Model 12C3.

5.1 Brazing

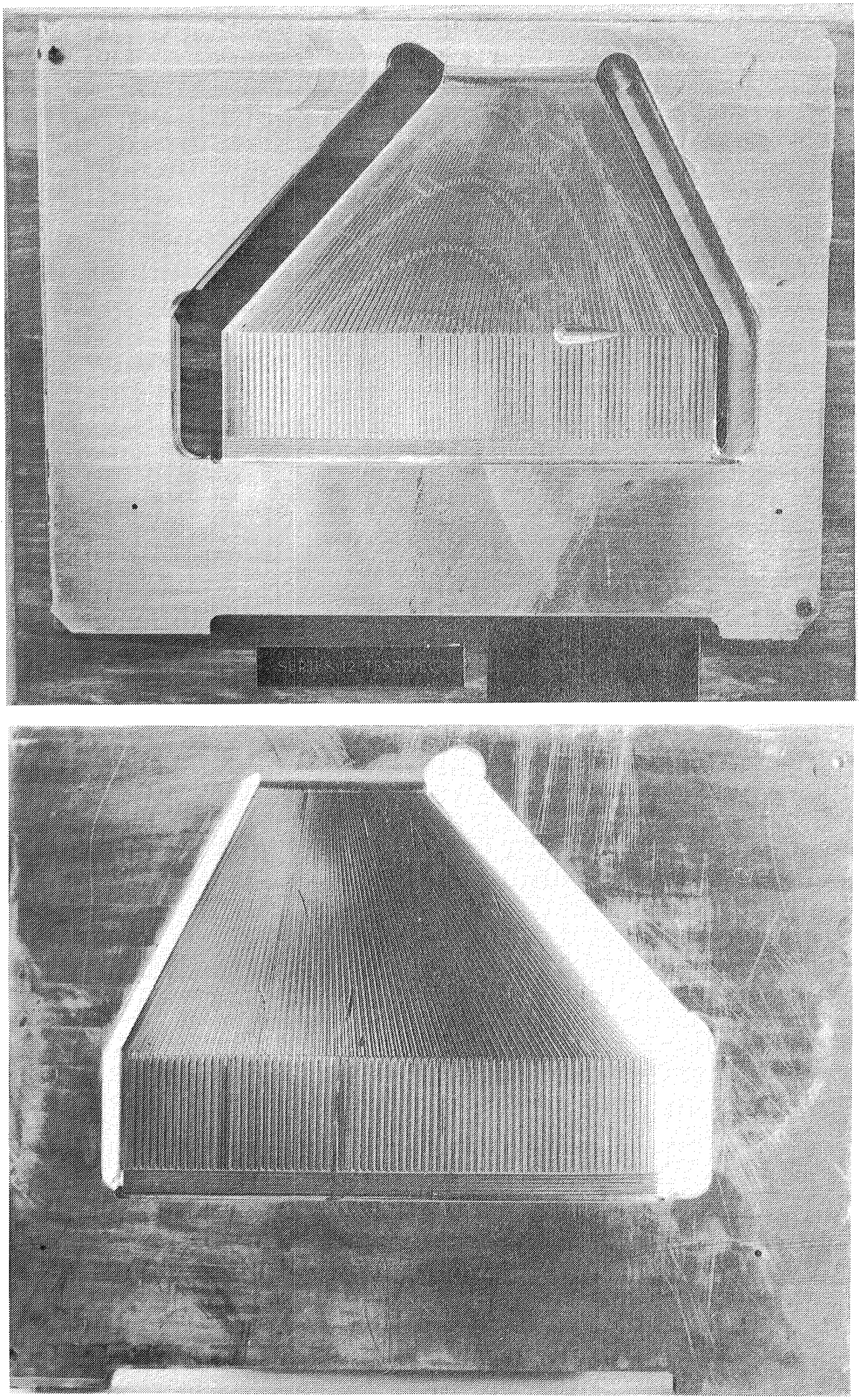
As noted above, the 3rd set of sheets, which had channels only 0.3 mm [0.012 in.] deep on sheets Top 1 and Top 2, had to be used for this model. The sheets were also modified slightly to allow unique identification of the location of the critical zero bond plane, (WRP). The earlier samples had highlighted the extreme importance of knowing and maintaining the exact location of the WRP.

The brazing operation was completly satifactory and it was found that a steel piano wire of diameter 0.175 mm [0.007 in.] could be probed to the ends of even the narrowest channels, thereby proving them to be un-blocked. It was considered to be better than the reserve laminate, 12C1, and 12C3 was therefore sent to the sub-contractor for machining.

5.2 CNC Ball-ended Milling

As a result of the need to keep a constant tool pressure on the ball-ended cutter to prevent it skidding and work hardening the surface, the rough cuts were made leaving 0.5 mm [0.020 in.] on the top and bottom surfaces. The final cut was made to net tolerance on the top surface, which was then released, turned and re-clamped for the final cut on the bottom surface.

State-of-the-art tolerances were stated to be +/- 0.075 mm [0.003 in.] for A286 due to the known difficulties in machining this material. Furthermore, as it was preferable to have a full contour to prevent break-through into channels, the technical monitor agreed that all the surface co-ordinates should be increased by 0.075 mm [0.003 in.] over the first 80% of the chord and that the thickness of the rest of the trailing edge would be increased gradually to give a thickness of 1 mm [0.040 in.] at the trailing edge. It was further agreed that +0.075/-0.000 [+0.003/-0.000 in.] would be accepted as the final tolerance.



(a)

(b)

Figs. 6. Photographs of the Damage Caused to Sample 12C2 Due to Machining Errors. (a) Upper Surface. (b) Lower Surface.

5.3 Hand Finishing.

Most of the hand finishing on 12C3 was carried out while the model was still in the 'window frame' that can be seen in Figs. 6 (a) and (b) for 12C2. The model was left in the 'window frame' while the orifices were drilled in the airfoil surface, in order to give it as much support and protection as possible. A small amount of further work to the leading edge, the canard tip and the root of the 2D section was carried out after the model had been wire-EDM plan-formed from the 'window frame'.

5.4 Tube Attachment.

At an earlier stage, the in-board edge of the model had been EDM wire-cut to give a clean section through the ends of the embedded passages. The ends of these passages had been drilled out to depth of about 4 mm [0.16 in.] and a diameter of 1.025 mm [0.041 in.] before the airfoil contours were machined.

After the airfoil had been machined successfully, short lengths of 1.00 mm [0.040 in.] diameter stainless steel hypodermic tube were soldered in place using the 50% Sn:49.5% Pb:0.5% Sb solder and the Eutector 157 flux as discussed earlier.

5.5 Orifice Drilling

In the earlier stages of development, X-ray photographs had been used to study the condition of the embedded passages. It was expected that the same technique would permit ready identification of the positions at which the orifices would need to be drilled to intersect the embedded passages. In the event, it was found that parallax errors were introduced by the conical nature of the X-ray beam. Furthermore, these errors made accurate location of the orifice positions increasingly more difficult the further they were from the optical axis. The problem was overcome by iterative drilling, re-X-raying, measurement and correction. The more orifices drilled successfully, the easier it became to locate the remaining positions.

Orifices were drilled with the A286 in the age-hardened condition using 0.325 mm [0.013 in.] twist drills and there were no abnormally high loss rate on break-through into channels.

In the end, a total of 56 orfices were placed on three rows on the upper surface of the airfoil. Of these, 24 were located at about 30% span, 19 at about 60% span and 13 at about 90% span. These are shown clearly in Figs. 7 and 8 (a).

A total of 37 orifices were placed in three similar rows on the lower surface, 14 on the inner row, 14 in the middle row and 9 in the outer row. These orifices are shown in Fig. 8 (b). A further 3 passages out-cropped at the tip itself to give a grand total of 96 pressure-measuring positions. These can be seen clearly in Figs. 9 (a) and (b).

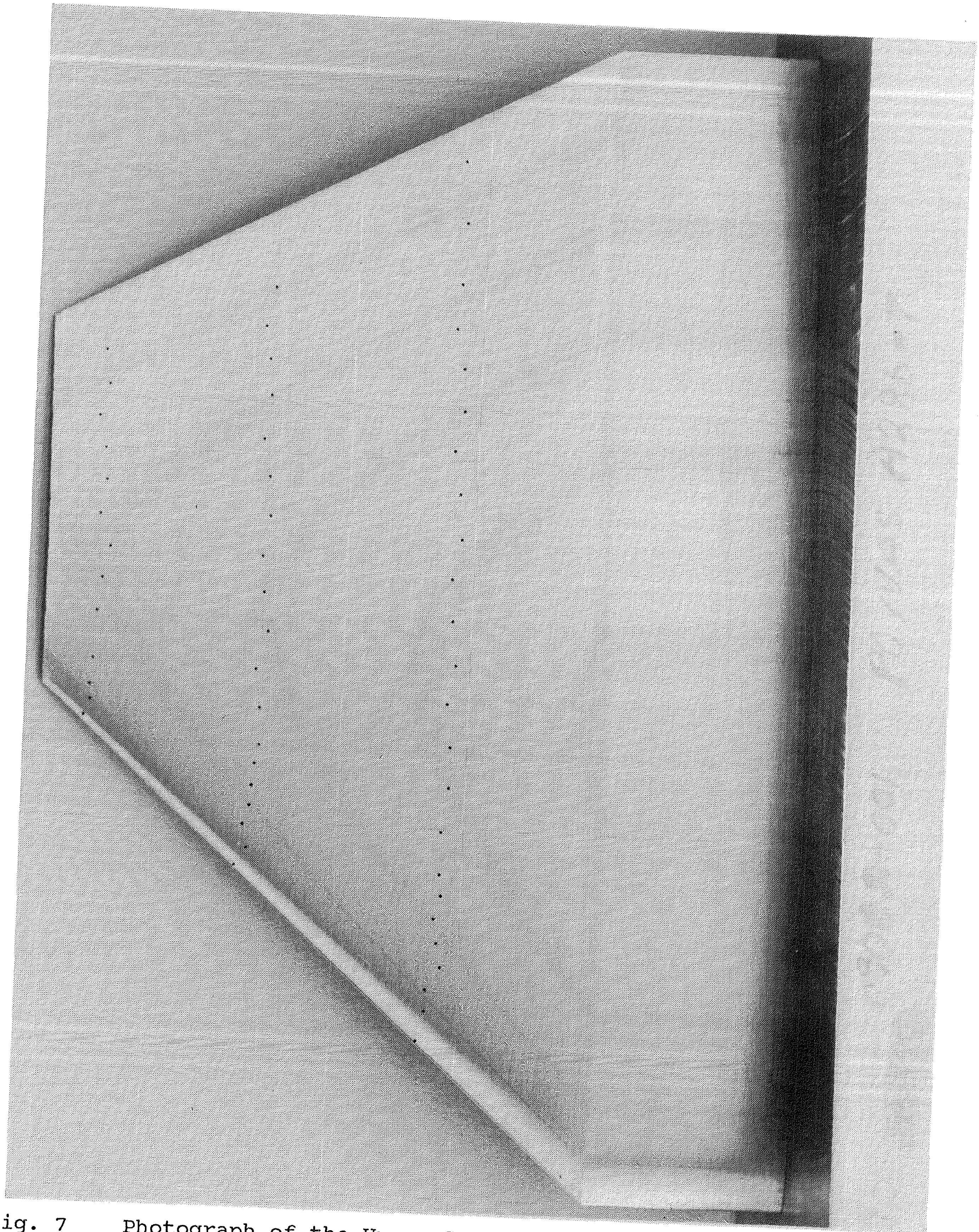
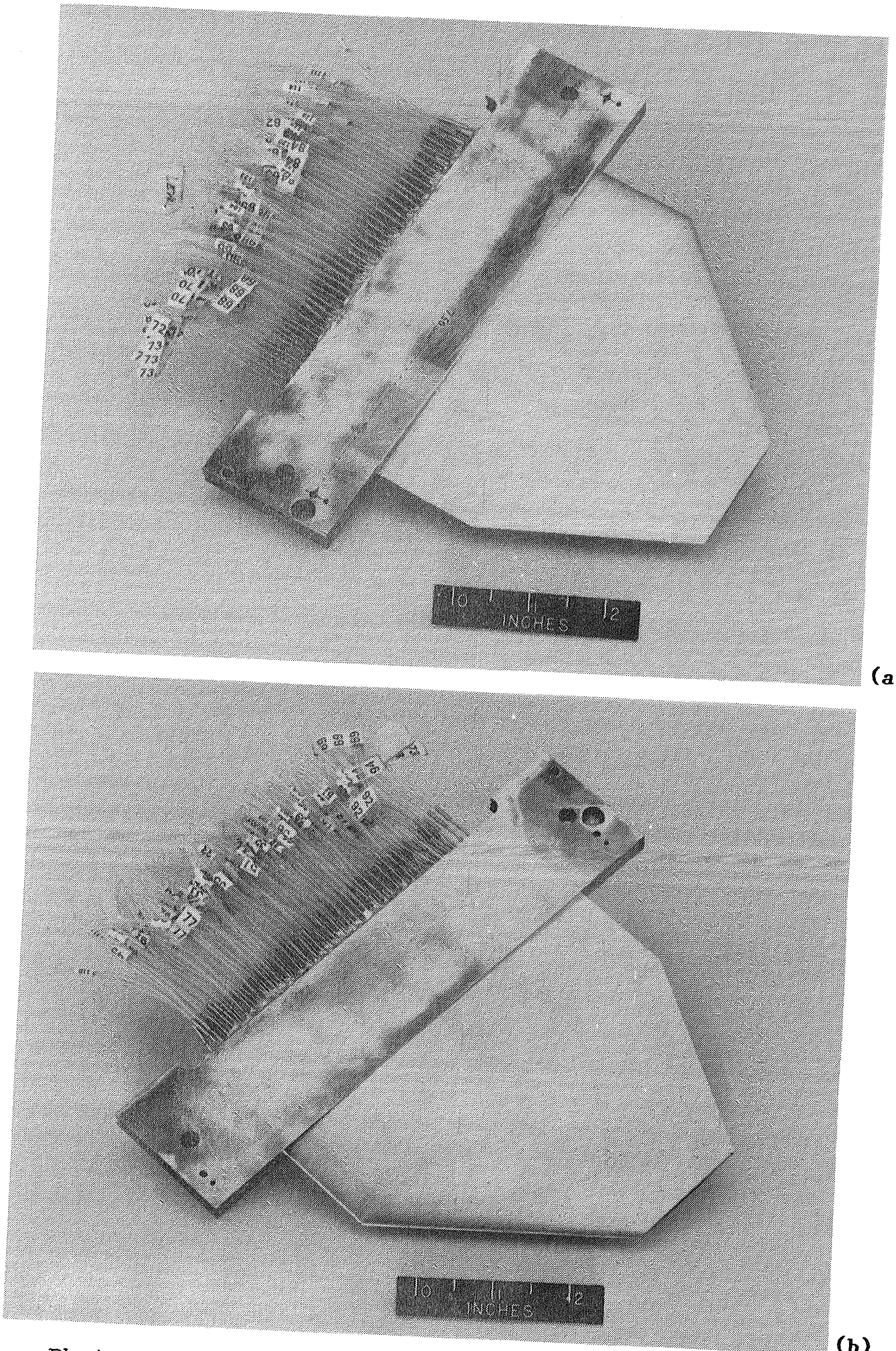


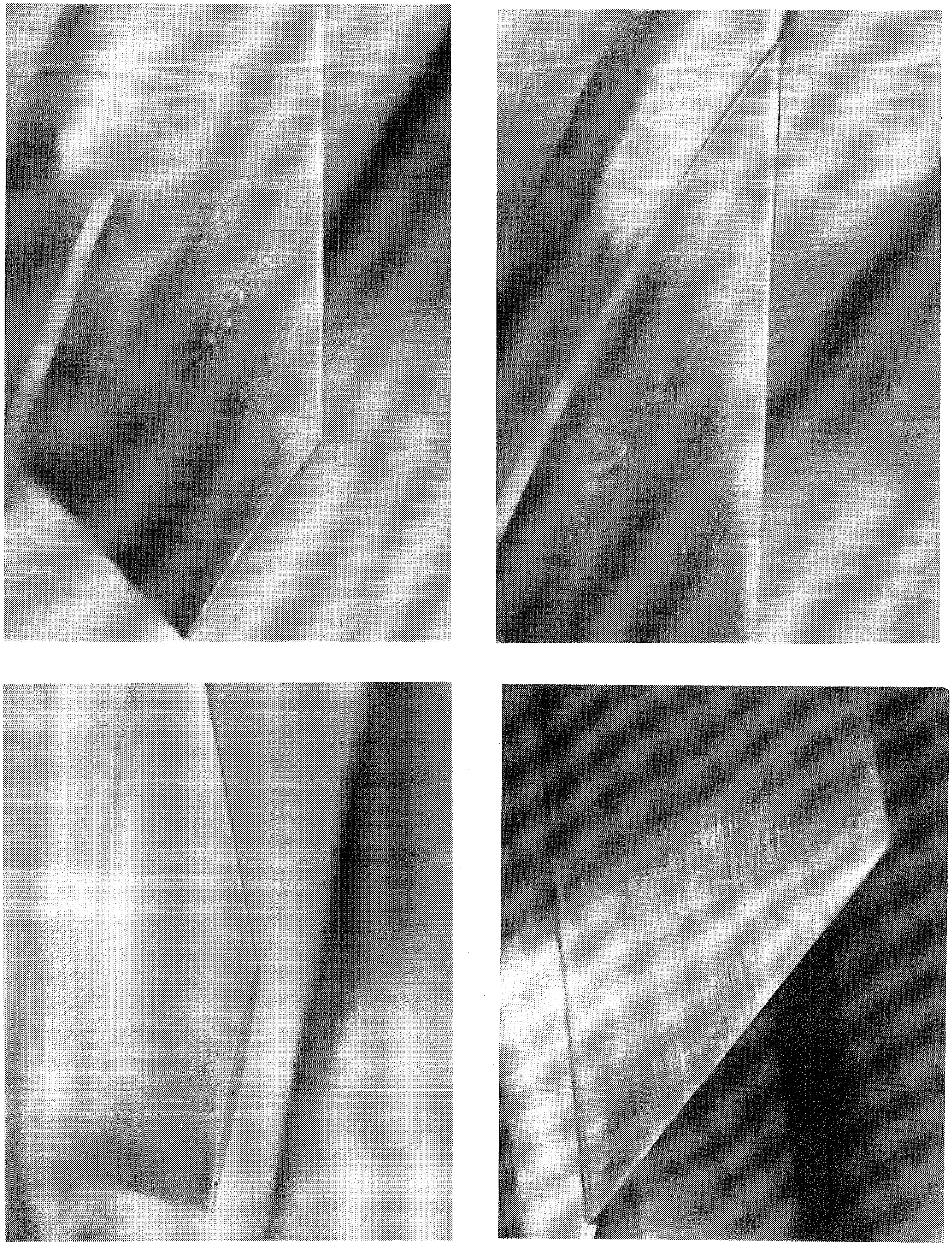
Fig. 7 Photograph of the Upper Surface of the Finished Canard Model.



(a)

(b)

Figs. 8 Photographs of the Finished Canard Showing the Stainless Steel Hypodermic Tubes and Plastic Jumper Tubes. (a) Upper, (b) Lower Surface.



Figs. 9 Photographs of the Orifices in the Canard Surface.

Figs. 8 (a) and (b) also show the short lengths of hypodermic stainless steel tubes soldered into the in-board edge of the model and the plastic jumper tubes that connect to them. These tubes were pressurised to a small over pressure during orifice drilling to help detect break-through of the drill bit into the sub-surface passage, which was marked by a series of bubbles in the cutting fluid around the drill bit.

5.6 Optical Fibres set into the Airfoil Tip

It was originally intended that the three passages that out-cropped at the canard tip would be used to give a visual indication of the tip and any possible movement due to aerodynamic loading. The technique of placing fiber-optic filaments in these passages was developed and demonstrated on a small proof-of-concept model. It was not, however, incorporated into the final model due to the conflicting operating requirements of the 0.3 m TCT. It was important to have a series of orifices in the tunnel wall opposite the model to obtain the far-wall pressure distribution and, unfortunately, these were in the position that was needed to view the optical fibers. It is necessary to view such fibers at almost normal incidence to get adequate luminance.

6. Mounting and Testing of Model 12C3.

6.1 Mounting.

A modified mounting block was made and fitted into a standard turntable to allow the model to be mounted on the sidewall of the 0.3 m TCT. As noted earlier, a special 'glove' was also made to fit over innner part of the 2D section to minimise wall-interference effects. These features can be seen in Fig. 10.

6.2 Testing

The model was tested successfully in the 0.3 m TCT at NASA Langley over the full range of temperatures, Reynolds numbers, subsonic and supersonic Mach numbers and dynamic pressures achievable in this cryogenic wind tunnel. The concept of the laminated sheet technique was fully validated and much unique data was obtained.

A typical set of data is illustrated in Fig. 11. The pressure coefficient is shown as a function of chordwise location for orifices located on the upper and lower surfaces of the model. Threee such plots are shown in Fig. 11 for orifice rows located at 0.28, 0.62 and 0.91 percent of the span.

The results shown are for a Mach number of 0.90, a Reynolds number of 28 million and an angle of attack of 8 degrees. Much other data was taken during the tests and it is still being reduced and plotted.

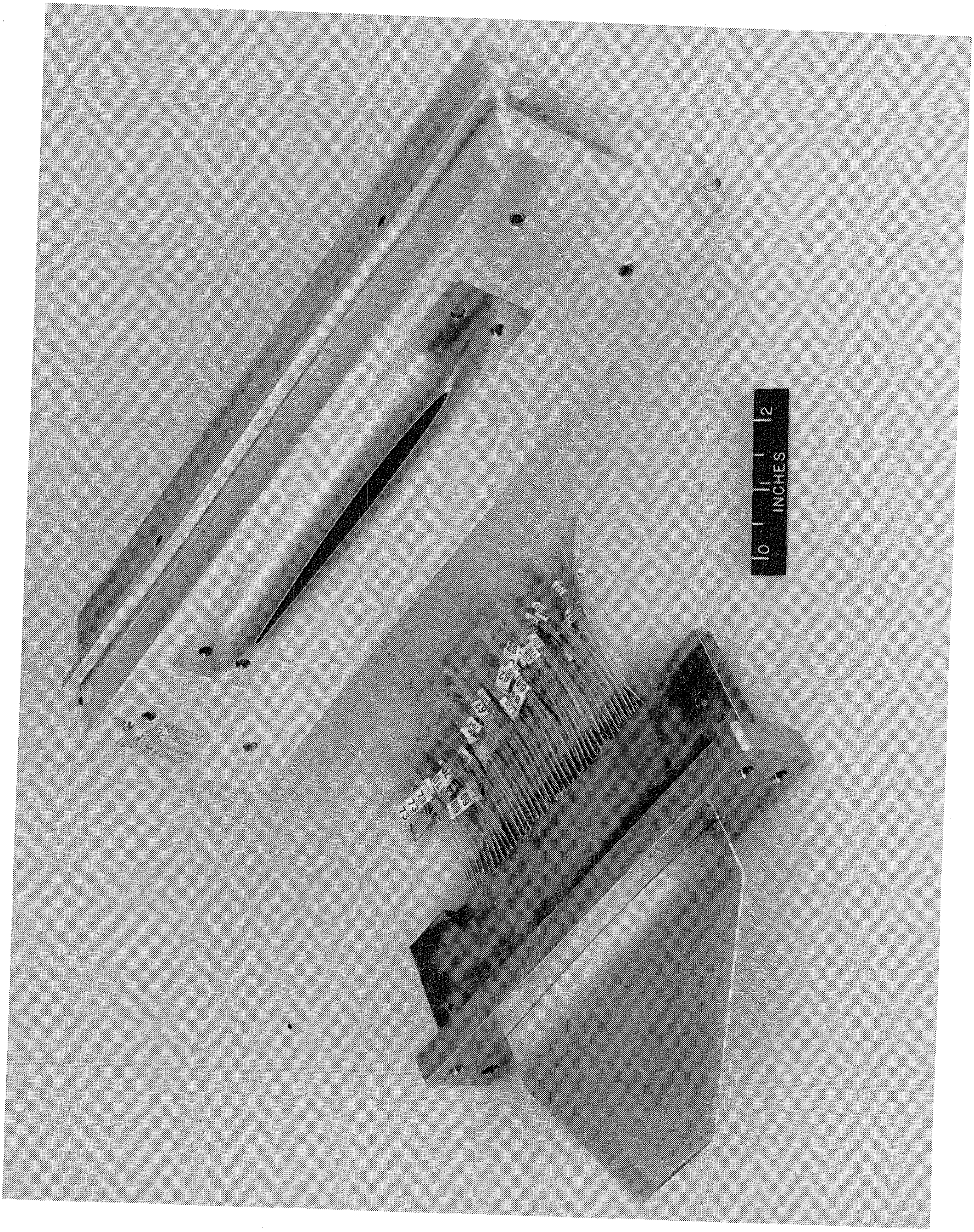


Fig. 10 The Finished Canard and Its Mounting Block and Glove.

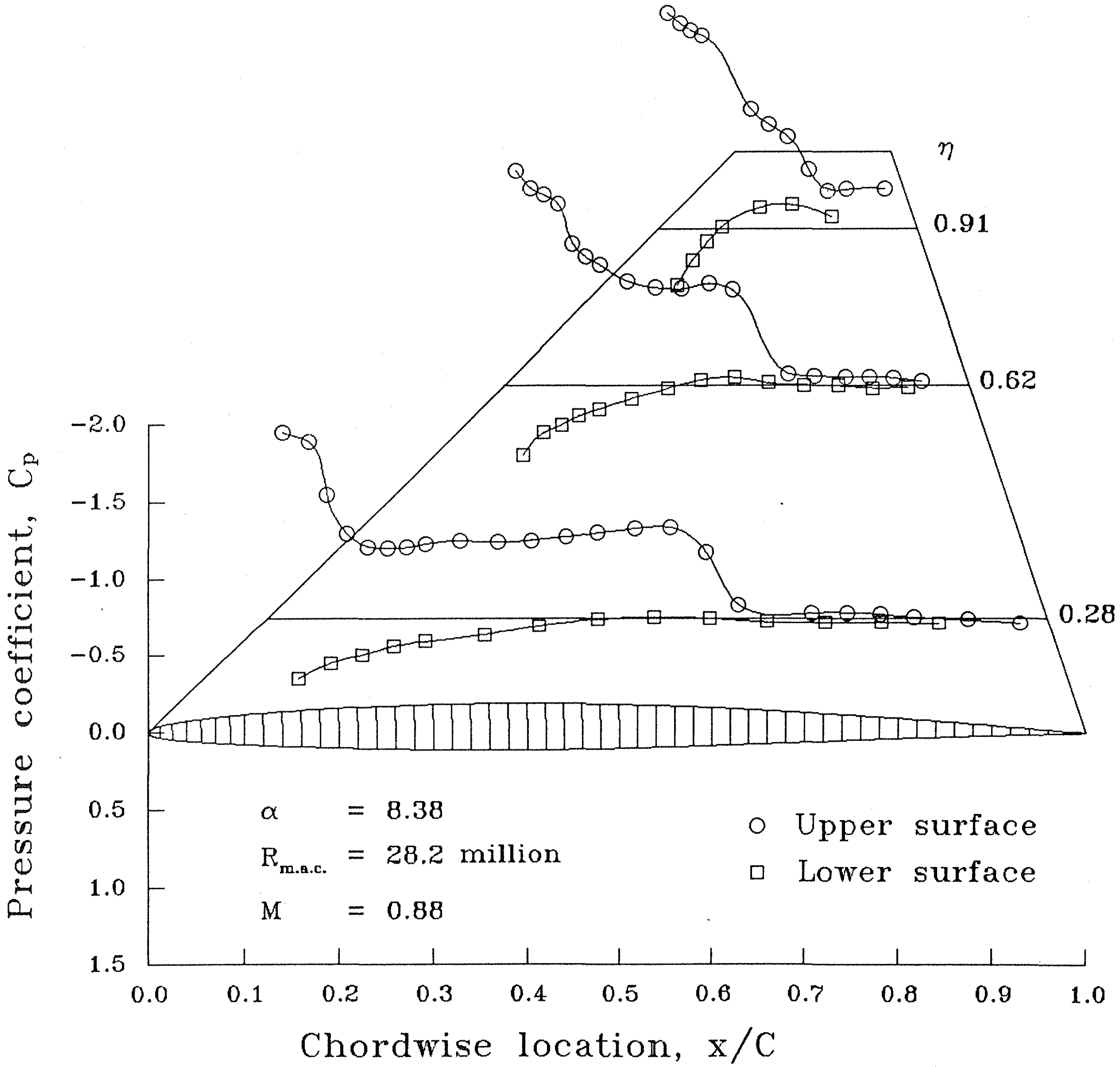


Fig. 11 A Typical Set of Data From Tests on the Model of the X29A Canard in the 0.3 m TCT Showing Pressure Coefficient as a Function of Chordwise Location for Orifices on the Upper and Lower Airfoil Surfaces.

7. Scale-Up and the NACA 65a-105 2D Airfoil.

Fabrication of larger sized airfoils was also investigated. In particular, a NACA 65a-105 airfoil section was chosen for this development as this thin airfoil has a direct application to the wing of a modern fighter aircraft. However, problems were encountered in scaling up the technique to the larger and thicker stacks needed for fabrication of 2D models for the 0.3 m TCT test section.

To fit in the 0.3 m TCT, a 2D airfoil needs to have a clear span of 330 mm [13 inches] between the test section walls. A further 38 mm [1.5 inches] was considered to be the minimum required for fixturing to the mounting turntables, giving a total span of 406 mm [16 inches]. Experience had shown that it was neccessary to braze an even larger dimension to avoid edge effects and thus the total sheet length became 432 mm [17 inches]. A similar logic gave a sheet width of 305 mm [12 inches] to obtain an airfoil with a chord length of 230 mm [9 inches].

Sheets size 230 x 178 mm [9 x 7 inches] were used in fabricating the 12 series canards, hence the area of the brazed sheets increased by a factor of 3.24 for the larger 2D model. Furthermore, 15 sheets were needed to give the thickness required for the NACA 65a-105 airfoil, compared with 10 for the X29A canard, an increase by a factor of 1.5. Taken together, these increases in size created problems that were not satisfactorily resolved during Phase II. Specifically, there were cross-leaks between some of the channels due to void formation and there was significant distortion of the bond plane.

The distortion in the laminate for the 2D airfoil created a serious problem. It was found that reference points near the two ends and at the center of the leading edge, together with one point near one corner of the trailing edge could all be located to within about 0.06 mm [0.0015 in.] Therefore, this was defined as the wing reference plane. A fourth reference point was measured as 0.95 mm [0.038 in.] above this plane due to the fixturing problems discussed earlier. It was impossible to fit the airfoil contours completely within the laminate in this area and a few channels were exposed during wire-cutting.

Returning to the better side, reference points established near the leading and trailing edges were used to define the wing reference plane. However, the bond plane at about the middle of the airfoil chord was found to be about 0.22 mm [0.009 in.] above the WRP. With the agreement of the technical monitor, the wire-cut sub-contractor was instructed to increase the airfoil co-ordinates by 0.2 mm [0.008 in] all round to prevent any channel break-out in the important center section of the 2D airfoil.

Nevertheless, a 2D airfoil model was EDM wire-cut and finished to provide a model capable of being tested in the 0.3 m TCT with a sufficient number of useable pressure orifices.

8. Other Airfoil Configurations and Possible Spin-Off.

The technique has also been evaluated for the construction of twisted sections and cusped leading and trailing edges. Considerable success has also been achieved with small-scale samples of exotic configurations such as gull-wing airfoil sections, typical of some designs for supersonic transports. At this stage in the development of the technique, further effort in fabricating small models of these more advanced configurations could produce results unachievable by any other technique.

The technology of using embedded passages could be applied to other areas of aerodynamic research other than pressure measurements. Possiblities include, boundry layer control by ducting flow through internal passages, seeding devices for flow visualisation studies, flaps and control surfaces, wake survey probes, optical position indicators using fibre optics, etc.

Finally, it is believed that the laminated thin sheet technology could be applied in non-aerodynamic applications, for example in building small heat-exchangers, fluid control devices and other devices that need the formation of complex channel geometries within a confined space.

9. Discussion and Recommendations.

9.1. Discussion

One target for the work carried out during Phase II was the development of a cost-effective technique for the contruction of airfoil models. It is thus relevant to consider the way in which the cost of a model, or test-piece, is influenced by its size. In general, small samples cost less and more tests can be carried out for a given level of resource. Large samples not only cost more, and failures are thus more expensive, but distortion tends to increase rapidly with increse in dimensions. Thus scale-up from a small, successful sample often hits problems when some critical dimension, such as the gap between two bonding surfaces, becomes out-of-tolerance in the larger sample.

The following cost / size / difficulty trends have been identified during the Phase II program.

9.1.1 Materials

The cost of both the A286 sheet and the MBF 20 braze foil is directly proportional to their surface area. However, larger sheets have a greater chance of being dented during handling and the proportion of usable material thus decreases. In the case of braze foil, the maximum width of 100 mm [4 in.] can create waste for some layouts.

9.1.2 Chemical Milling

This is much less sensitive to size as actions such as preparation of the initial drawings are driven more by the complexity of the lay-out, total line length, etc., than by the area. Similarly, although materials costs are greater for larger sheets, preparation time is almost size-independant.

The time taken to chemically mill the channels on a plate is almost independant on its size and the effective life of the chemical bath is a function of the total weight of metal removed.

9.1.3 EDM Wire-Cut

The cost of this process is determined by the cutting speed, which, to a first approximation, is inversely proportional to the length of cut. For example a 200 mm [8 in.] cut would take about four times as long as a 50 mm [2 in.] cut. However, a 400 mm [16 ich] cut is at the limit of the technical capability of the sub-contractor and a number of problems become severe at these sizes. For example, one essential requirement for a steady cutting speed is the ability to flush the debris away from the wire. When the wire cuts through a slab of metal, stresses are released and the componant relaxes and often deforms. If this deformation makes the component close-up behind the wire, it can cause it to break, thus causing frequent delays and lost time.

It was found that one aspect of the laminated plate technology exacerbated this problem as compared to machining a similar airfoil from a solid block. No extra sheets had been brazed to the top and bottom of the stack and the wire tended to break through the outermost sheets at the maximum thickness positions of the airfoil. A thick plate of aluminum had been fixed to each side of the A286 laminate to minimise this problem, but the rough cuts through these regions had to be taken very slowly and carefully. The distortion to the wing reference plane discussed earlier made this problem even more severe.

9.1.4 CNC Milling using Ball-Ended Cutters

This is the standard state-of-the-art technology for fabricating 3D airfoils. A286 is known to be a difficult material to machine due to its 'gummy' nature and tendancy to work-harden. Machining-induced stresses are also large in this alloy. This is discussed at length in Refs. 7 to 9. Larger sizes take longer to machine and are thus more expensive. Far more important, however, is the greater loss in time and material if an irrecoverable mistake is made during machining.

This point was particularly apposite to the X29A canards, three of which were subjected to irrecoverable operator errors. In the case of the two 9 series development prototypes, this was not too serious, as valuable lessons were gained from getting them to this stage. In the case of 12C2, its loss was a serious setback which caused a delay to the program. It also put a lot of pressure on those researchers who were to test the model during a limited period of availabity of the 0.3 m TCT. The ultimately successful machining of the final brazed laminate, 12C3, was a great relief to all concerned.

The lesson to be learnt from this episode is the importance of ensuring good communications between all involved parties: between the designer/main contractor and the sub-contract fabricator and particularly within the command chain at the sub-contract fabricator. This latter factor is very difficult for the designer/main contractor to monitor, especially as problems have a habit of always occurring during second shift!

9.1.5 Laminated Brazed Sheets Compared to a Solid Block.

As far as the actual machining is concerned, there is little, if any, difference between machining an airfoil from a stack of laminated brazed sheets or from a solid block of A286.

The critical difference is the unique character of the zero bond plane in a laminated stack. In the laminate, all the channels are located relative to this plane and if it is allowed to move, upwards for example, the channels will also move upwards and run the risk of being exposed when the upper airfoil surface is machined.

There are two major causes of this problem, warpage during brazing and subsequent deformation due to machining-induced stresses.

Considering first the warpage that can be created during brazing. In the case of the 12 series canards, the position of the zero bond plane remained within about 0.05 mm [0.002 in.] over the whole area of the laminate. The accepable tolerances within the dimensions of the airfoil contours could accomodate this degree of movement without creating a serious problem.

In contrast, the distortion in the larger laminate for the 2D airfoil created a much more serious problem. One corner was measured as 0.95 mm [0.038 in.] above the WRP due to the fixturing problems discussed earlier. This corner could not be fitted within the airfoil contours and a few channels were exposed during wire-cutting. Furthermore, the bond plane at about the middle of the airfoil chord was also found to be about 0.22 mm [0.009 in.] above the WRP. The airfoil co-ordinates were therefore increased by 0.2 mm [0.008 in] all round to prevent any channel break-out in the important center section of the 2D airfoil.

If we now consider that a laminate has been brazed with a perfectly flat WRP and consider machining-induced stresses. It is customary practice to rough machine one side about 0.5 mm [0.020 in.] full, release it and then turn it over and rough machine the second side, also about 0.5 mm full. In this way it is hoped that the stresses induced in opposite surfaces will balance and not create any distortion. There should be no problems with channel break through at this stage given this thickness of metal on top of the channels.

However, the fine cut is normally taken net to the final surface contour, as this helps to identify the required airfoil contour during subsequent hand finishing. As before, the model is then released after the fine cut, turned over and re-clamped before fine-machining the second surface. Ideally, the stresses induced by this second fine cut are exactly the same as those induced in ther first side. The two sets of stresses balance and the airfoil remains undistorted. Should this not be the case, for example if more stress hawo sets
of stresses balance and the airfoil remains undistorted. Should this not be the case, for example if more stress had been induced on one side due to the use of a blunt cutter, the airfoil would warp when released, being either bent or twisted from root to tip. Thankfully, this did not occur with 12C3 and the finished canard appeared to be within tolerance.

9.2 Further Work.

It is important to decide on priorities for the next stage of development on the laminated brazed sheet concept. Some possible directions are outline below:

9.2.1 Refine Configurations Within the 'Known Envelope'

There are many other interesting 3D airfoil configurations that could be fabricated within the known constraints of the brazing parameters. A number of aspects could be refined further, such as fixturing to obtain high relative accuracies between the sheets, optimised channel lay-outs to give even higher orifice densities, flap and strake configurations, manifolded internal passages, etc.

9.2.2 Extend Upwards, Explore Ultimate Thicknesses.

Staying within the 175 x 275 mm [7 x 11 in.] sized sheets successfully used for the 5% thickness canard, a family of similar, but increasingly thicker airfoils could be developed sequentially until a useful limit was achieved, or problems were encountered due to load limitations within the furnace.

9.2.3 Extend Outwards in One Dimension.

A sheet of dimensions 100 x 500 mm [4 x 20 in.] would have almost the same area as that of the sheets used to make the 12 series canards. (500 mm is the greatest length that can be fitted into our brazing furnace.) Development of a fixturing system that could be used to braze undistorted launinates, 10 sheets thick and with one large dimension, would go a long way towards understanding the problems encountered with the large 14 Series 2D airfoils. This would give a 10% thick airfoil which would be directly applicable to commercial transports. Furthermore, airfoils with high aspect ratios are of research interest for high performance sailplanes, high altitude reconnaissance aircraft and other specialized applications. Such configurations could provide suitable targets for this development.

9.2.4 Extend Outwards in Two Dimensions.

Keeping to the known thickness of 10 sheets, a <u>gradual</u> increase in area should be explored to 'expand the envelope' in a logical manner. It would obviously be useful if a series of meaningful objectives, in the form of airfoils that have worthwhile research interest, could be identified for this development.

9.2.5 Investigate Curvature in One Bending Direction.

This is probably one of the areas in which pay-off would be most rapid as it would cover important configurations such as flaps, cusped leading and trailing edges and other small, but important types of airfoil.

9.2.6 Investigate Reversed Curvature in Bending.

The gull-wing proof-of-concept test-piece showed that it was possible to place unblocked, leak-free passages inside a small sample that had five changes of curvature in a 175 mm [7 inch] length. If this can be scaled up to larger and thicker sizes, it would have obvious applications for supersonic transport configurations.

10. Conclusions.

The major accomplishment of Phase II of this SBIR program has been the successful development of the laminated brazed sheet concept of airfoil construction.

This novel concept has been taken from its inception and proof-of-concept stages, through the development of all the required supporting technologies and culminating in the reproducible fabrication of medium-sized laminates. The supporting technologies include; design, channel lay-out, chemical-milling of channels, braze foil shaping, sheet fixturing, zero plane location, etc. The major vacuum brazing parameters, time, temperature and load have also been optimized.

Furthermore, the associated technologies required to transform the laminated brazed sheets into a finished model have also been developed, either in-house or in conjunction with NASA engineers or the model shop sub-contractor. These include: tube attachment to the ends of the embedded passages, orifice location, orifice drilling, fibre-optic mounting and pre-test verification.

The development and integration of these technologies culminated in the fabrication of a 6.25% scale model of the X29A canard that was tested successfully in the 0.3 m TCT at NASA LaRC. This model was fabricated with a total of 96 orifices, 87 of which were used in the tests.

The model was tested over the full range of temperatures, Reynolds numbers, subsonic and supersonic Mach numbers and dynamic pressures achievable in this cryogenic transonic wind tunnel. A large body of unique aerodynamic test data was obtained during during this initial series of tests and there is every reason to expect that further valuable data could be obtained either by re-testing the existing airfoil, or after small modifications. For example, variation in the shape of the glove on the 2D section could give information on side-wall interference effects, while small modifications to the leading edge contour could determine how critical this factor was to the overall performance of the airfoil.

A number of more ambitious airfoil configurations were developed successfully as far as the proof-of-concept stage. These include: cusped leading and trailing edges, airfoils with +/- 6 degrees of twist and airfoil sections with multiply curved sections, such as the gull-wing shapes typical of current concepts for supersonic transports. Relatively small scale models of these configurations could probably be developed to a testable stage with a modest amount of further effort.

In effect, the Phase II program has defined a 'known envelope' of parameters for fabricating simple airfoils that can be inscribed in a laminate of size 175 x 275 mm [7 x 11 inches] and 10 sheets, or 8 mm [0.32 inches] thick.

Vacuum brazing is a highly reproducible process, once the brazing conditions and variables have been defined. If the configuration of a new airfoil falls within the 'known envelope' of the brazing parameters, it should be reasonably easy to design and fabricate new configurations.

Limited success was also achieved in scaling up the concept to a larger laminate of size 275 x 425 mm [11 x 17 inches] and thickness 13 mm [0.510 in.]. However, this simultaneous increase by factors of x 3.25 in area and x 1.5 in thickness turned out to be too large an excursion beyond the 'known envelope'. Fixturing problems were encountered that created warpage of the wing reference plane, localised regions of distortion and some areas of voidage in the bond planes that caused cross-leaks between some passages.

Nevertheless, one of the two large laminates that had been vacuum brazed was EDM wire-cut to form a 2D airfoil with a NACA 65a-105 section. This airfoil had a chord of 230 mm [9 in], a clear span of 330 mm [13 in.] and an overall span of 406 mm [16 in.]. However, a 400 mm cut is at or near the extreme limit of the wire-EDM machines capabilities and many problems had to be overcome by the sub-contractor in order to get the initial rough-cut airfoil shape from the laminated stack.

Thus, scale up to the larger size airfoil stretched the technique to, or beyond, the limits of two essential technologies, the vacuum brazing and EDM wire-cutting. With the experience now available, it should be possible to solve the outstanding problems, if significant resources were made available. As noted in section 9, this would probably be best achieved by a locical and gradual series of steps that would 'expand the envelope' in a technically sound manner.

Before much further work is carried out on the laminated brazed sheet technology, a decision should, however, be taken on the most appropriate direction in which the development should be directed. In particular, it is important to decide the relative priorities of the different potential objectives that could be set.

Specifically, is the highest priority to be given to carrying out an extensive program to determine the process variables that control the vacuum brazing of large, thick laminates?

Alternatively, should effort be directed towards development of small models of the more exotic configurations that appear to be ideal for application of this unique technology for airfoil fabrication?

Finally, the limited success of the larger 2D NACA 65a-105 airfoil should in no way be allowed to overshaddow the outstanding success of the X29A canard, a unique research airfoil that has already contributed to the NASA transonic aerodynamic research program.

The achievements of this Phase II project are summarised in Fig. 12.

Fig. 12 SUMMARY OF THE MAIN ACHIEVEMENTS OF THE PHASE II SBIR PROGRAM

Technology for Pressure-Instrumented Thin Airfoil Models

* Development of a Unique Laminated Brazed Thin Sheet Fabrication Technique for Airfoil Models.

* Achievement of 100% Void-Free Brazed Bonds.

* Fabrication of a 7.6 mm [0.3 inch] Thick Model of the X29A Canard.

* Location of Over 90 Pressure Orifices in a 5% Airfoil Section.

* Measurement of Unique Aerodynamic Data at Flight Reynolds Numbers and Transonic Mach Numbers.

* Tested over the Full Range of Cryogenic Temperatures and Dynamic Pressures Achievable in the 0.3 m TCT at NASA LaRC.

* Demonstation of Small Samples of Airfoil Sections with Single and Multiply-Reversed Curvature.

* Technology Transferable to Fuel Injectors, Boundary Layer Control, Cooling Passages and Other Applications Needing Embedded Passages.

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16 Abstract

A novel method of airfoil model construction has been developed during this program. This "Laminated Sheet" technique uses 0.8 mm thick sheets of A286 containing a network of pre-formed channels which are vacuum brazed together to form the airfoil. A 6.25 percent model of the X29A canard, which has a 5 percent thick section, has been built using this technique. The model contained a total of 96 pressure orifices, 56 in three chordwise rows on the upper surface and 37 in three similar rows on the lower surface. It was tested in the NASA Langley 0.3-m Transonic Cryogenic Tunnel. Unique aerodynamic data was obtained over the full range of temperature and pressure. Part of the data was at transonic Mach numbers and flight Reynolds number. A larger two dimensional model of the NACA 65a-105 airfoil section was also fabricated. Scale-up presented some problems, but a testable airfoil was fabricated.

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