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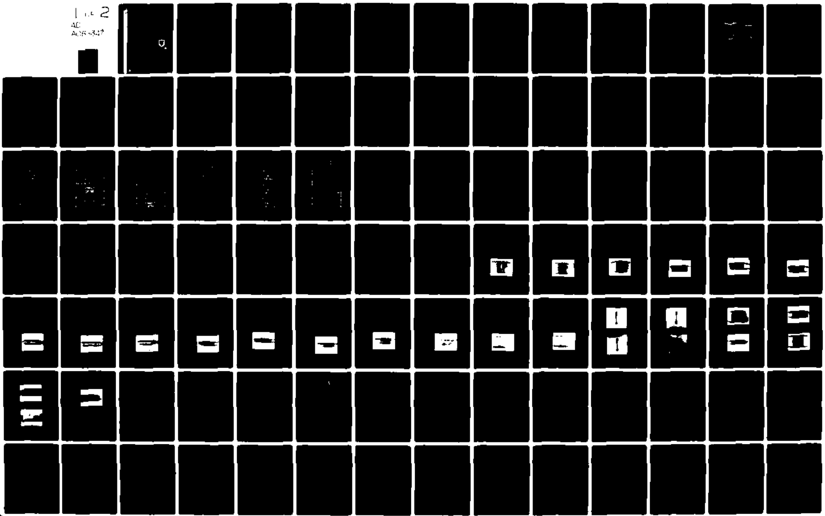

HDL-CR-80-074-2

Fineblanking, Diffusion Bonding, and Testing of Fluidic Laminates

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July 1980

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Under contract

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Two manufacturing processes that show promise of improving the performance of laminated aluminum fluidic components are fineblanking and semi-solid-state diffusion bonding. A representative three-stage amplifier design was used as the basis for evaluating these processes. Amplifier and manifold laminates were produced by fineblanking, and amplifier modules were fabricated by diffusion bonding of the fineblanked laminates. Functional (pressure gain) tests conducted before and after bonding showed gain changes in all bonded

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modules, but the number of modules bonded was too small to permit determination of any pattern. Surface and dimensional quality of the fineblanked laminates was excellent in laminate thicknesses up to 0.51 mm for amplifier elements, and up to 3.18 mm thickness for manifold laminates. Overall quality was judged to be equivalent to that normally achieved by the photochemical etching process. Due primarily to high initial die cost, fineblanking is economically feasible only where large production quantities are required; diffusion bonding, at the present state-of-the-art, relies heavily on human operator technique and appears to need further development before it can be considered a viable production process.

SUMMARY

The techniques of fineblanking and semi-solid-state diffusion bonding were studied to determine their applicability to the manufacture of fluidic components. A representative three-stage amplifier design was used as the basis for evaluating these processes. Fineblanking, a precision stamping process, was used to fabricate aluminum alloy (6061) amplifier and amplifier manifold laminates in thicknesses ranging from 0.20 to 3.18 mm. Satisfactory laminates were produced having good internal sheared surface quality and excellent dimensional repeatability. The complex contour of the amplifier was reproduced within the design tolerances in a thickness of 0.20 and 0.51 mm, but laminates of 1.27 mm thickness showed unacceptable distortion (die roll). However, where the geometry of the fineblanked part contained only circular holes and slots, laminates 3.18 mm thick were produced within design tolerances. Fineblanking was judged to be a satisfactory process, producing laminates of overall quality comparable to that obtained by photochemical etching.

Using the fineblanked amplifier laminates, three modules each of three aspect ratios (0.4, 1.0, and 2.5) were fabricated using the semi-solid-state bonding process. Hard tempered laminates (6061-T6) were used for the module cover plates and amplifier laminates, but due to the high bonding temperatures (568°C), the resulting bonded modules were annealed. In the annealed condition the modules were too soft to be clamped against O-ring seals without stiffening back-up cover plates. This difficulty could be remedied in the future by reheat treatment after bonding.

Pre-bond and post-bond gain tests were conducted on eight of the bonded modules, with all eight showing changes in gain ranging from 8% to 43%. There was no evident pattern in the gain changes. If a bonding-related pattern does exist, a much larger number of samples would be required to define it.

After individual gain tests, the bonded amplifier modules were assembled with the fineblanked manifold laminates and installed on the three-stage amplifier chassis. Gain tests demonstrated satisfactory performance of the whole assembly.

It was concluded that both fineblanking and semi-solid-state diffusion bonding showed promise of being useful in the fabrication of fluidic components. Laminates produced by fineblanking have excellent dimensional characteristics and internal surface quality. From a cost standpoint, the high initial die cost would have to be amortized over a large number of parts for the process to be economically feasible. The bonding process produced sealed modules that were mechanically satisfactory, but the effects of the process on functional performance were inconclusive. This process relies heavily on operator technique to maintain very tight temperature tolerances and needs further development before it can be considered a reliable production technique.

PREFACE

This is the final report on an investigation into the feasibility of using the techniques of fineblanking and semi-solid-state diffusion bonding in the fabrication of fluidic components. This work was performed by TRITEC, INC. of Columbia, Maryland under Contract DAAK21-79-C-0074 during the period of May 1979 through July 1980. The U.S. Army Electronics Research and Development Command, Harry Diamond Laboratories, Adelphi, Maryland, sponsored the program, with Mr. James W. Joyce acting as the Contracting Officer's Representative (Technical). Acknowledgement is extended to Mr. William J. Rotariu of TRITEC for his technical assistance in this program.

This project was accomplished as part of the U.S. Army manufacturing technology program. The primary objective of this program is to develop, on a timely basis, manufacturing processes, techniques, and equipment for use in production of Army materiel.

CONTENTS

FIGURES

TABLES

1. INTRODUCTION

In the fabrication of fluidic amplifier assemblies, the component parts are usually formed by photochemical etching of steel or aluminum laminates. The laminates are then mechanically clamped together to form a modular unit. When the laminate thickness exceeds the capability of the etching process, laminates are stacked to the desired depth. This procedure is limited in the dimensional accuracy, repeatability, laminate thickness, internal surface quality, and sealing that can be economically achieved. A fabrication process which promises to relieve some of these limitations is fineblanking. Parts produced by fineblanking exhibit excellent dimensional repeatability, good internal surface quality, and can often be made in greater single laminate thickness than can be obtained by photochemical etching. Where the laminate material is aluminum alloy, the Semi-Solid-State Diffusion Bonding process (SSDB) can be used to join the laminates, forming a sealed unit. The purpose of this investigation is to explore the techniques of fineblanking and SSDB with the objective of determining their suitability in the production of fluidic amplifiers.

To accomplish the program objectives, a representative three-stage amplifier design (HDL Drawing 11729642) was used. Amplifier and manifold parts were fineblanked, and amplifier modules were bonded by the SSDB process. A complete three-stage amplifier was assembled and tested. The results are presented in this report.

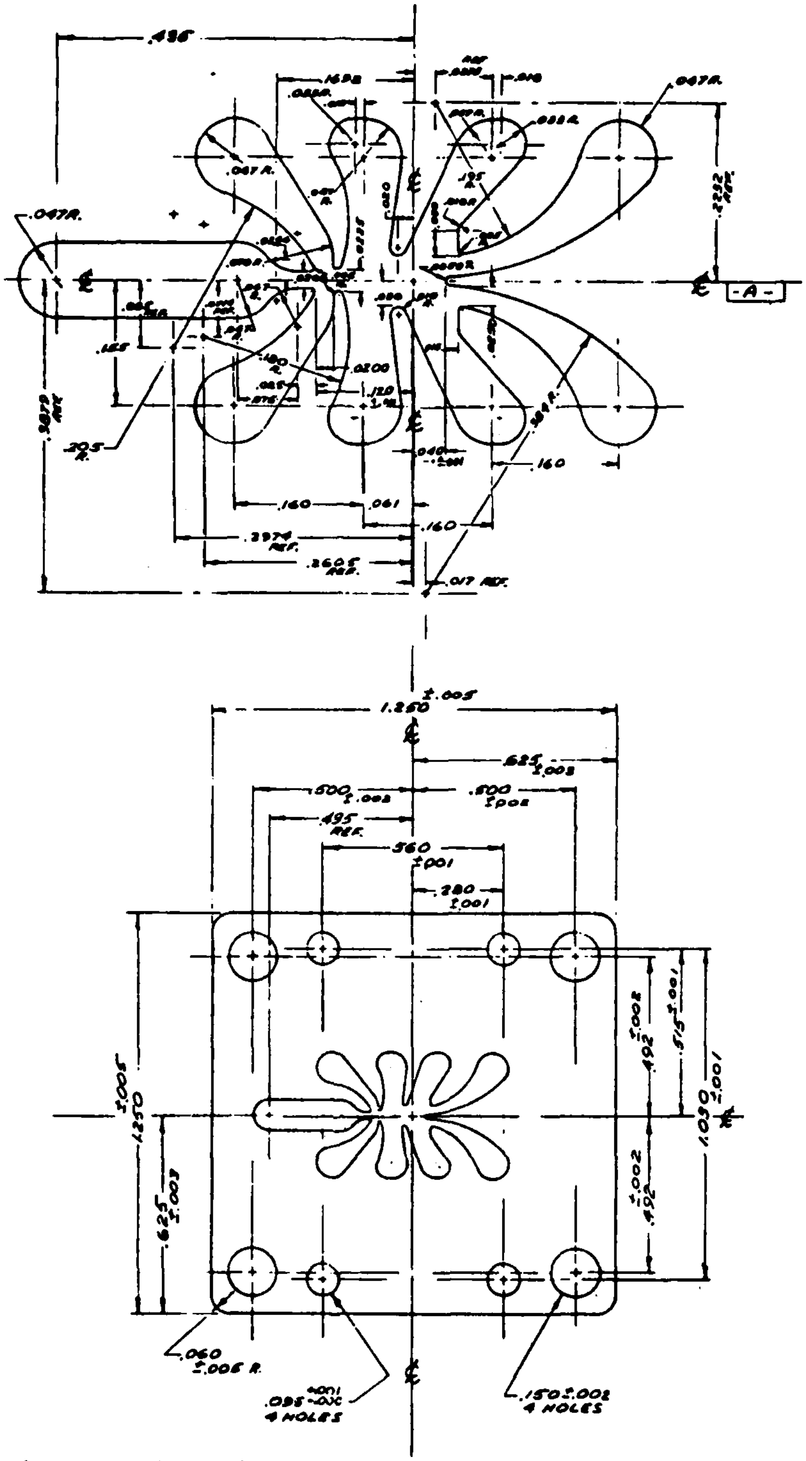
2. BACKGROUND

2.1 Fineblanking

Fineblanking is a precision metal stamping process. It is particularly suited to the production of small intricately contoured parts such as fluidic amplifier laminates (Figure 1). A recent study[1] by the Harry Diamond Laboratories presents a quantitative comparison of fineblanked laminates with chemically etched laminates. This report indicates that significant improvement can be attained in dimensional repeatability and amplifier performance when parts are fineblanked rather than chemically etched.

Parts produced by fineblanking differ from those produced by conventional stamping in that the edges are sheared cleanly over the thickness of the metal. Conventionally punched parts show "die break," the tearing process that produces rough edges. Due to the clearance between a conventional punch and die, only about one-third of the part is cleanly sheared; the remainder is torn, leaving a rough fractured surface. The fineblanking process is characterized by a nearly zero punch-to-die clearance (typically about ½% of the stock thickness). A triple-action

1 Phillipi, R. Michael, "A Study of Fineblanking for the Manufacture of Flueric Laminar Proportional Amplifiers," Report No. HDL-TM-77-8, U.S. Army Material Development and Readiness Command, Harry Diamond Laboratories, Adelphi, Maryland, May 1977.



Dimensions are in inches.

Figure 1. Amplifier contour.

press applies a clamping force around the periphery of the punched area, a cutting force and a counter force holding the stock securely against the face of the punch. Figure 2 illustrates, schematically, the difference between fineblanking and conventional stamping.

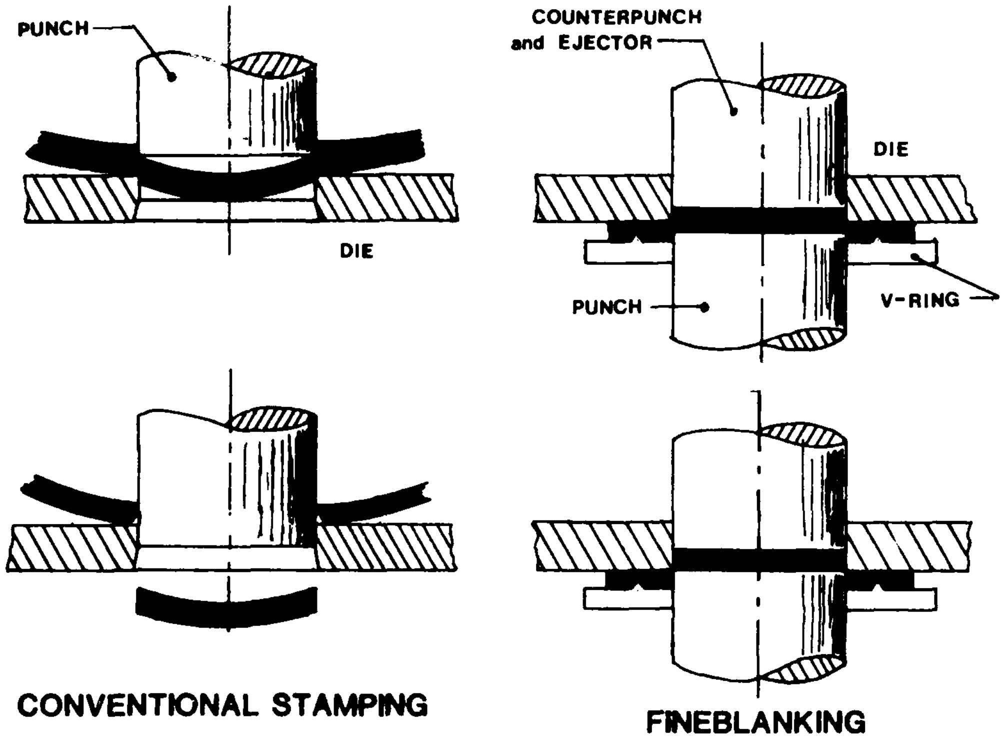


Figure 2. Comparison of fineblanking and conventional stamping.

Fineblanking, in common with all stamping processes, has disadvantages. Most significant are the presence of die roll and burr on the edges of the punched part (Figure 3). Both die roll and burr interfere with proper sealing between the laminations of an amplifier assembly. The effects of die roll and burrs can be minimized by secondary operations such as abrasive machining, but this adds to the expense of manufacture and, in the case of die roll, can result in dimensional degradation of the part due to excessive removal of material. The effects of die roll increase with material thickness. If die roll is not eliminated, internal flow may occur across the tips of slender amplifier elements such as flow splitters, with consequent adverse effects on functional performance. Economically, the cost of the die must be amortized over a large number of parts, making the process feasible only where large production quantities are involved.

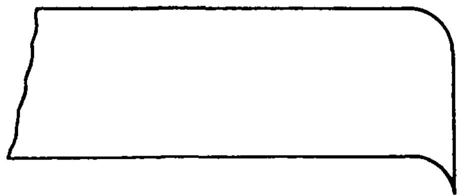


Figure 3. Die roll and burr.

2.2 Semi-Solid-State Diffusion Bonding

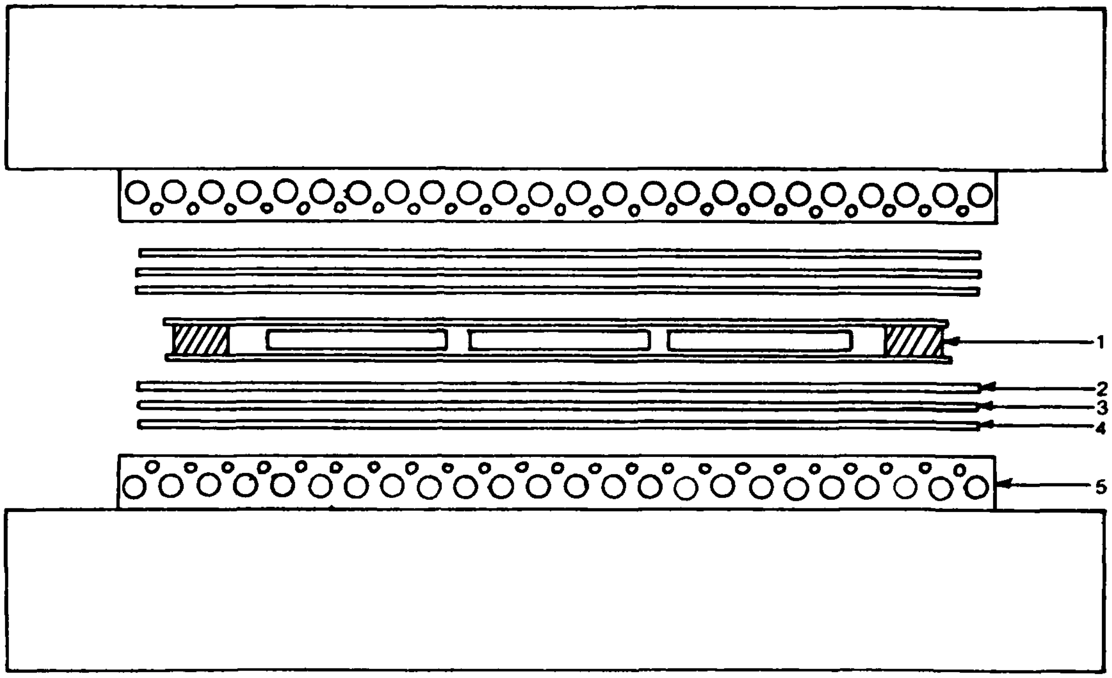
Semi-solid-state diffusion bonding, hereafter referred to simply as SSDB, is a fluxless brazing process by which aluminum alloy laminates may be sealed together to provide an integral unit. In this process, one of each pair of mating surfaces is clad with a brazing alloy consisting of 90% aluminum and 10% silicon; a satisfactory cladding thickness is 0.0375 mm. The laminations to be bonded are assembled in a sealed tooling envelope made of a stainless-steel sheet. This envelope is designed so that creation of a partial vacuum within the envelope causes a uniform pressure to be applied to the laminate stack during bonding. The tooling envelope is assembled between heating platens with thermocouple and heat distribution layers as shown in Figure 4. Bonding is accomplished by raising the temperature to a level just sufficient for the cladding material to diffuse into the laminate surfaces, but not high enough for the cladding material to run into and clog the internal passageways of the unit being bonded. The time for which the temperature is maintained also influences the extent to which the cladding material acts. The optimum combinations of temperature and time for particular lamination thicknesses have been determined experimentally; for typical fluidic amplifier assemblies, using a vacuum pressure of 50 kPa (15 in. Hg), a temperature of about 568°C (1055°F) applied for about one-half hour has been found to produce a satisfactory bond. The basic tooling, procedures, and bonding parameters used in this program were based on a study conducted by AVCO Aerostructures Division, Nashville, TN, for the Harry Diamond Laboratories[2].

3. FINEBLANKED PARTS FABRICATION

Using government furnished equipment (GFE) tooling, the amplifier and manifold laminates comprising the modules shown in Figure 5 and 6 were fineblanked by Florida Fineblanking Corporation, Fort Lauderdale, FL.

The amplifier modules (HDL Drawing 11729648) were made up of three fineblanked laminates, each 31.75 x 31.75 mm. The top and bottom cover plates were 0.25 mm thick, with the sandwiched amplifier laminate either 0.20, 0.51, or 1.27 mm thick according to the respective aspect ratio of 0.4, 1.0, or 2.5. The amplifier manifold (HDL Drawing 11729645) was made up of three fineblanked laminates, each 48.25 x 48.25 mm. Top and bottom cover plates were 0.41 mm thick with a center manifold plate of 3.18 mm

2 AVCO Aerostructures Division Report No. R-1144, March 24, 1977, prepared for Harry Diamond Laboratories under Contract DAAG39-76-C-0150.



AVCO UNIT TOOL & WORK PACKAGE

1 - Braze Package & Envelope (Cross Section)

2 - Stainless Steel Thermocouple Sheet

3 - Copper Heat Sink

4 - Refrasil

5 - Ceramic Heating & Cooling Platen

6 - Ceramic Insulating Base

Figure 4. Cross section of a typical bonding set-up.

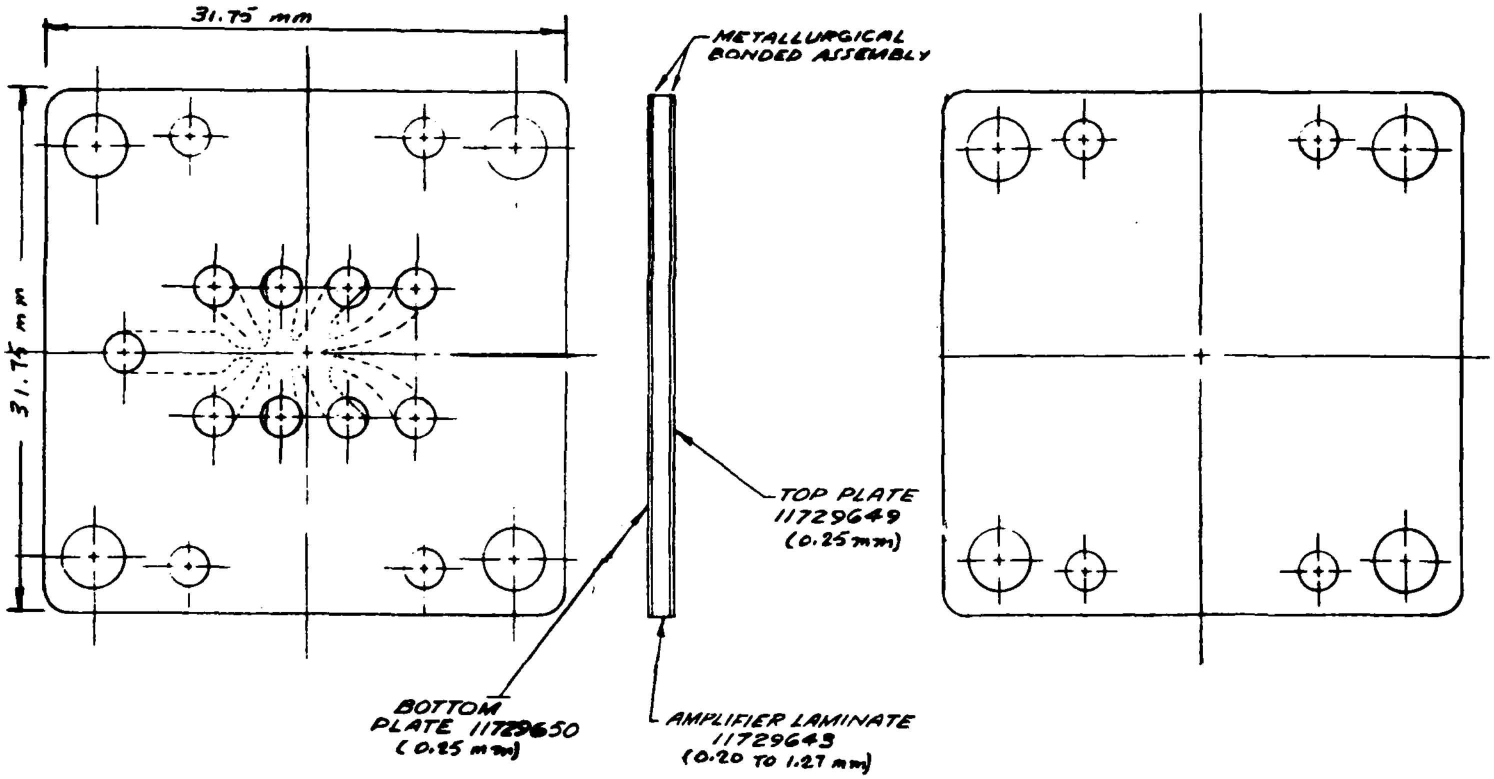


Figure 6. Amplifier module.

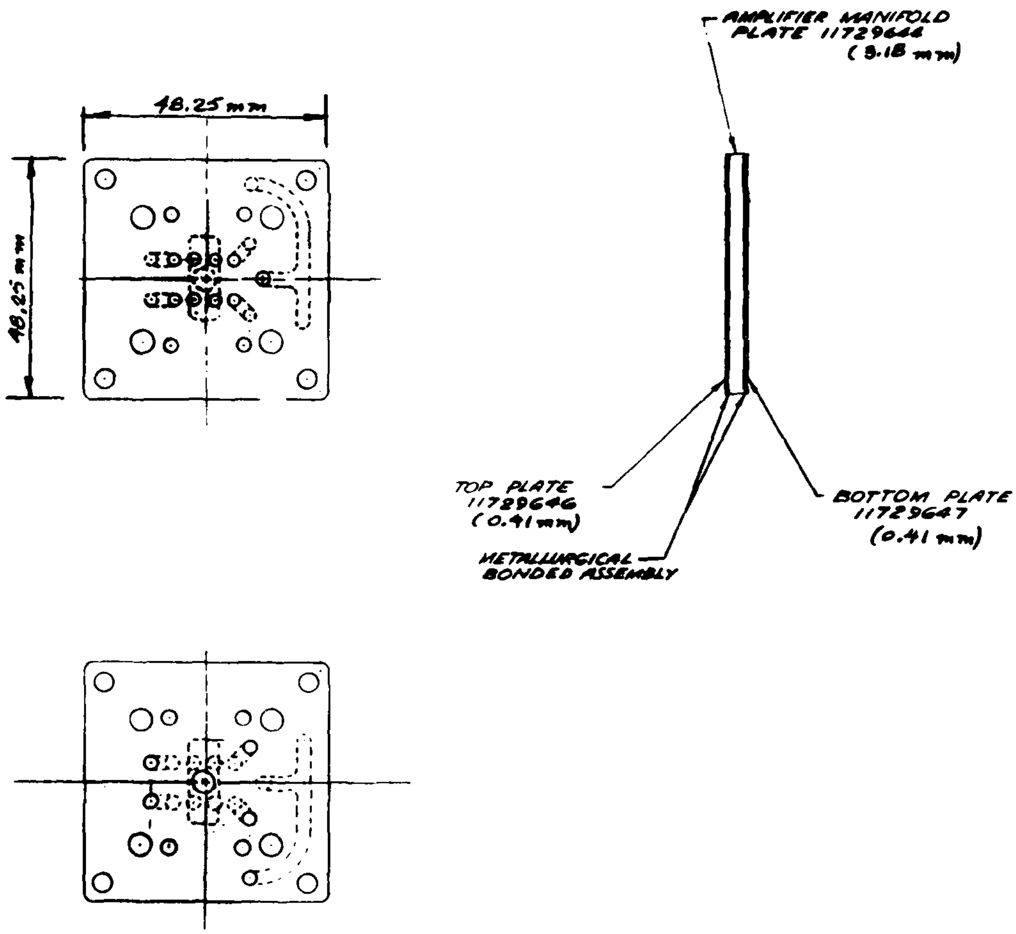


Figure 6. Amplifier manifold module.

thickness. Aluminum alloy stock, clad and unclad, was stamped in the thickness, quantities, and material tempers shown in Table I.

TABLE I. FINEBLANKED PARTS

Part	HDL Dwg. No.	Material	Thickness (mm)	Quantity
Amplifier Laminate	11729643	6061-T6	0.20	60
Amplifier Laminate	11729643	6061-T6	0.51	60
Amplifier Laminate	11729643	6061-0	1.27	60
Top Plate	11729649	#23BS*	0.25	180
Bottom Plate	11729650	#23BS	0.25	180
Amplifier Manifold Plate	11729644	6061-0	3.18	24
Bottom Plate	11729647	#23BS	0.41	24
Top Plate	11729646	#23BS	0.41	24

* #23BS is a brazing sheet manufactured by Alcoa having a 90% aluminum/10% silicon cladding layer of 0.038 $\pm$ 0.008 mm thickness. This cladding forms the metallurgical bond.

Clad laminates were stamped with the burr side opposite the clad side to facilitate bonding. All fineblanked parts exhibited die roll and burr; both die roll and burr increased as the material thickness increased. Die roll was particularly noticeable on the 1.27 mm amplifier laminates where the material thickness was reduced by up to 40% at the tips of slender "fingers" such as the amplifier flow splitter (Figure 7).

Visual inspection of the fineblanked parts showed good sheared surface quality with no evidence of tearing. Inspection by HDL showed all parts to be dimensionally within drawing tolerances.

4. BONDING PROCESS

4.1 Bonding Set-Up and Procedure

Although the basic parameters of time, temperature, and pressure, as well as tooling techniques for bonding, were established by AVCO Aerostructures during an earlier program, it was found that the process had to be "fine-tuned" for the particular laminate thicknesses required for the amplifier and manifold portions of the HDL three-stage amplifier design. At the time the bonding process was established, fineblanked laminates were not available, so simulated amplifier modules (SAM's) were used. Parameters established through use of the SAM's were later confirmed by bonding actual amplifier modules comprised of fineblanked parts.

The physical set-up for bonding consisted essentially of a sealed stainless steel envelope, or frame, containing the modules to be bonded. This frame was stacked with pressure sheets and spacers as shown in Figure 8. This stack-up comprised the braze package and envelope, item 1, of Figure 4.

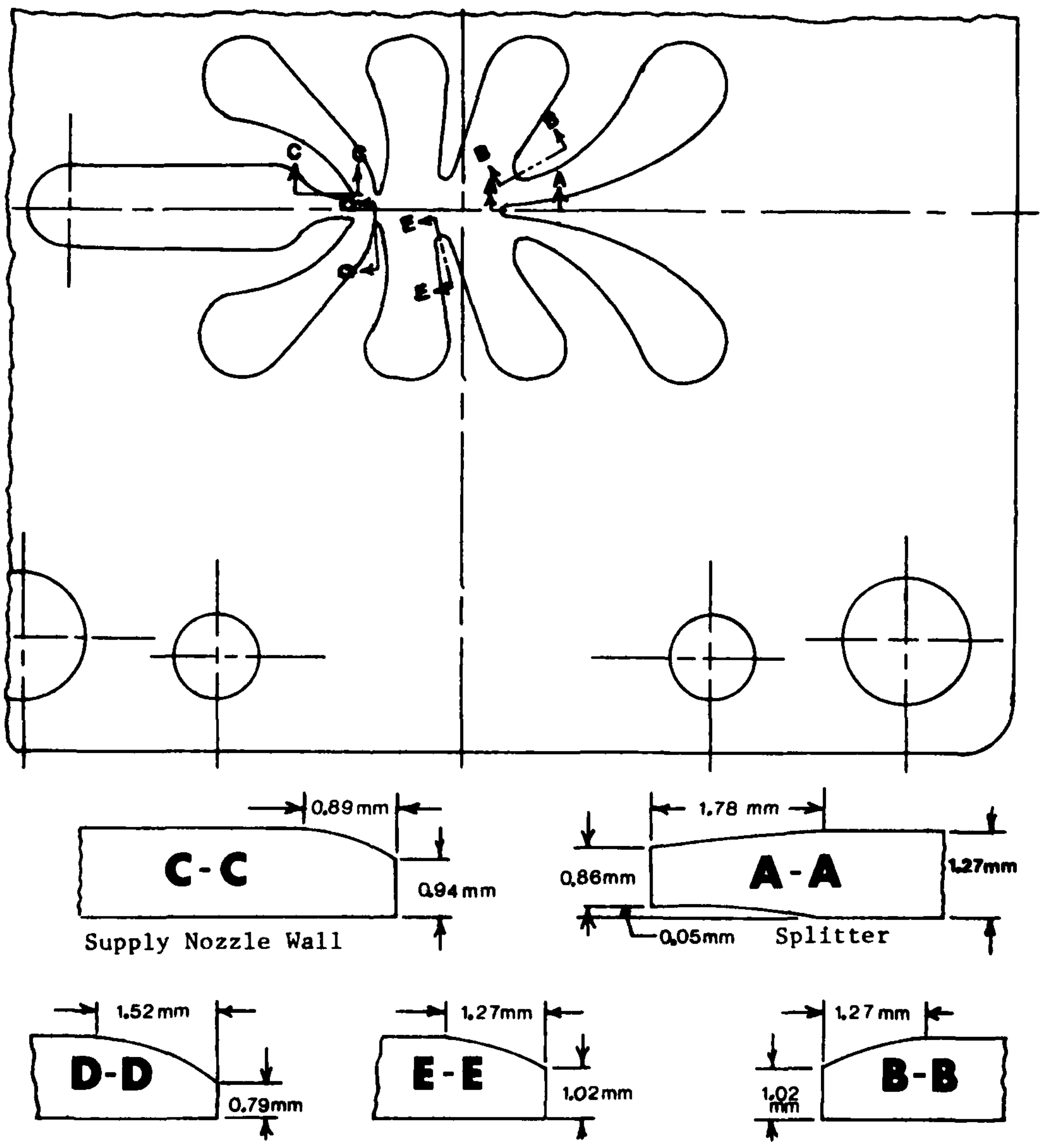
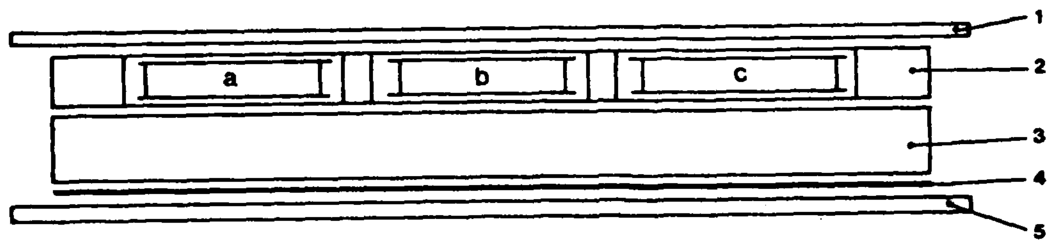


Figure 7. Die roll effects on 1.27 mm laminates.

MODULES BEING BONDED (a,b,c)



1.	Top Pressure Sheet 321 SS	0.635 mm
2.	Frame 6061 Al	1.953 mm
3.	Spacer 6061 Al	8.415 mm
4.	Bottom Pressure Sheet 321 SS	0.635 mm
5.	Spacer 3003 Al	1.062 mm
	TOTAL	12.700 mm

Figure 8. Details of tooling stack-up.

Referring to Figure 8, the frame (item 2) holding the modules had top and bottom stainless-steel covers of 0.635 mm thickness. The enclosed modules were held in proper alignment during bonding by dowel pins which could not protrude beyond the module surfaces by more than the 0.635 mm thickness of the frame covers. This required special dowels which, for the aspect ratio 0.4 amplifiers, were 1.98 mm long by 2.39 mm in diameter. These dowels tended to become bonded to the amplifier modules. When this occurred, it was necessary to drill them out after bonding, resulting in oversized dowel holes.

Sixteen SAM's were used to establish the bonding procedure. A typical bonding cycle (SAM No. 16) is given in Figure 9 to illustrate the procedure.

The operation sequence used to obtain the bonding cycle of Figure 9 is given in the following steps:

1. Evacuate sealed envelope for 30-60 minutes.
2. Using full static vacuum, leak check envelope for a minimum of 30 minutes. Maximum allowable leak rate shall be 0.1 in. Hg/Hr.
3. Purge envelope for 30 minutes. Evacuate and then back fill with Argon gas to a slight positive pressure approximately every 5 minutes. Use a minimum of 5 purges.
4. Begin heating envelope.

8704

Semi-Solid
Braze Type Diffusion Bonding

Braze Temp. 1040-1045 F.

Time at Temp. 30 mins

Filler Metal .050 6061

Cleaning Process AVCO 7.59c

SAMPLE # SAM #16

BRAZE CYCLE DATA
TRITEC

Date: 11-8-79

Page 1 of 2

TIME	TEMPERATURE °F 1	TEMPERATURE °F 2	TEMPERATURE °F 3	TEMPERATURE °F 4	VOLTAGE 1	VOLTAGE 2	AMPERAGE 1	AMPERAGE 2	GAS c.f.	VAC. mm. Hg.	OBSERVATIONS	REMARKS
	Bott	Top					Bott	Top			60 min evac.	OK
											30 min leak check	OK
											R.T. Purges	5
12:04	65	66					23.0	21.0			Power On/Full Vac.	Zones 2 & 4 17Amp
12:15	259	219							7.0	15.0	250	
12:26	517	481									500	
12:37	755	739									750	
12:53	960	958					17.0	17.0			960 Power Back	Zones 2 & 4 12Amp
12:57	1025	1023					15.0	15.0			1025 Power Back	
1:04	1040	1040					13.5	13.5			1040 Power Back/In Cycle	
1:06	1042	1042	2 mins									
1:08	1041	1041	4									
1:10	1041	1041	6									
1:12	1041	1041	8									
1:14	1041	1042	10								Mount # 2521	
1:16	1042	1043	12								Leak Test @ 100 psi	Leaks at 30 psi
1:18	1044	1044	14								X-Ray 11/10/79.	
1:20	1044	1044	16									
1:22	1043	1043	18									
1:24	1042	1042	20									
1:26	1042	1042	22									
1:28	1043	1043	24									
1:30	1044	1043	26 mins									
1:32	1045	1045	28								Curtains up/Power Off/Air On	
1:34	1041	1041	30								End Cycle	
	1042.3	1042.3 Avg.										

Figure 9. Typical bonding cycle.

5. Maintain full vacuum pressure on envelope to 121°C (250°F). At this temperature, initiate continuous Argon purge at rate of 7.0 ± 1.0 cfh. Reduce vacuum pressure to 15.0 ± 0.5 in. Hg. Both settings shall be maintained.

6. At 521 ± 7°C (970 ± 15°F) reduce power to decrease rate of approach.

7. At 552 ± 5°C (1025 ± 10°F) reduce power for final approach to cycle.

8. Begin bond cycle as coolest thermocouple reaches specified temperature range.*

9. Bond cycle shall be maintained at specified temperature range for 28-32 minutes. Power settings may be regulated as necessary to control temperature.*

10. Approximately 2-3 minutes prior to completion of cycle, cease power and insert cooling manifolds.

11. Apply forced air through cooling manifolds in this time span or as required to comply with bond cycle parameters (step 9).

12. Argon inlet and vacuum valves may be closed anytime after envelope temperature reaches 316°C (600°F).

13. Continue forced air cooling to 66°C (150°F). Caution -- use protective gloves when removing hot envelope. To minimize warpage, cool envelope to room temperature before removal.

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* See Section 4.2 for temperature ranges.

4.2 Bonding Results, Simulated Amplifier Modules

Sixteen SAM's were used to establish the bonding process. The SAM's consisted of 31.75 x 31.75 x 0.25 mm clad cover plates and 0.20, 0.51 and 1.27 mm center laminates. The center laminates each had a 3.18 x 19.05 mm slot whose ends were aligned with 3.18 mm dia. holes in the cover plates. After bonding, each SAM was pressure tested and subjected to radiographic and metallographic examination. As a result of the SAM tests, the following temperature ranges were established for one-half hour of bonding at 50 kPa vacuum pressure on the module bonding envelope:

0.20 mm center laminate - 560/563°C (1040/1045°F)
0.51 mm center laminate - 563/566°C (1045/1050°F)
1.27 mm center laminate - 566/568°C (1050/1055°F)
3.18 mm center laminate - 566/568°C (1050/1055°F)

4.3 Bonding Criteria of Acceptability

The criteria used to evaluate the bonded modules are described in the following sections.

4.3.1 Visual

Surfaces adjacent to the bonded edges and passage ports should exhibit a minimal amount of filler metal wetting. Generally, wetting indicates sufficient heat for bonding. However, excessive wetting can result in erosion of the base metal and also cause filling of the passageways due to the capillary nature of the clad material. Experience has shown that a clad thickness of 0.038 ± 0.008 mm is required for the semi-solid diffusion bonding process. The composition of the clad surface is 90% aluminum and 10% silicon. The braze sheet itself is manufactured by Alcoa and is referred to either as braze sheet No. 23, which is clad on one surface only, or braze sheet No. 24, which has braze cladding on both surfaces.

Visual examination for distortion of the coverplates over the passage areas was also part of the selection process. Those modules termed good visually were checked with a dial indicator. This check showed distortion in the passage area to be 0.025 mm or less.

4.3.2 Radiographic Examination

Only those modules having no alloy filling of the passageways as determined by x-ray were considered candidates for the selection process. Because of the small amount of mass involved, faying surface voids cannot be detected using this method.

4.3.3 Proof Pressure Testing

All bonded modules were pressure tested with helium at 50kPa (100 psi) for one hour. The modules were submerged in water and visually observed for leaks during this test. Modules which leaked were obviously unacceptable.

4.3.4 Metallographic Examination

All modules were cross-sectioned in the passage area and mounted for metallographic examination. Particular attention was given to the amount of intercrystalline growth across the interface (diffusion bond line). Virtually complete intercrystalline growth is indicative of a good bonded joint. In this case, the amount of primary silicon diffusion, or coalescence, is a function of surface preparation, temperature, pressure, and time. Previous evaluations have shown that silicon diffusion into the base metal should be in the 0.038 - 0.076 mm range. An increased amount of silicon diffusion could result in complete erosion of the base metal. This is particularly true in the case of the 0.20mm laminate module as evidenced by the photomicrographs of SAM's Nos. 7, 8, 9, and 10. (see Appendix A for photomicrographs). Conversely, an insufficient amount of silicon diffusion into the base metal can be seen as a distinct line of demarcation and indicates poor bond quality. The photomicrograph of SAM No. 12 shows a borderline example of this.

Those bonded modules which successfully met the above guidelines are:

a. SAM No. 11 - 0.20 mm center laminate
b. SAM No. 13 - 0.50 mm center laminate
c. SAM No. 3 - 1.27 mm center laminate
d. SAM No. 17 - 1.27 mm triple laminate

4.4 Bonding Results, Fineblanked Amplifier Modules

After bonding the SAM's, three each of the three aspect ratio fineblanked modules (HDL Drawing 11729648) were bonded to confirm the time/temperature/pressure parameters. Each of these modules consisted of top and bottom cover plates of 0.25 mm thickness and center amplifier laminates of 0.20 mm for aspect ratio 0.4; 0.51 mm for aspect ratio 1.0; and 1.27 mm for aspect ratio 2.5. Pre- and post-bond pneumatic pressure gain tests were run on each amplifier to determine the effects, if any, of bonding on amplifier performance. During bonding of the aspect ratio 1.0 amplifiers, the temperature overshot the required temperature by about $3^{o}C$, resulting in plugging of one amplifier cavity. Metallurgical cross-section views of this module (Module No. 2) are included in Appendix A. All remaining modules were acceptable by the visual and metallographic criteria. Attempts to pressure test the modules were not successful because the bonded modules deformed when clamped against the O-ring seals of the pressure test fixture. It should be noted at this point that the bonding temperature/times used were sufficient to anneal the 6061-T6 fineblanked laminates. Reheat treatment would probably correct this condition, but at the risk of further deformation.

The gain test procedure was as follows. First a null offset curve was obtained for each amplifier with blocked outputs. This curve was generated by sweeping the supply air pressure, P_S, from zero to the point where turbulence was evident in the output pressure differential level, ΔPo. From this curve, the supply pressure corresponding to the onset of turbulence, P_T, was determined. Gain tests were then run at a supply pressure equal to 70% of P_T, and a control bias pressure of 10% of P_S Results of the gain tests are summarized in Table II. These results have been corrected for pressure drops in the test fixture which were noted after completion of the tests. Gain curves and test set-up details are included in Appendix B.

TABLE II. PRE-BOND AND POST-BOND GAIN TEST SUMMARY

Module No.	Aspect Ratio	Air Supply Pressure (mmHg)	Modified Reynolds No.*	Pre-Bond Gain	Post-Bond Gain
1	0.4	21.0	94	6.3	6.8
2	0.4	21.0	94	6.3	-**
3	0.4	21.0	94	6.0	4.4
4	1.0	5.0	141	8.8	9.5
5	1.0	5.0	141	9.2	7.7
6	1.0	5.0	141	7.2	8.1
7	2.5	0.65	103	6.0	4.3
8	2.5	0.65	103	6.8	4.5
9	2.5	0.65	103	6.5	3.7

NOTE: * Modified Reynolds Number, as derived by Drzewiecki,[3] takes into account the aspect ratio and nozzle geometry of a fluid amplifier. See Appendix B for explanation of values tabulated.

** Module No. 2 was not functional after bonding due to plugging of the amplifier cavity.

As can be seen from Table II, all post-bond gain values differ from their respective pre-bond values. Three amplifiers showed increases in gain while five decreased after bonding. There is no evident pattern in the gain changes, although all of the aspect ratio 2.5 amplifiers showed a loss in gain of from 28% to 43%. If a bonding-related pattern does exist, its precise definition would require a much larger number of samples. In addition, it is likely that comparative null-offset data would be of value in understanding the effects of bonding on the amplifier functional characteristics.

3 Drzewiecki, T.M., A Fluid Amplifier Reynolds Number, II. Proceedings of the 1974 Fluidic State-of-the-Art Symposium, Harry Diamond Laboratories, (October 1974).

5. THREE-STAGE AMPLIFIER

5.1 Continuity Test

The three-stage amplifier assembly shown in Figure 10 utilizes the amplifier and amplifier manifold modules previously described (Figures 5 and 6). Four sets of parts for the gain block chassis were fabricated with the ultimate goal of joining each set of parts by the SSDB process. Although time did not permit bonding of the chassis or manifold modules, preliminary functional tests were conducted by clamping the parts of one chassis and one set of manifold module parts together with one set of bonded amplifier modules. Due to the complexity of the chassis worm-plate and flow-hole pattern, continuity tests were first conducted to verify the design concept and accuracy of manufacture. Figure 11 is a schematic of the three-stage amplifier assembly showing the flow paths. Different portions of the flow paths were blocked or interconnected in six separate continuity tests. Standard cover plates were used to block flow through resistor and amplifier portions. For amplifier interconnections, slotted cover plates were used. Standard resistor laminations were used to join resistor portions. Figures 12-17 show schematically the flow paths for these six tests. Pressures were applied and measured statically. Figure 18 shows a matrix of test conditions for these tests. Results verified the accuracy of manufacture and validity of design.

Two types of small leaks occurred which, due to their low flow rates, were evidently not caused by improper design or manufacture. Nor did they have any effect on the utilization of the chassis for gain tests. Both types of leaks evidently resulted from the clamping arrangement. The close spacing of cover plates on the chassis permitted clamping only at the periphery of the chassis plates. Because of this uneven clamping, some leakage occurred at the common power supply duct and at the flow paths to the chassis bottom (rate sensor) plate.

The effect of the power supply leak was to reduce the recovered pressure at the test points to approximately 85% when pressure was applied to the common power supply. For continuity tests Nos. 1 through 3, the pressures measured at test points 1 through 3 respectively were approximately 5.9 kPa (0.85 psi) for 6.9 kPa (1.00 psi) test pressure applied at the common power supply inlet. It is pointed out that the individual amplifier power supply pressures were adjusted by resistor laminates for the gain tests, making this pressure drop inconsequential. Despite this pressure drop, the variation between test points was only a few percent, identifying the location of the leak as being along the common duct.

For the continuity tests where pressure was applied at the control ports of the first stage amplifier, the recovered pressures were over 95%. This was indicative of proper design and manufacture of these flow paths. None of the cover plates or modules exterior to the chassis plates leaked.

An analysis of the continuity test results verifies the accuracy of manufacture and validity of the design. The leaks had no measurable effect on the subsequent gain tests.

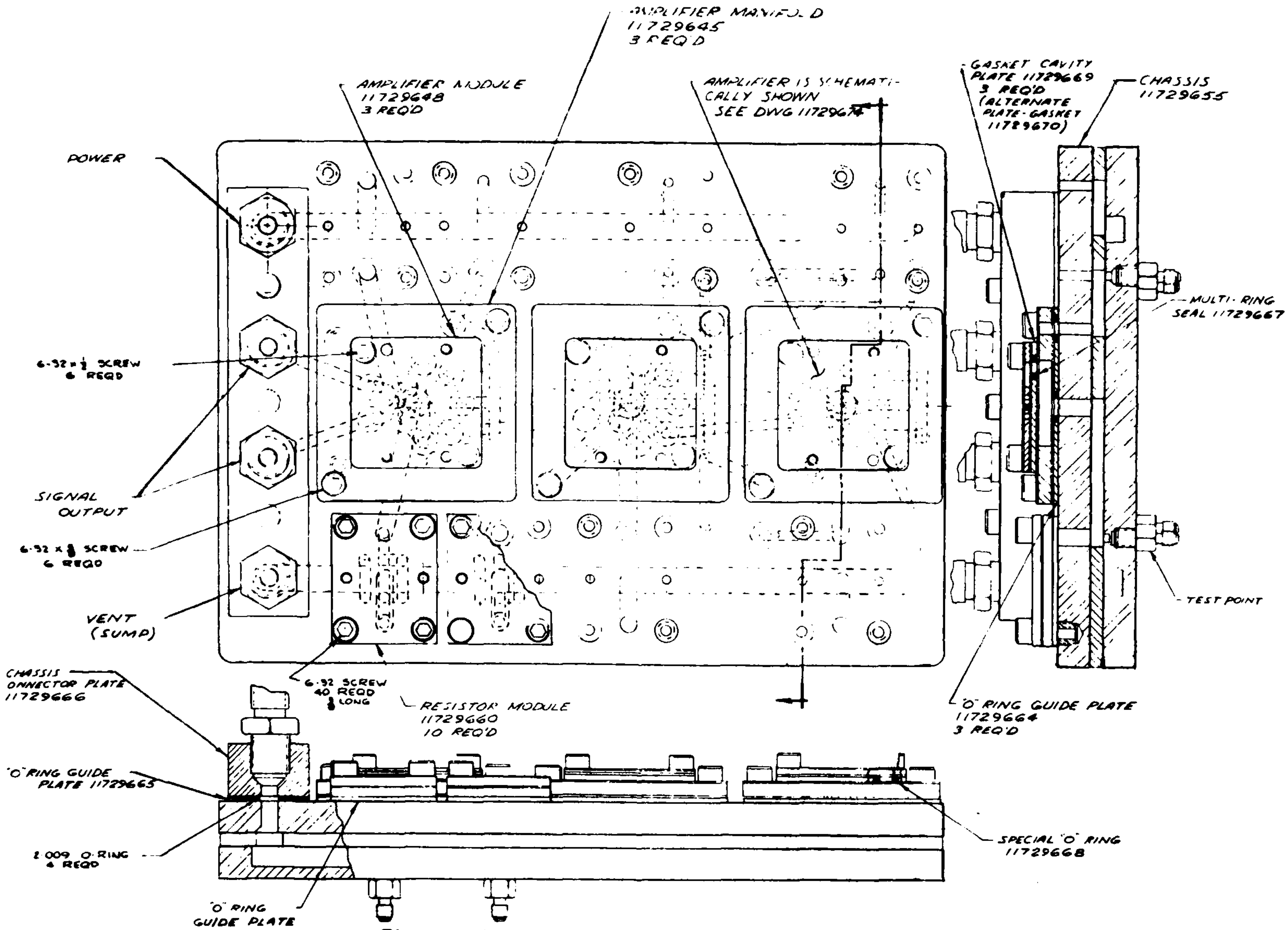

Figure 10. Three-stage amplifier assembly.

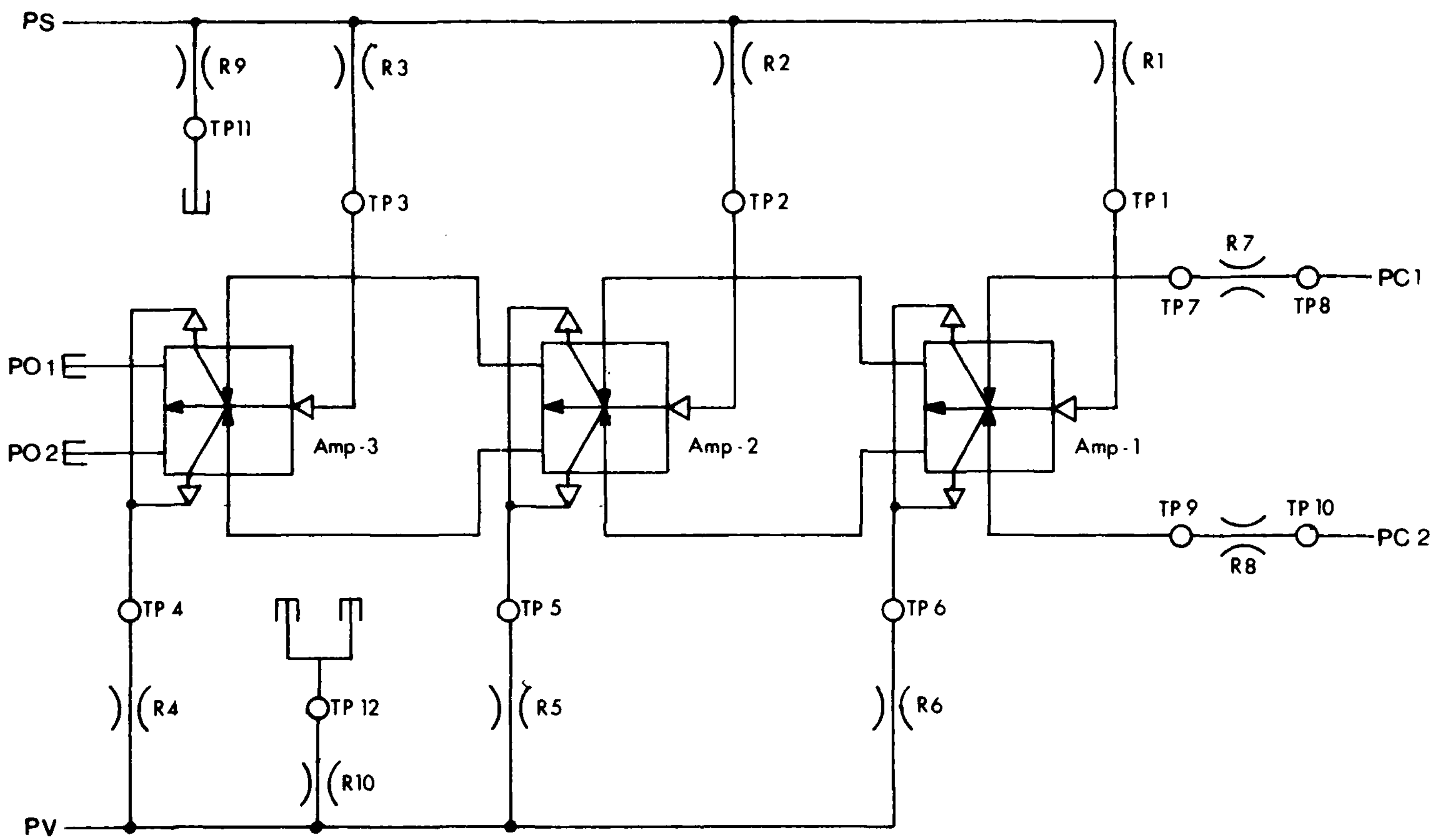

Figure 11. Three-stage amplifier schematic.

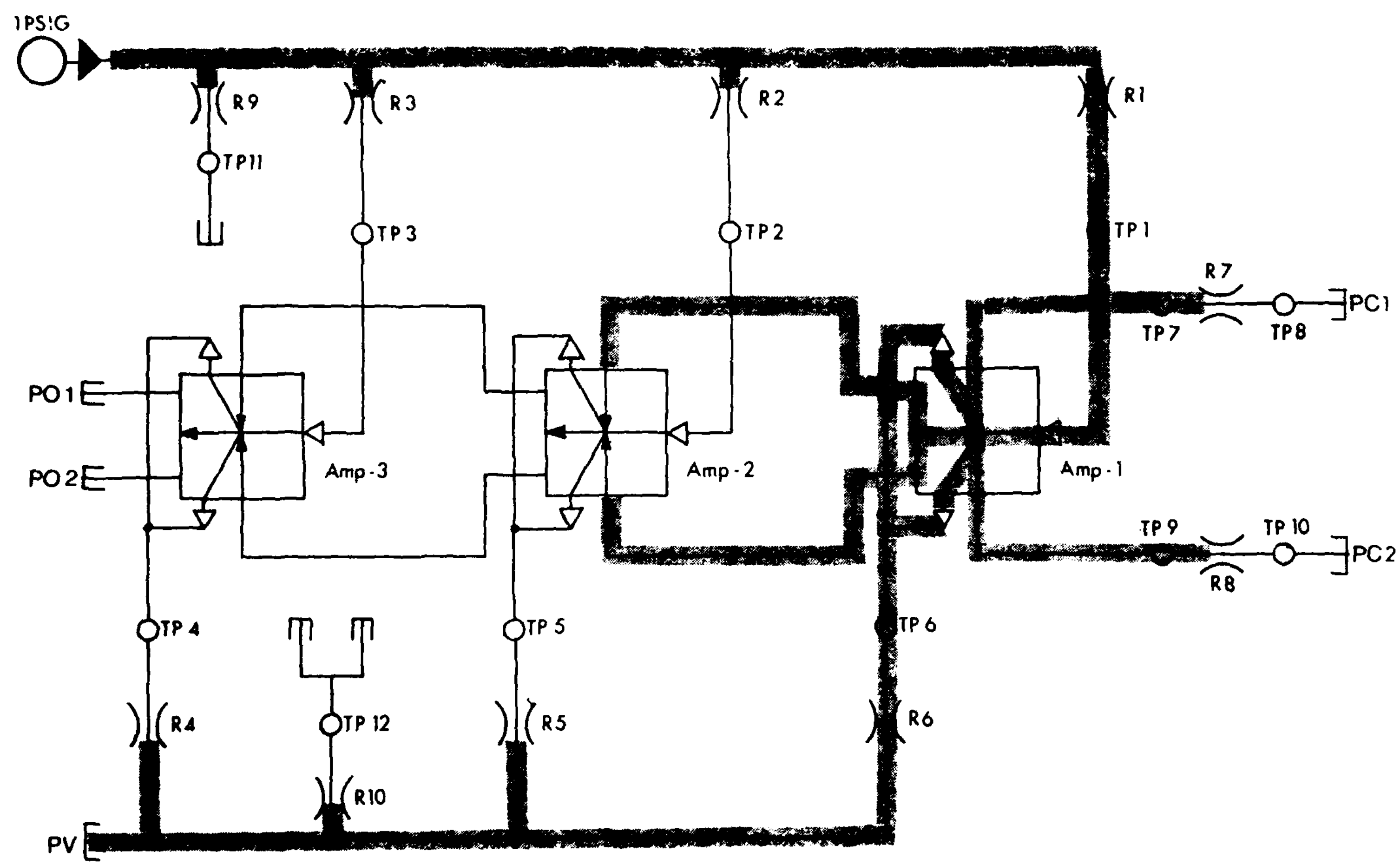

Figure 12. Continuity test number 1.

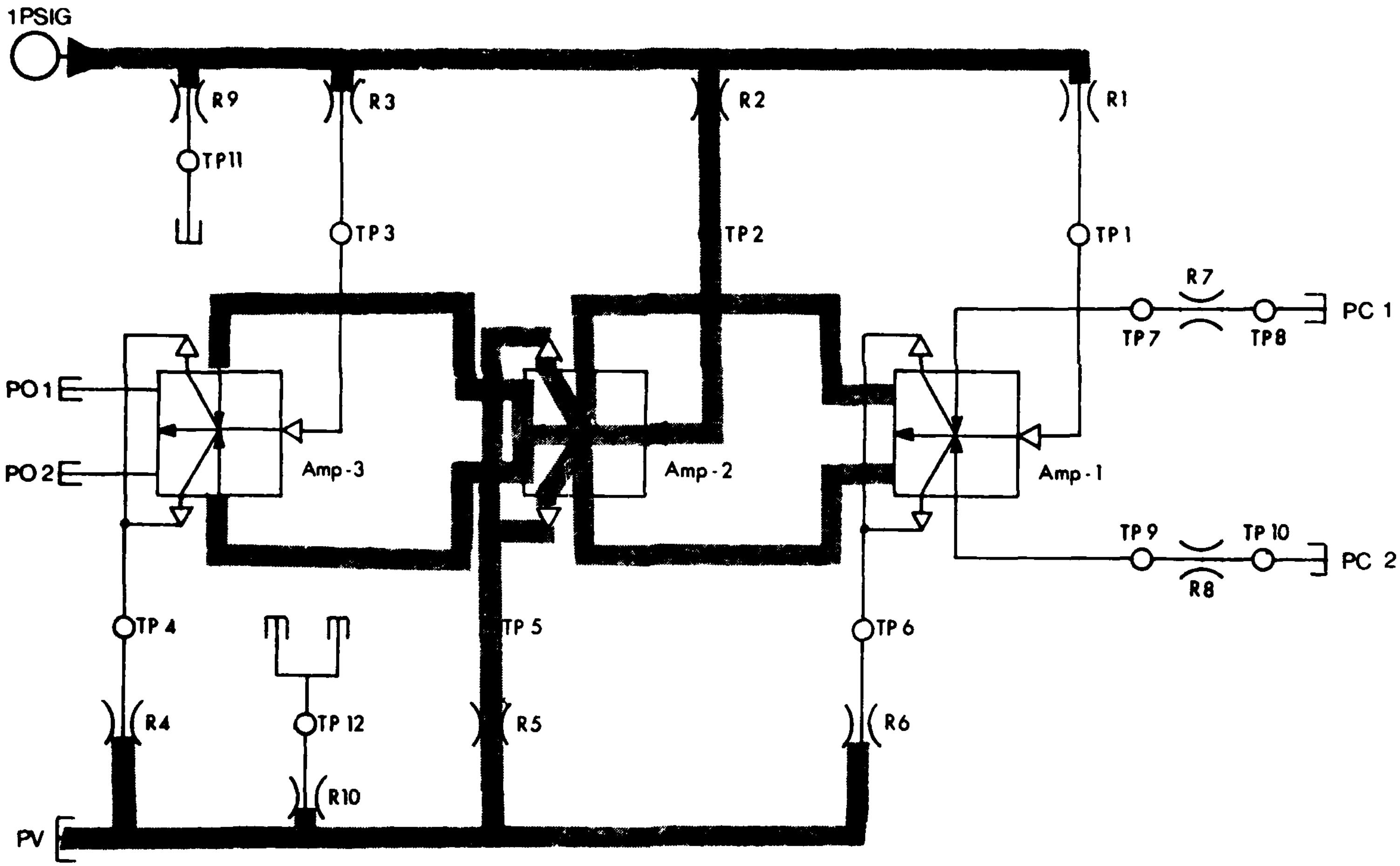

Figure 13. Continuity test number 2.

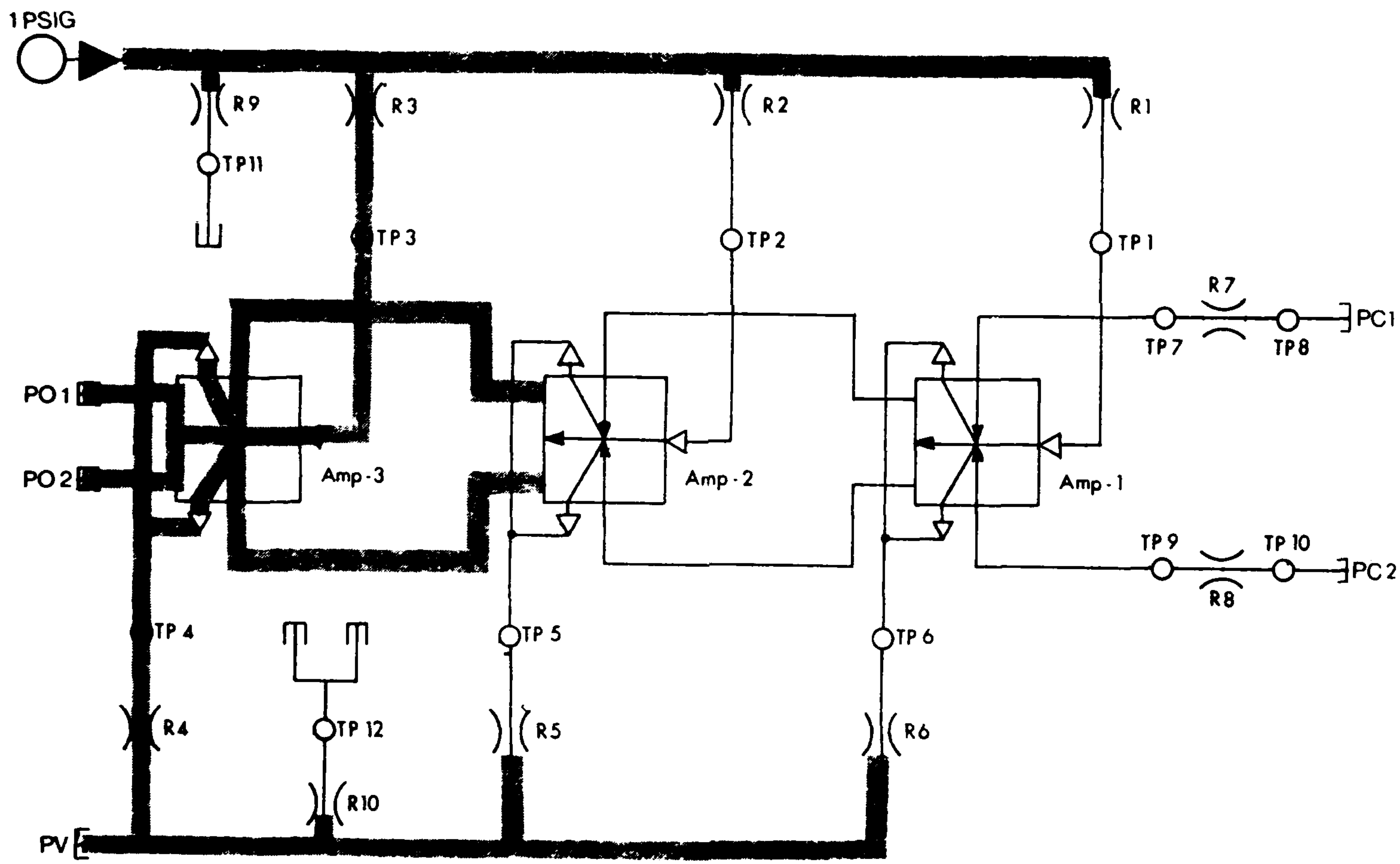

Figure 14. Continuity test number 3.

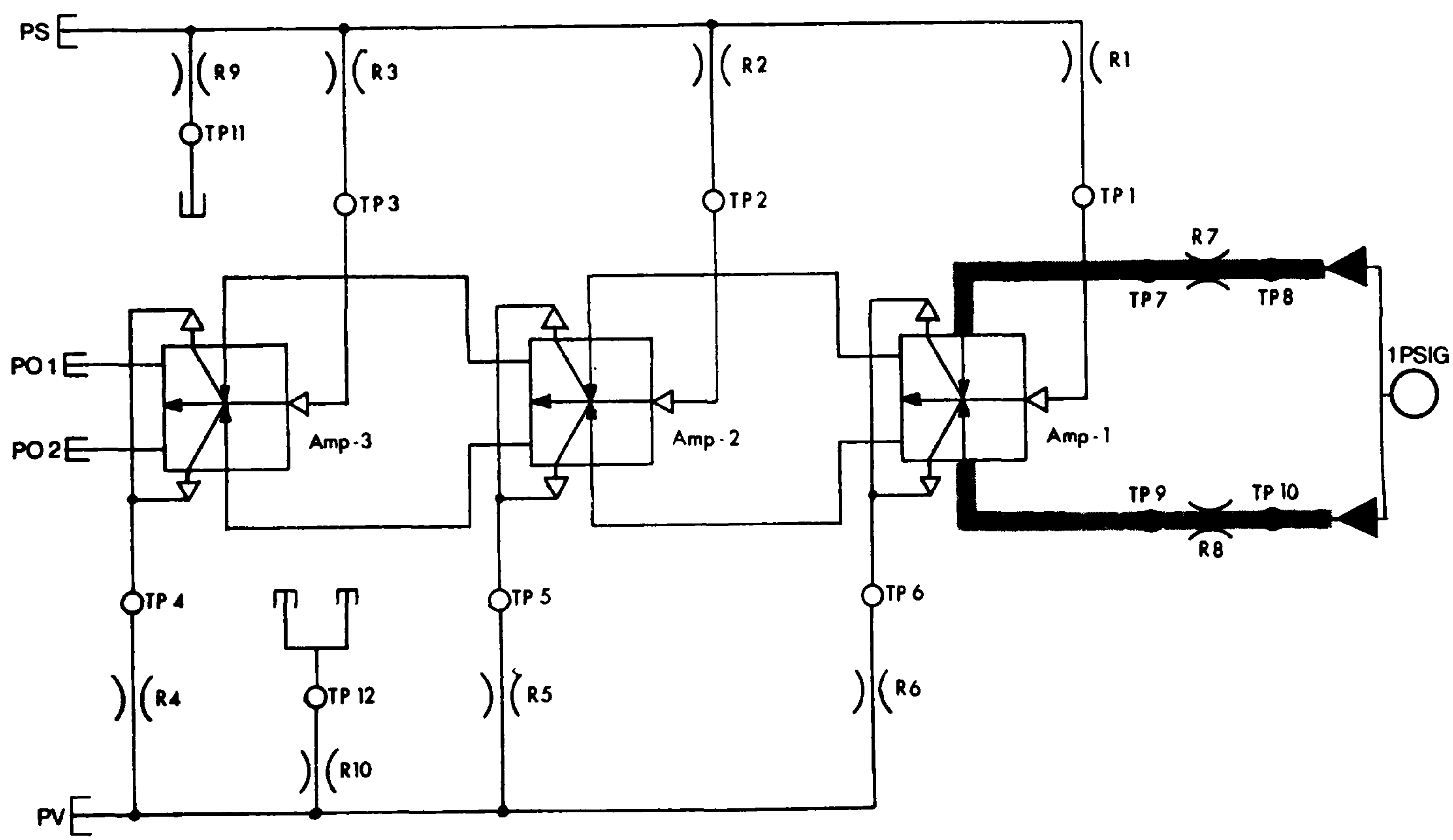

Figure 15. Continuity test number 4.

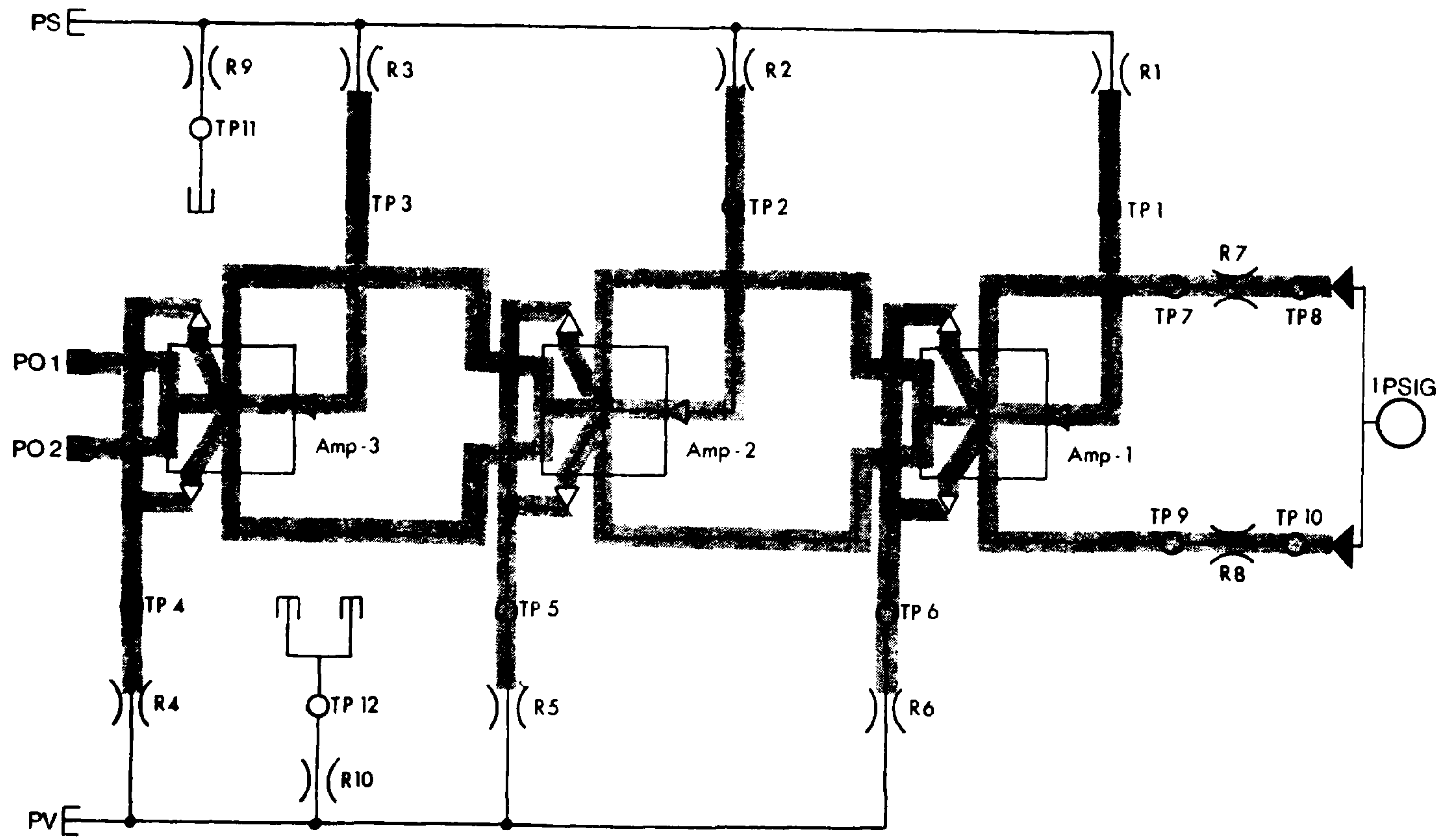

Figure 16. Continuity test number 5.

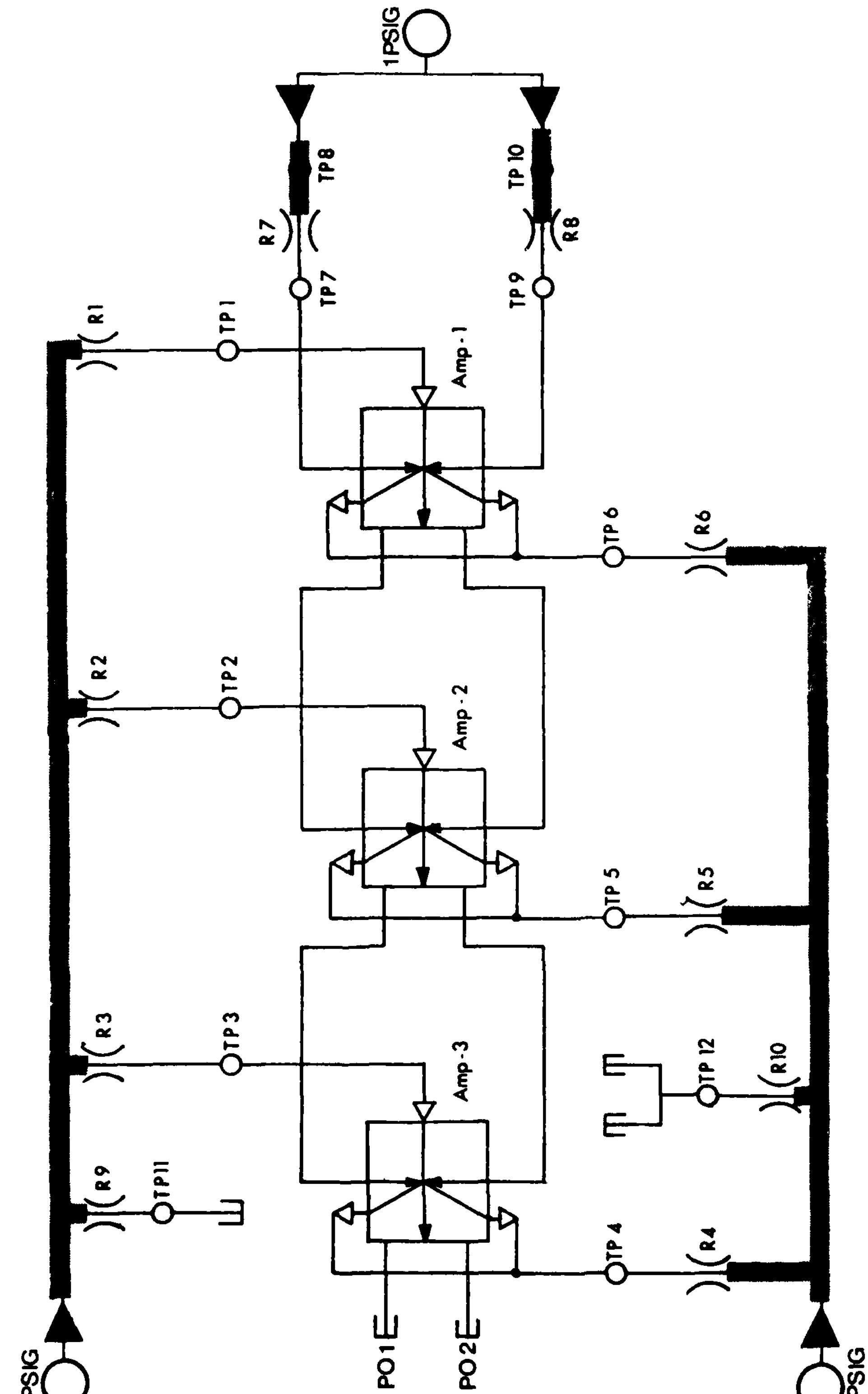

Figure 17. Continuity test number 6.

CONTINUITY TEST #	TEST CONDITIONS																												
	INPUTS		RESISTORS/AMPLIFIERS													OUTPUTS													
	P_s	P_c	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	A1	A2	A3	TP1	TP2	TP3	TP4	TP5	TP6	TP7	TP8	TP9	TP10	TP11	TP12	P_e	P_v
1	P	0	1	0	0	0	0	1	0	0	0	0	1	0	0	1	0	0	0	0	1	1	0	1	0	0	0	0	1
2	P	0	0	1	0	0	1	0	0	0	0	0	0	1	0	0	1	0	0	1	0	0	0	0	0	0	0	0	1
3	P	0	0	0	1	1	0	0	0	0	0	0	0	0	1	0	0	1	1	0	0	0	0	0	0	0	0	1	1
4	0	P	0	0	0	0	0	0	1	1	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	1	0
5	0	P	0	0	0	0	0	0	1	1	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	0
6	P	P	0	0	0	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	0	0	1	0	1	1	1	0	P
	P = Pressure Applied 0 = Blocked		1 = Slotted cover plates or connecting laminates used 0 = Blocked by standard cover plates													1 = Pressure present for proper functioning 0 = Pressure not present for proper functioning P = Pressure applied													

Figure 18. Continuity test matrix.

5.2 Gain Test

After establishing the three-stage gain block continuity, a gain test was conducted. Bonded amplifier modules No. 8 (aspect ratio 2.5), 4 (aspect ratio 1.0) and 1 (aspect ratio 0.4) were assembled (in that order) to the gain block chassis and leak tested.

Resistor modules were then assembled to provide power supply pressures equal to those used in the individual module post-bond tests. Since the ratio of cross sectional areas of the test point flow paths to the nozzles of the amplifiers was greater than 10 to 1, it was assumed that the measured power supply pressures were close to the actual power supply pressures. To minimize vent loading of the amplifiers, all three vent resistor modules (R4, R5, and R6) were completely removed from the gain block chassis. A control bias pressure (as measured at TP7) equal to 10% of the supply was set at the PC1 inlet. Pressure at the PC2 inlet was then swept from zero to 20% of the first-stage supply pressure (as measured at TP9). A gain curve was plotted automatically with an x-y recorder as shown in Figure 19. The x-axis is the control differential pressure as measured at TP7 and TP9 with Barocel pressure transducers. The y-axis is the output differential pressure of the third-stage amplifier measured block loaded with Barocels. The measured gain was 153.

The product of the individual block-loaded gains (from Table II) for the three stages used is 291. A combination of pressure losses in interconnection lines between stages and gain reduction caused by loading effects (as opposed to a block-loaded condition) will cause the three-stage gain to be lower than this value of 291. As an example, if the first two stages experience a 15 percent gain reduction due to loading (the third stage is still block loaded), and there is a 10 percent pressure loss to the inputs of all three stages, then the net three-stage gain would be reduced from 291 to 153. Therefore, the measured value of 153 is reasonable for the test set-up used.

6. CONCLUSIONS

6.1 Fineblanking

The three-stage amplifier design was reviewed for compatibility with the fineblanking process. Laminates for the amplifier and manifold modules were produced by fineblanking. Inspection of these laminates showed good surface quality on the internal sheared surfaces and excellent dimensional repeatability. Die roll and burr were evident on all amplifier laminates, but did not interfere with bonding in thicknesses of 0.20 and 0.51 mm. However, with a laminate thickness of 1.27 mm die roll was excessive and unacceptable. Where the laminate design did not include long, slender elements, such as the amplifier splitter, greater thicknesses were fineblanked with acceptable die roll. The manifold plate, which was 3.18 mm thick, did not exhibit excessive die roll. Hard tempered aluminum alloy (6061-T6) was satisfactorily fineblanked in thicknesses up to 0.51 mm, but annealed 6061 was used for greater thicknesses. Economically, the high initial die cost makes fineblanking feasible only where thousands

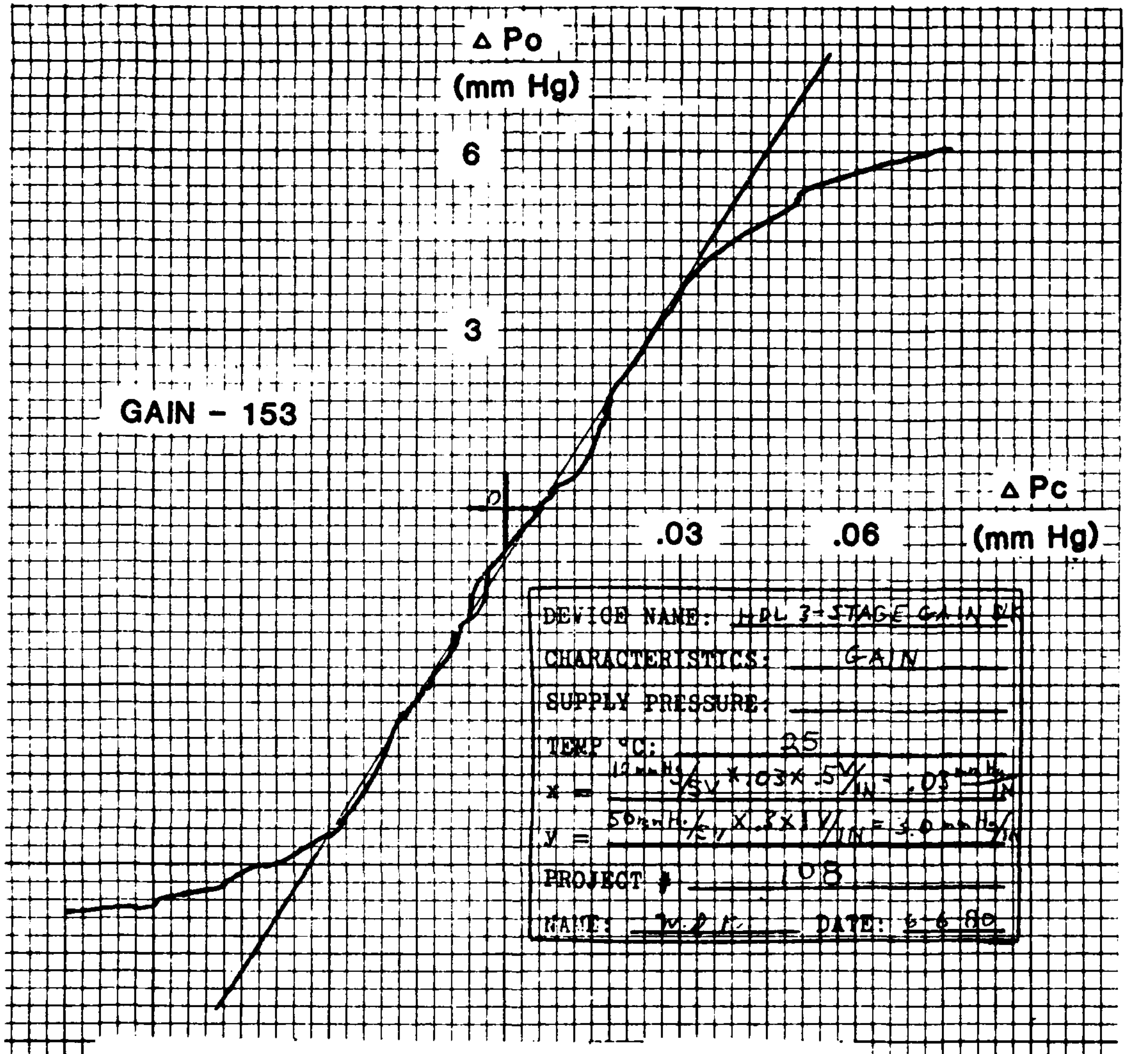

Figure 19. Three-stage amplifier gain curve.

of identical laminations are to be produced.

6.2 Semi-Solid-State Diffusion Bonding

Bonding was done on a small-scale basis with all bonding parameters being controlled manually. It was evident that this procedure was highly dependent on the skill and attentiveness of the operator. Temperature tolerances were very tight; temperatures had to be held within a 3°C range for one-half hour. In one instance, where the temperature was allowed to exceed this range by an additional 3°C, one of three amplifiers being bonded became clogged and was unusuable. It is concluded that further development of the process is required before it can become a viable production process. A detracting element of the SSDB process is the fact that the 565°C temperature and one-half hour time required for bonding removed the temper from the 6061-T6 aluminum alloy laminates. As a result, the bonded modules were extremely soft and could not be satisfactorily clamped down against O-ring seals without permanent distortion. The remedies for this condition could be either the use of much heavier cover plates for the modules (0.25 mm cover plates were used and found to be much too light) or a reheat treatment of the bonded assemblies after bonding. Reheat treatment would require care to prevent the introduction of further distortion. In general, the bonding results were promising but inconclusive. Eight of the nine amplifiers bonded met the visual and metallographic criteria for satisfactory bonding, but exhibited gain changes between the pre- and post-bond functional tests. An insufficient number of modules were bonded to establish a pattern between the before and after tests, or to determine what, if any, corrective action could be taken.

7. RECOMMENDATIONS

7.1 Fineblanking

Based on the results of this program, it is recommended that additional amplifier laminates be fineblanked in the thickness range of 0.51 to 1.27 mm to determine via amplifier performance degradation the point at which die roll becomes excessive. It would also be of value to fineblank sufficient quantities of laminates to determine useful die life, die sharpening and refurbishing costs, and laminate cost data over the die life. Also, since a previous HDL study[1] showed a favorable comparison of fineblanking with photochemical etching (although using a different amplifier laminate design and material), it is recommended that the amplifier design used in the current program be made the basis for further comparison, including both cost and function, with photochemically etched elements.

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1 Phillipi, R. Michael, "A Study of Fineblanking for the Manufacture of Flueric Laminar Proportional Amplifiers," Report No. HDL-TM-77-8, U.S. Army Material Development and Readiness Command, Harry Diamond Laboratories, Adelphi, Maryland, May 1977.

7.2 Semi-Solid-State Diffusion Bonding

It is recommended that additional quantities of amplifier modules be bonded to permit statistical data to be developed on both cost and functional characteristics.

Because of the annealing effect of the bonding temperatures, it is recommended that a study be made to determine whether stainless-steel metal alloys of other metals might be more suitable for bonding. At the same time, a parallel study to determine the feasibility of reheat treatment should be carried out. The alternative to this is to modify the existing amplifier design (and similar designs) to incorporate cover plates heavy enough to be structurally rigid in the annealed condition if the SSDB process is to be used.

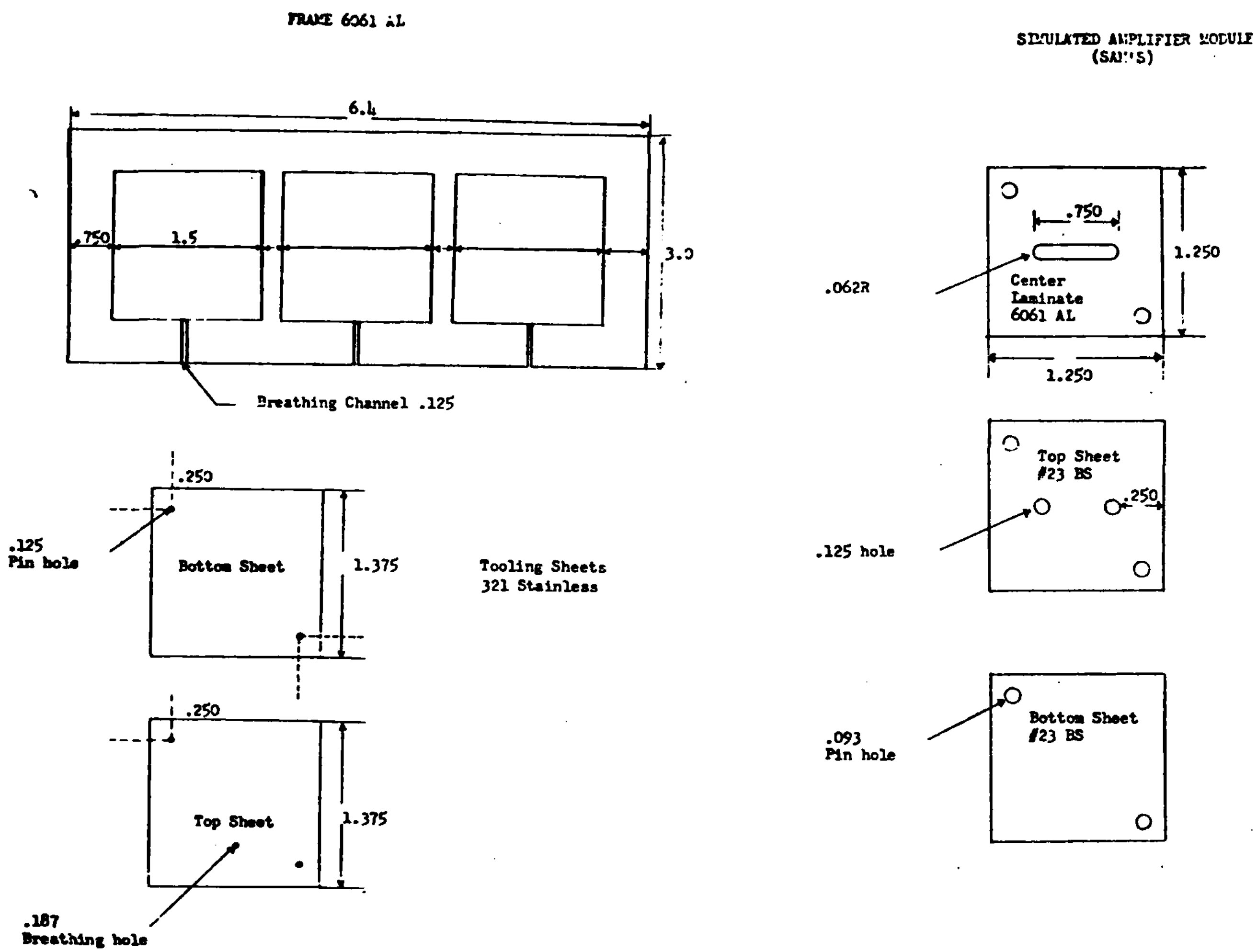
Due to the present critical dependence of the SSDB process on human operator technique, cooperative efforts should be made with the bonding vendor to increase the reliability of the process by automation, possibly computer-aided. This would also result in a process more suited to volume production and more compatible with the potential of the fine-blanking process.

During the current program, laminates up to 3.18 mm thick were bonded; these were dummy modules simulating the manifold module. It is recommended that bonding be extended to the actual amplifier manifold modules and to the three-stage amplifier chassis, and that appropriate functional, mechanical, and metallurgical tests be done to verify the bonding process.

To further enhance the bonding process, additional development of the bonding tooling is recommended. For instance, the tendency of alignment dowels to become bonded to the product modules is costly and should be eliminated. Also, up to this point a capacity for bonding only three modules at a time has been demonstrated. This capacity should be increased if maximum economy is to be achieved.

APPENDIX A.-- DIFFUSION BONDING PROCESS DATA

This appendix presents the information and data developed in setting up the semi-solid-state diffusion bonding process for this program. The process was set up by AVCO Aerostructures Division of Nashville, TN. Simulated amplifier modules (SAM's) were used to determine the appropriate values of temperature, time, and pressure for the different laminate thicknesses called for in the amplifier and manifold designs. Included in the appendix are details of the tooling, results of metallographic analyses, and photomicrographs of the SAM's and of the one fineblanked amplifier module that became clogged during bonding. All of the material in the appendix is original data and is presented as received from AVCO without modification or interpretation.

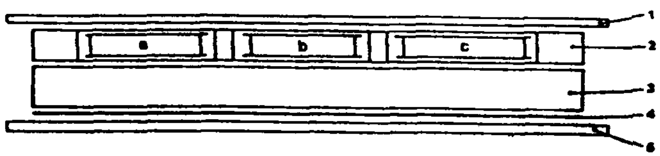

FRAME 6061 AL
6.4
.750
1.5
3.0
Breathing Channel .125
.250
.125
Pin hole
Bottom Sheet
1.375
Tooling Sheets
321 Stainless
.250
Top Sheet
1.375
.187
Breathing hole
SIMULATED AMPLIFIER MODULE
(SAM'S)
.750
.062R
Center
Laminate
6061 AL
1.250
1.250
Top Sheet
#23 BS
.250
.125 hole
Bottom Sheet
#23 BS
.093
Pin hole

SAM # 7,8 & 9 . **PART STACK-UP**

1.	Slip Sheet 321 SS	.0245
2.	Top Cover #23 BS	.0107
3.	Center Laminate 6061 Al.	.0085
4.	Bottom Cover #23 BS	.0107
5.	Slip Sheet 321 SS	.0245
	TOTAL	.0789

TOOLING STACK-UP

MODULES BEING BONDED (a,b,c)



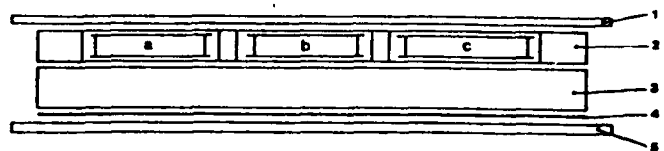
1.	Top Pressure Sheet 321 SS	.0250
2.	Frame 6061 Al.	.0769
3.	Spacer 6061 Al.	.3313
4.	Bottom Pressure Sheet 321 SS	.0250
	TOTAL	.4582
5.	Spacer 3003 AL	.0418
		.5000 TOTAL

SAM # 10,11 & 12 **PART STACK-UP**

1.	Slip Sheet 321 SS	.0247
2.	Top Cover #23 BS	.0107
3.	Center Laminate 6061 Al.	.0086
4.	Bottom Cover #23 BS	.0107
5.	Slip Sheet 321 SS	.0247
	TOTAL	.0791

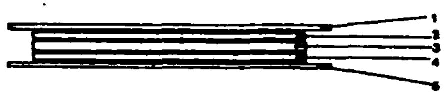
TOOLING STACK-UP

MODULES BEING BONDED (a,b,c)



1.	Top Pressure Sheet 321 SS	.0250
2.	Frame 6061 Al.	.0769
3.	Spacer 6061 Al.	.3313
4.	Bottom Pressure Sheet 321 SS	.0250
	TOTAL	.4582
5.	Spacer 3003 AL	.0418
		.5000 TOTAL

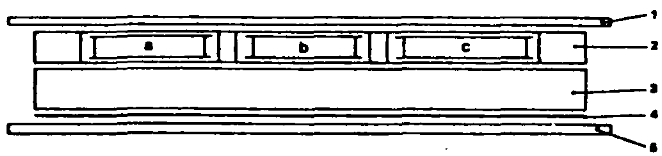
SAM # 1,2 & 3.   PART STACK-UP



1.	Slip Sheet 321 SS	.0246
2.	Top Cover #23 BS	.0107
3.	Center Laminate 6061 Al.	.0498
4.	Bottom Cover #23 BS	.0107
5.	Slip Sheet 321 SS	.0246
	TOTAL	.1204

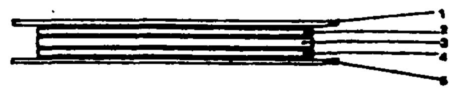
TOOLING STACK-UP

MODULES BEING BONDED (a,b,c)



1.	Top Pressure Sheet 321 SS	.0246
2.	Frame 6061 Al.	.1190
3.	Spacer 6061 Al.	.3318
4.	Bottom Pressure Sheet 321 SS	.0246
	TOTAL	.5000

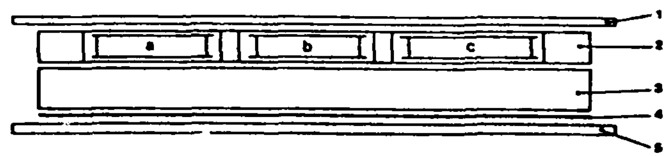
SAM # 4,5 & 6.   PART STACK-UP



1.	Slip Sheet 321 SS	.0245
2.	Top Cover #23 BS	.0107
3.	Center Laminate 6061 Al.	.0200
4.	Bottom Cover #23 BS	.0107
5.	Slip Sheet 321 SS	.0245
	TOTAL	.0904

TOOLING STACK-UP

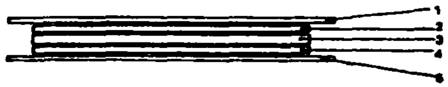
MODULES BEING BONDED (a,b,c)



1.	Top Pressure Sheet 321 SS	.0250	
2.	Frame 6061 Al.	.0875	(Chem mill from .[illegible])
3.	Spacer 6061 Al.	.3313	
4.	Bottom Pressure Sheet 321 SS	.0250	
	TOTAL	.4688	
5.	Spacer 3003 AL	.0324	
		.5012 TOTAL	

SAN # 13 & 14 .

PART STACK-UP

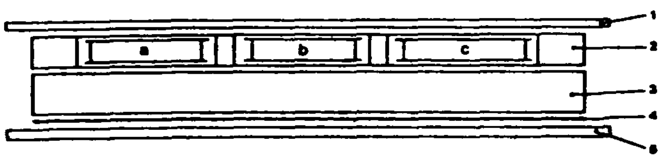


1. Slip Sheet 321 SS — .0246
2. Top Cover #23 BS — .0102
3. Center Laminate 6061 Al. — .0195
4. Bottom Cover #23 BS — .0108
5. Slip Sheet 321 SS — .0245

TOTAL — .0896

TOOLING STACK-UP

MODULES BEING BONDED (a,b,c)



1. Top Pressure Sheet 321 SS — .0250
2. Frame 6061 Al. — .077
3. Spacer 6061 Al. — .3313
4. Bottom Pressure Sheet 321 SS — .0250

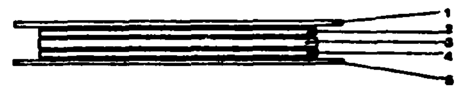
TOTAL — .4583

5. Spacer 3003 AL — .010
6. Spacer 3003 AL — .0314

.4997

SAN # 15 & 16 .

PART STACK-UP

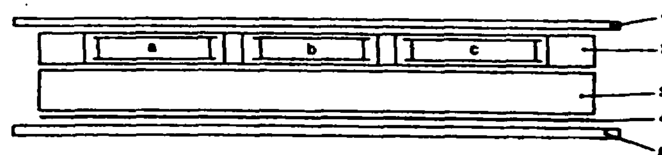


1. Slip Sheet 321 SS — .0246
2. Top Cover #23 BS — .0114
3. Center Laminate 6061 Al. — .0499
4. Bottom Cover #23 BS — .0114
5. Slip Sheet 321 SS — .0246

TOTAL — .1219

TOOLING STACK-UP

MODULES BEING BONDED (a,b,c)



1. Top Pressure Sheet 321 SS — .0250
2. Frame 6061 Al. — .120
3. Spacer 6061 Al. — .330
4. Bottom Pressure Sheet 321 SS — .0250

TOTAL — .5000

TRITEC
Metallographic Sections

Mount No. 2522 .
Date 10/25/79.

Material: No. 24 Braze sheet. Material "as is" (before chem milling) typically measures 0.0205 thick, with 0.00226 braze alloy on both sides. See test #2504 for data.

Remove 1.5 mils total both sides for a final thickness/braze alloy as follows.

Desired thickness, .019 Braze alloy both sides .0015 plus/minus .0003.
Chem mill to measure .020 to .0225 and metallographic section to check thickness and braze alloy.

TEST: Two sheets 10.5" X 32.0".
Samples opposite corners.

SHEET 1

Sample	Thickness (80X)	Braze alloy (400X)
1X	.01926	.00164/.00164
2X	.01905	.00133/.00133-.00144
3X	.01937	.00164/.00164
4X	.01894	.00133/.00133

SHEET 2

Sample	Thickness (80X)	Braze alloy (400X)
5X	.01915	.00164/.00164
6X	.01937	.00154/.00154-.00164
7X	.01915	.00154/.00154
8X	.01915	.00144-.00154/.00154

One sheet sheared 1.65 X 32.0 inches into six strips and shipped to Florida Fine Blanking Co. 10/24/79 for stamping. The other sheet identified and stored.

TRITEC
Metallographic Sections

Mount No. 2523.
Date 10/26/79.

Material: Braze Sheet #23 chem milled one side (non-clad side). Mic. .013 at one corner. Remove by chem milling 2.2 mils and check clad thickness and sample thickness. Check four corners. This is a test sheet.

Sample	Thickness	Braze alloy
1A	.0107	.00154
2A	.0106	.00144
3A	.0107	.00144
4A	.0110	.00164

Note: Need .00150 braze alloy plus/minus .0003.
Material OK. Remove 2.2 mils.

Mount No. 2524-A .
Date 10/29/79 .

Material: Same as above. No. 23 Braze sheet. Chem mill 2.2 mils two sheets (2) numbered A and B sheets.

Sheet	Mic.	Chem Mill	Mic.	Sample	Thickness	Braze Alloy
1	.013	2.2 mils	10.8	1A-1	.01107	.00154
				1A-2	.01115	.00164
				1A-3	.01107	.00164
				1A-4	.01107	.00164
2	.013	2.2 mils	10.8	2A-1	.00984	.00154
				2A-2	.00984	.00144
				2A-3	.00943	.00144
				2A-4	.00964	.00144

Mount No. 2524-B.

Sheet	Mic.	Chem Mill	Mic.	Sample	Thickness	Braze Alloy
2	.012	2.2 mils	9.8	3A-1	.00984	.00144
				3A-2	.00984	.00154
				3A-3	.00984	.00154
				3A-4	.00943	.00154
2	.0121	2.2 mils	.0099	4A-1	.0098	.00151
				4A-2	.00964	.00151
				4A-3	.0099	.00151
				4A-4	.01005	.00151

SUBJECT: Parameter Evaluation
Semi Solid Diffusion Bonding Process
Simulated Amplifier Module (SAM)

GENERAL: The nominal parameters for semi-solid-diffusion bonding as outlined in the HDL report were used in the following test to verify temperature, pressure cladding thickness etc., and acquaint the operator with the process.

PARTS AND MATERIAL: Each Simulated Amplifier Module (SAM) consists of three parts.

Top Cover. No. 23 braze sheet chem milled to .010 in. thickness with an interleaf (alloy) thickness of 0.00146 in. Alloy range maintained at 0.0015 - 0.0003 in.

Bottom Cover. Same as top cover.

Center Laminate. 6061-T6 Al.

TOOLING: Standard tooling procedures were used as outlined in HDL report. The braze package was designed to accomodate three parts at one time.

TEST: SAM NO. 1.
One part was selected for this run. Desired temperature was about 1055°F. Actual temperature was (low/high) 1053-1062°F. Average temperature was 1057°F.

Micro examination indicated excessive alloy flow for this temperature, based on past experience.

Additional tests required in the 1055°F degree range.

SAM NO. 2.
Excessive alloy flow noted again. Suspect thermocouples in error. Thermocouple calibration test performed and found to be in error -- eight degrees low. New wire to be used on all future runs.

SAM NO. 3.
Good bond integrity noted here without excessive alloy flow. Average temperature now adjusted for 1055°F average.

Additional tests will be conducted at lower temperatures.

SAM NO. 4, 5 & 6
Three units bonded in one operation. Desired temperature range 1055. Actual temperature 1053-1060. Average 1054.75°F.

Excessive alloy flow into cavity indicated bond temperature to high.

SAM NO. 7, 8 & 9.
Three units bonded in one operation. Desired temperature 1050-1053 degree range. Actual temperature 1049 to 1052°F. Average temperature 1050.7.

SAM NO. 10.
Tested conducted in the 1045-1050 degree range. Low/high temperature 1044-1050 averaging 1046.9°F.

Good bond. Cavity not plugged with alloy. Run additional sample at 5 degrees lower to reduce crystalline growth and excessive alloy diffusion into parent metal.

SAM NO. 11.
Test temperature 1040 to 1045°. Actual temperature 1039-1045, averaging 1042.8°F.

Good quality bond joint.

SAM NO. 12.
Test temperature range 1035-1040°F. Actual temperature low/high 1032-1038°F. Average 1036.3°F.

Lack of alloy penetration into center laminate. Temperature not high enough for good joint integrity. Failed leak test.

SAM NO. 13.
Temperature range 1045-1050°F. Actual temperature 1045-1050. Average 1047.9°F.

Good joint integrity and alloy diffusion into center laminate.

SAM NO. 14.
Temperature range 1040-1045°F. Actual temperature 1040-1050. Average 1042.2°F.

Minimal alloy diffusion into parent metal, although bond joint appears acceptable (borderline).

SAM NO. 15.
Desired temperature range 1045-1050°F. Actual temperature 1045-1050. Average 1047.5°F.

Minimal alloy diffusion into parent metal, although bond joint appears acceptable (borderline).

SAM NO. 16.
Temperature range desired 1040-1045°F. Actual low/high 1040-1050°F. Average 1042.3°F.

Lack of alloy diffusion into center laminate. Failed leak test.

TRITEC INC. - PARAMETER EVALUATION - SEMI SOLID DIFFUSION BONDING PROCESS

SIMULATED AMPLIFIER MODULE

Run No.	Laminate Thickness (in)	Interleaf Alloy Thickness (in)	Bond Temp. (°F)	Bond Time Minutes	Bond Pressure (in. Hg)	Pressure Test (1 hr. @ 100psi)
SAM-1	0.050	0.00146	1053-1062 1057 AVG.	21	15.0	OK
SAM-2	0.050	0.00146	1053-1059 1056 AVG.	30	15.0	OK
SAM-3	0.050	0.00146	1053-1057 1055 AVG.	30	15.0	OK
SAM-4	0.020	0.00146	1053-1060 1054.75 AVG.	30	15.0	OK
SAM-5	0.020	0.00146	1053-1060 1054.75 AVG.	30	15.0	OK
SAM-6	0.020	0.00146	1053-1060 1054-75 AVG.	30	15.0	OK
SAM-7	0.008	0.00146	1049-1052 1050.7 AVG.	30	15.0	OK
SAM-8	0.008	0.00146	1049-1052 1050.7 AVG.	30	15.0	OK
SAM-9	0.008	0.00146	1049-1052 1050.7 AVG.	30	15.0	OK
SAM-10	0.008	0.00146	1044-1050 1046.9 AVG.	30	15.0	OK
SAM-11	0.008	0.00146	1039-1045 1042.8 AVG.	30	15.0	OK
SAM-12	0.008	0.00146	1032-1038 1036.3 AVG.	30	15.0	Leaks at 20psi
SAM-13	0.020	0.00146	1045-1050 1047.9 AVG.	30	15.0	OK
SAM-14	0.020	0.00146	1040-1045 1042.2 AVG.	30	15.0	OK
SAM-15	0.050	0.00146	1045-1050 1047.5 AVG.	30	15.0	OK
SAM-16	0.050	0.00146	1040-1045 1042.3 AVG.	30	15.0	Leaks at 30psi

PHOTOMICROGRAPH DATA

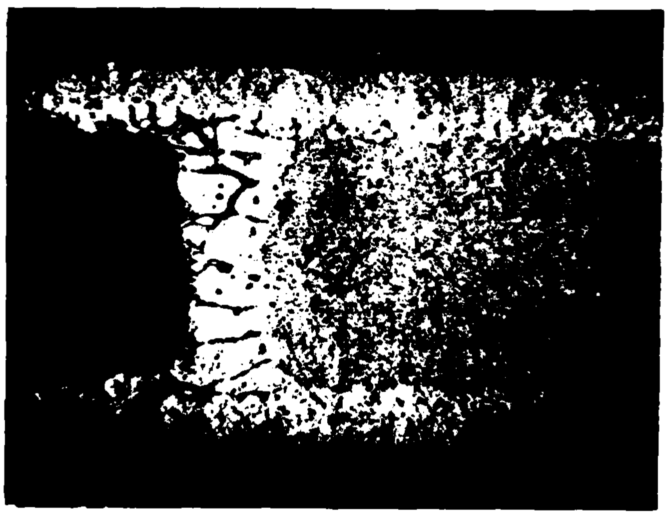
PROJECT: TRITEC   DATE: 9/12/79   MOUNT NO.: 2513
SAM #1

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze sheet. Center laminate 6061-T6 AL .050

PURPOSE OF TEST: Metallographic examination of bonded assembly at 1057°



PHOTOMICROGRAPH DATA

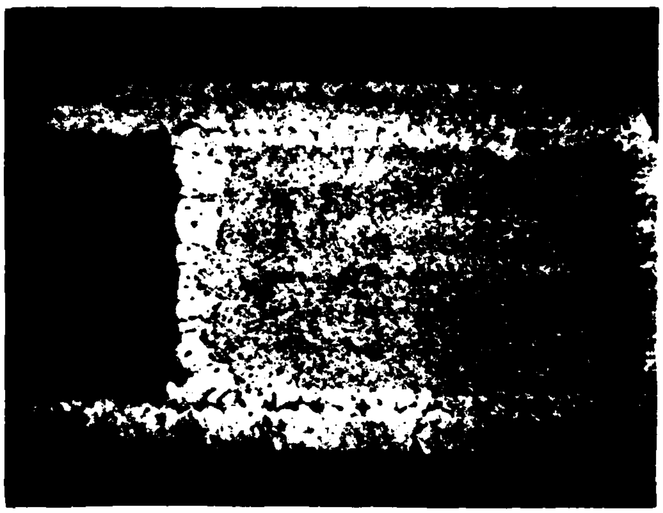
PROJECT: TRITEC DATE: 9/13/79 MOUNT NO.: 2513
SAM #2

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets #23 Braze sheet. Center sheet 6061-T6 AL .050.

PURPOSE OF TEST: Metallographic examination of bonded assembly at 1056°F.



PHOTOMICROGRAPH DATA

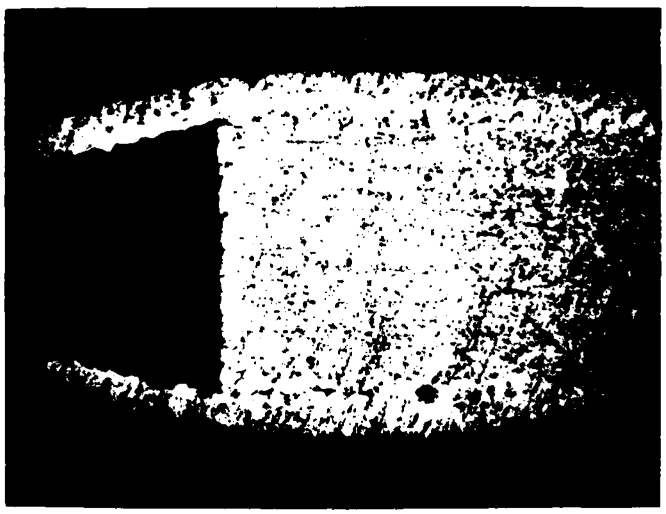
PROJECT: TRITEC DATE: 9/20/79 MOUNT NO. 2515
SAM #3

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze Sheet. Center sheet 6061-T6 AL .050.

PURPOSE OF TEST: Metallographic examination of bonded assembly at 1055°F.



PHOTOMICROGRAPH DATA

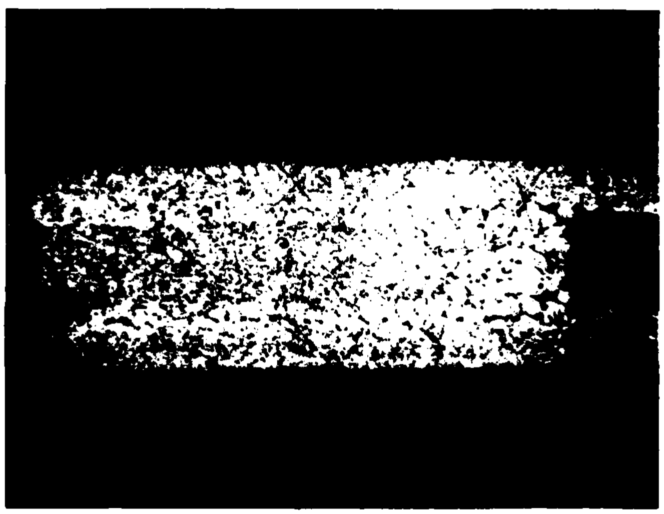
PROJECT: TRITEC DATE: 9/26/79 MOUNT NO. 2516
SAM #4

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze sheet. Center 6061-T6 AL .020.

PURPOSE OF TEST: Metallographic examination of bonded assembly at 1055°F.



PHOTOMICROGRAPH DATA

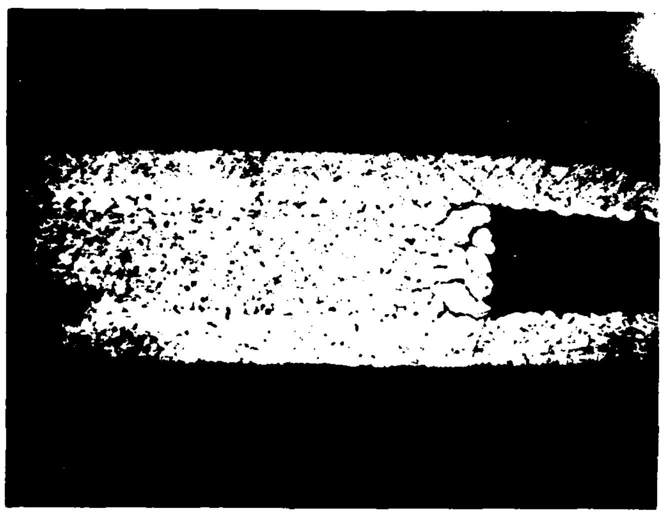
PROJECT: TRITEC DATE: 9/26/79 MOUNT NO. 2516
SAM #5

MAGNIFICATION 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze sheet. Center sheet 6061-T6 Al .020.

PURPOSE OF TEST: Metallographic examination of bonded assembly. At 1055°F.



PHOTOMICROGRAPH DATA

PROJECT: TRITEC

DATE: 9/26/79

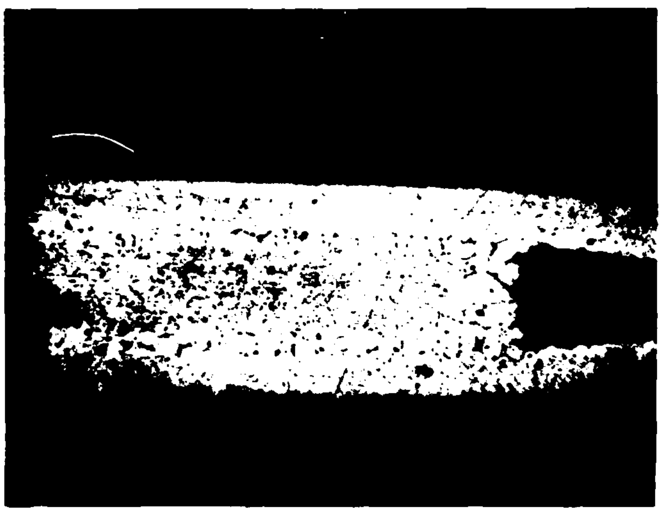
MOUNT NO. 2516
SAM #6

MAGNIFICATION 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze sheet. Center sheet 6061-T6 Al .020.

PURPOSE OF TEST: Metallographic examination of bonded assembly at 1055°F.



PHOTOMICROGRAPH DATA

PROJECT: TRITEC DATE: 9/27/79 MOUNT NO. 2517
SAM #7

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze sheet. Center sheet .008 6061-T6 AL.

PURPOSE OF TEST: Metallographic examination of bonded assembly at 1050.7°F.

PHOTOMICROGRAPH DATA

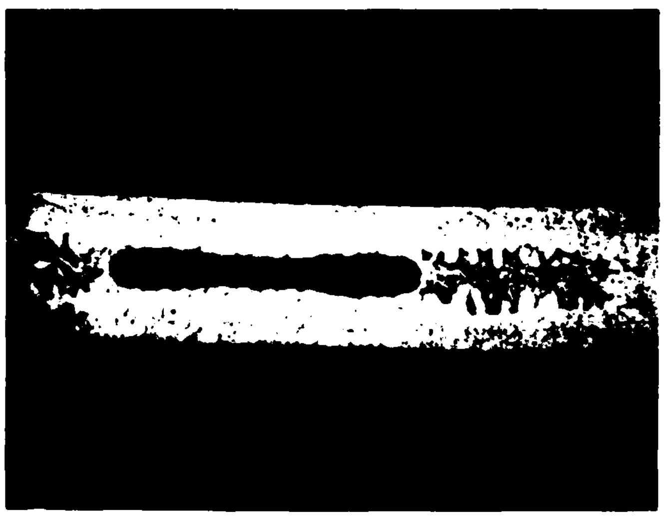
PROJECT: TRITEC DATE: 9/27/79 MOUNT NO. 2517
SAM #8

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze sheet. Center sheet 6061-T6 Al .008.

PURPOSE OF TEST: Metallographic examination of bonded assembly (1050.7°F)



PHOTOMICROGRAPH DATA

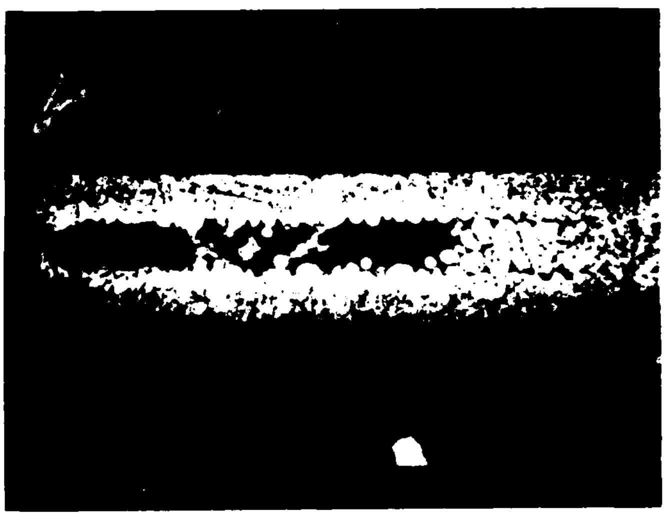
PROJECT: TRITEC DATE: 9/27/79 MOUNT NO. 2517
SAM #9

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze sheet. Center sheet 6061-T6 AL .008.

PURPOSE OF TEST: Metallographic examination of bonded assembly (1050.7°F).



PHOTOMICROGRAPH DATA

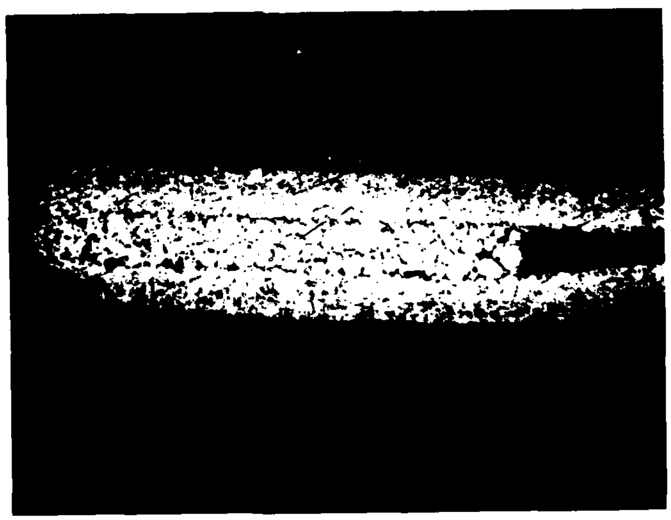
PROJECT: TRITEC DATE: 10/9/79 MOUNT NO. 2518
SAM #10

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze sheet. Center sheet 6061 AL .008.

PURPOSE OF TEST: Metallographic examination of bonded assembly at 1045-1050°F.



PHOTOMICROGRAPH DATA

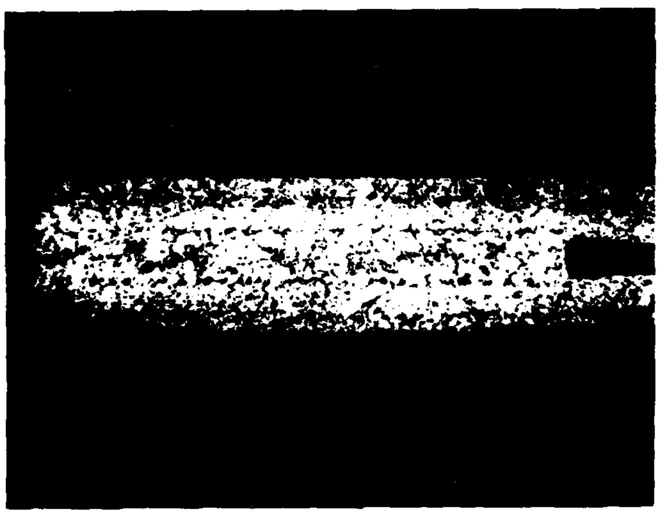
PROJECT: TRITEC DATE: 10-10-79 MOUNT NO. 2519
SAM #11

MAGNIFICATION : 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze sheet. Center sheet 6061 AL .008.

PURPOSE OF TEST: Metallographic examination of bonded assembly at 1042.8°F.



PHOTOMICROGRAPH DATA

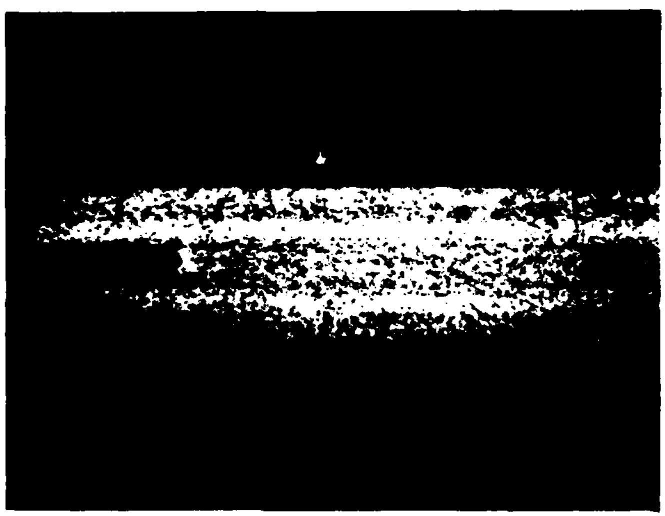
PROJECT: TRITEC DATE: 10-11-79 MOUNT NO. 2518
SAM #12

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze sheet. Center sheet 6061 AL .008.

PURPOSE OF TEST: Metallographic examination of bonded assembly at 1035-1040°F.



PHOTOMICROGRAPH DATA

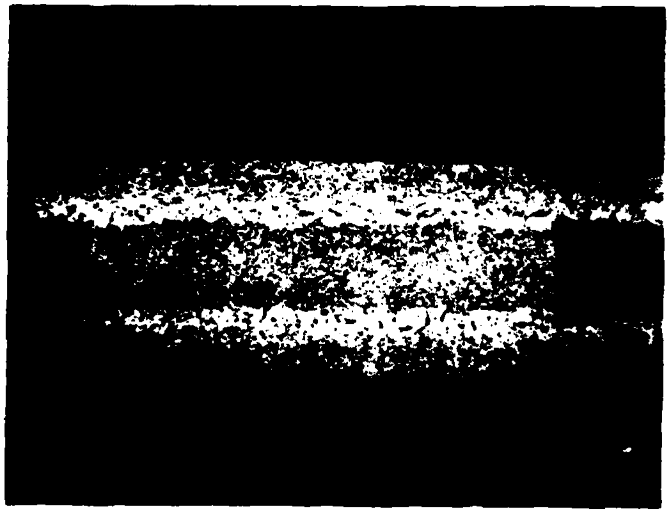
PROJECT: TRITEC   DATE: 10/16/79   MOUNT NO. 2519
SAM #13

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze sheet. Center sheet 6061 AL .020.

PURPOSE OF TEST: Metallographic examination of bonded assembly at 1047.9°F.



PHOTOMICROGRAPH DATA

PROJECT: TRITEC

DATE: 10/18/79

MOUNT NO. 2519
SAM #14

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze Sheet. Center sheet 6061 AL .020.

PURPOSE OF TEST: Metallographic examination of bonded assembly at 1042.2°F.

PHOTOMICROGRAPH DATA

PROJECT: TRITEC DATE: 10/6/79 MOUNT NO. 2521
SAM #15

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

ETCHANT: Kellers

MATERIAL: Cover sheets .010 #23 Braze sheet. Center laminate 6061-T6 AL .050.

PURPOSE OF TEST: Metallographic examination of bonded assembly at 1047.5°F.

PHOTOMICROGRAPH DATA

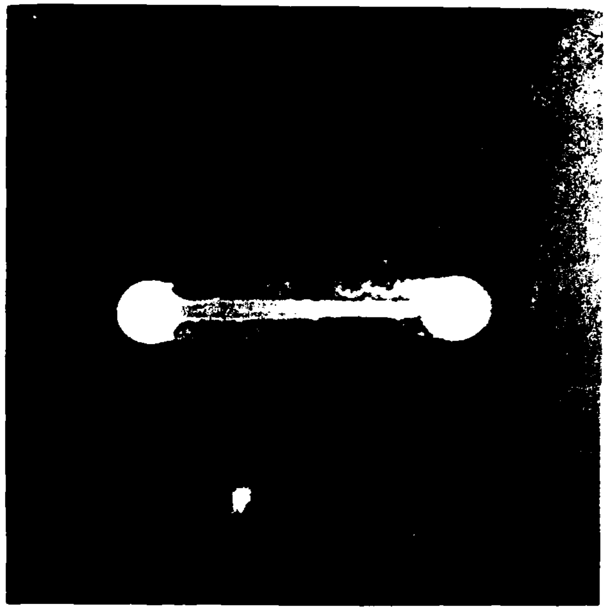
PROJECT: TRITEC   DATE: 11/8/79   MOUNT NO. 2521
SAM #16

MAGNIFICATION: 30X
(Objective) 5X
(Eyepiece) 5X
(Bellows) 5X

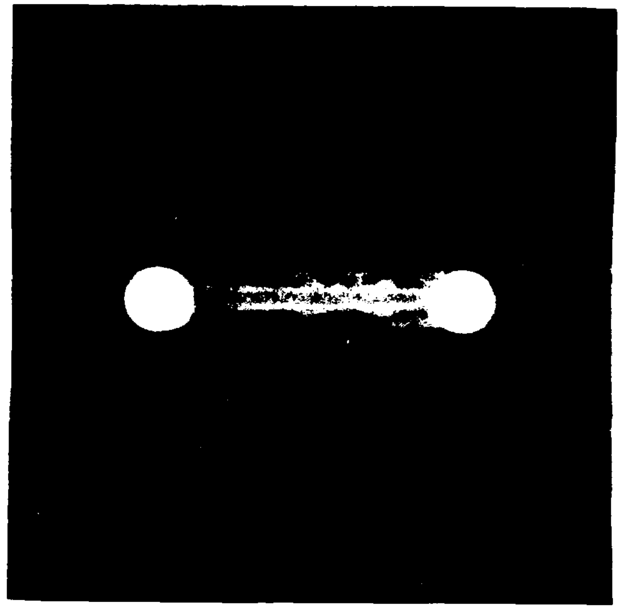
ETCHANT: Kellers

MATERIAL: Cover sheets #23 Braze sheet .010. Center laminate 6061-T6 AL .050.

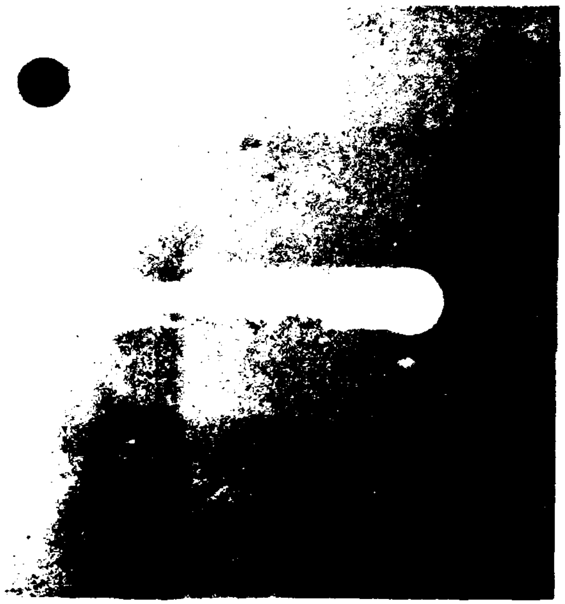
PURPOSE OF TEST: Metallographic examination of bonded assembly at 1042.3°F.



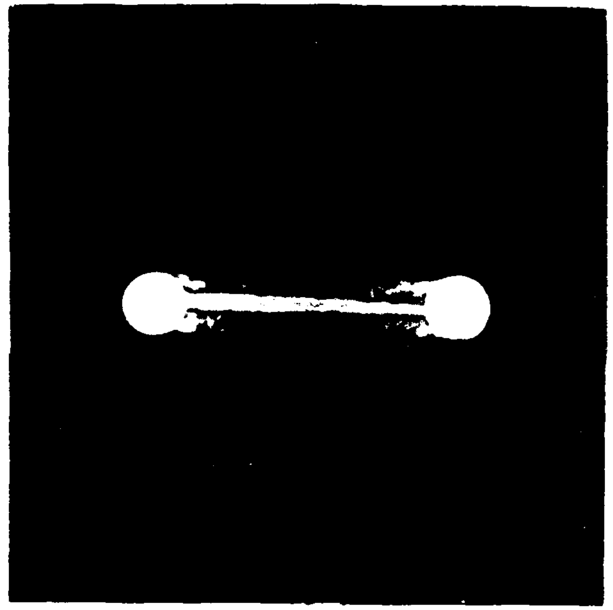
RADIOGRAPH SAM 7



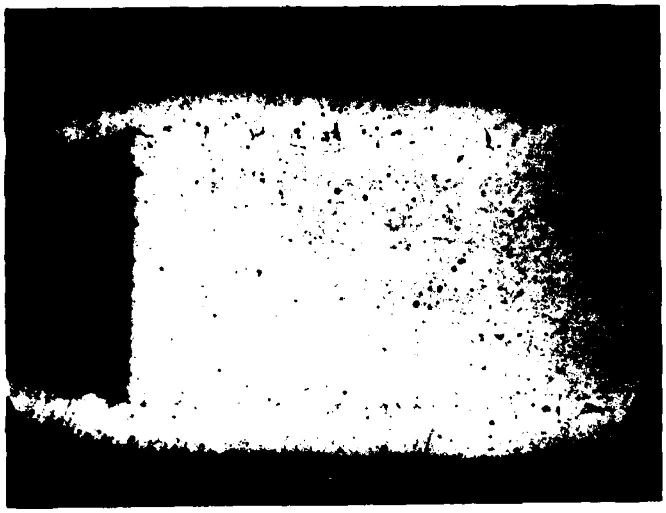
RADIOGRAPH SAM 8



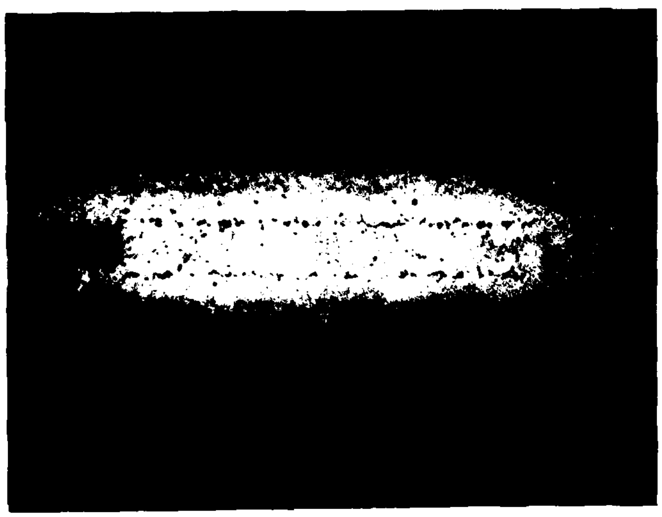
RADIOGRAPH SAM 8



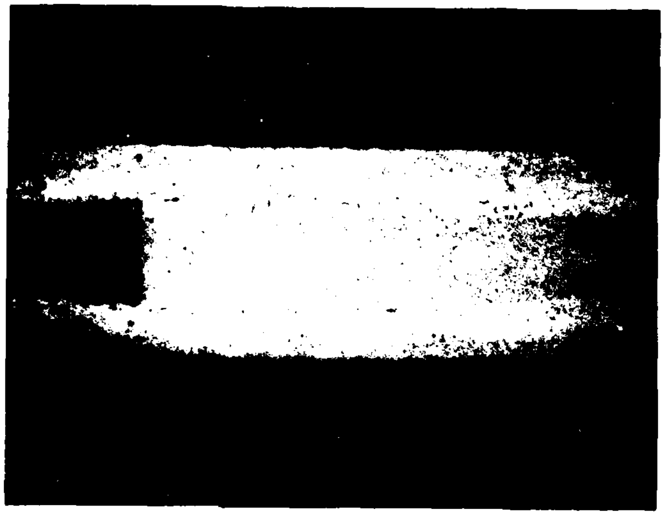
RADIOGRAPH SAM 9



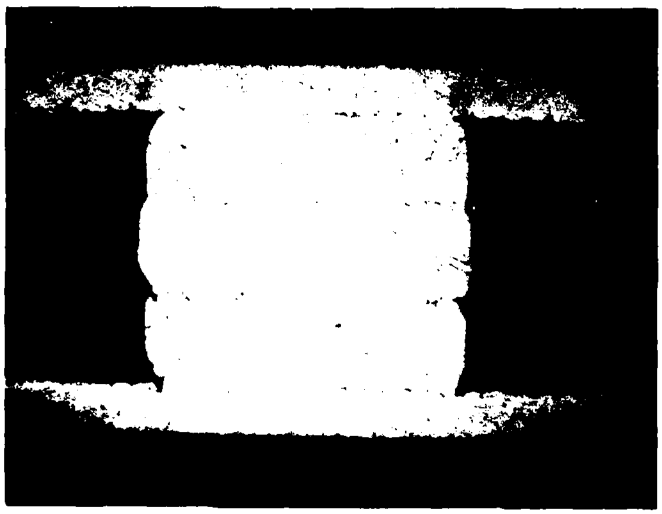
SAM #3 1.27 mm $1055^{o}F$
KELLER'S ETCH 30 X



SAM #11 0.20 mm $1042.8^{o}F$
KELLER'S ETCH 30 X



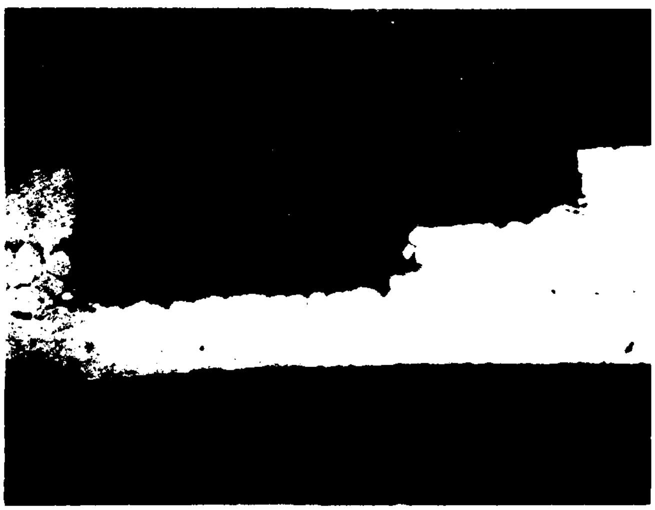
SAM #13 0.51 mm 1047.9°F
KELLER'S ETCH 30 X



SAM #17 1.27 mm 1047.7°F
KELLER'S ETCH 30 X

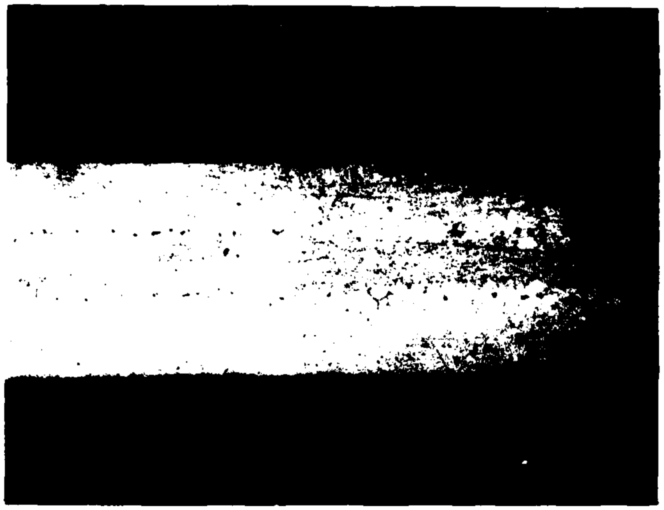
AMPLIFIER MODULE #2, 0.20 mm LAMINATE
KELLER'S ETCH

OUTLET PASSAGE 40 X



INLET HOLE 40 X

AMPLIFIER MODULE #2   0.20 mm   LAMINATE
KELLER'S ETCH



APPENDIX B.--AMPLIFIER GAIN TESTS

B1. AMPLIFIER GAIN TEST SET-UP AND PROCEDURE

To determine the effects of bonding on amplifier performance, gain tests were conducted on nine amplifier modules, three of each aspect ratio (0.4, 1.0 and 2.5), both before and after bonding. Air was used as the test fluid. To assure that the amplifiers were being operated in the laminar flow region, null offset tests were conducted first. These tests provided curves of output pressure differential, ΔPo, versus supply pressure, P_s. From these curves, an estimate was made of the pressure, P_T, at which the flow underwent transition from laminar to turbulent. After determining the value of P_T for each of the three aspect ratios, gain tests were conducted using power supply pressures of 70% of the respective P_T values and control bias pressures of 10% of the P_s values. Motor-driven regulators were used to vary the supply and control pressures. A schematic diagram of the gain test set-up is given in Figure B1. Recordings of the null offset tests are shown in Figures B2, B3, and B4. Gain curves are given in Figures B5 through B21.

B1.1 Test Fixture Pressure Corrections

The test fixture used for these tests employed a manifold assembly that conducted air to the amplifier supply and control ports through short (approximately 4 in.) lengths of 1.75 mm ID tubing. Control and supply pressures were measured at the upstream ends of these tubes during the foregoing tests. Subsequent to the tests, it was noted that the pressure drop in these lengths of tubing might have caused erroneous data. To evaluate the effects of these pressure drops, pressure taps were installed in the test fixture immediately adjacent to the amplifier inlet ports. Figures B22, B23, and B24 represent the supply pressure variation at the upstream point used during the gain and null offset tests versus the pressure drop to the amplifier supply ports, permitting determination of the true supply pressures to the amplifiers. Correction factors were then arrived at by running gain tests on three amplifiers of each aspect ratio. The original test levels of supply pressure and control bias were duplicated at the upstream points and gain curves were obtained by plotting ΔPc at the upstream points (corresponding to the original tests) and at the inlet ports (to determine the true gain curve). The test setup used is shown schematically in Figure B1. The two locations corresponding to the upstream points and inlet ports are labeled A and B, respectively. The ratios of the average gains (gain taken at inlet ports divided by gain taken upstream) were used as correction factors. The data used for this purpose is shown in Table B1. The corresponding gain curves are given in Figures B25 through B33.

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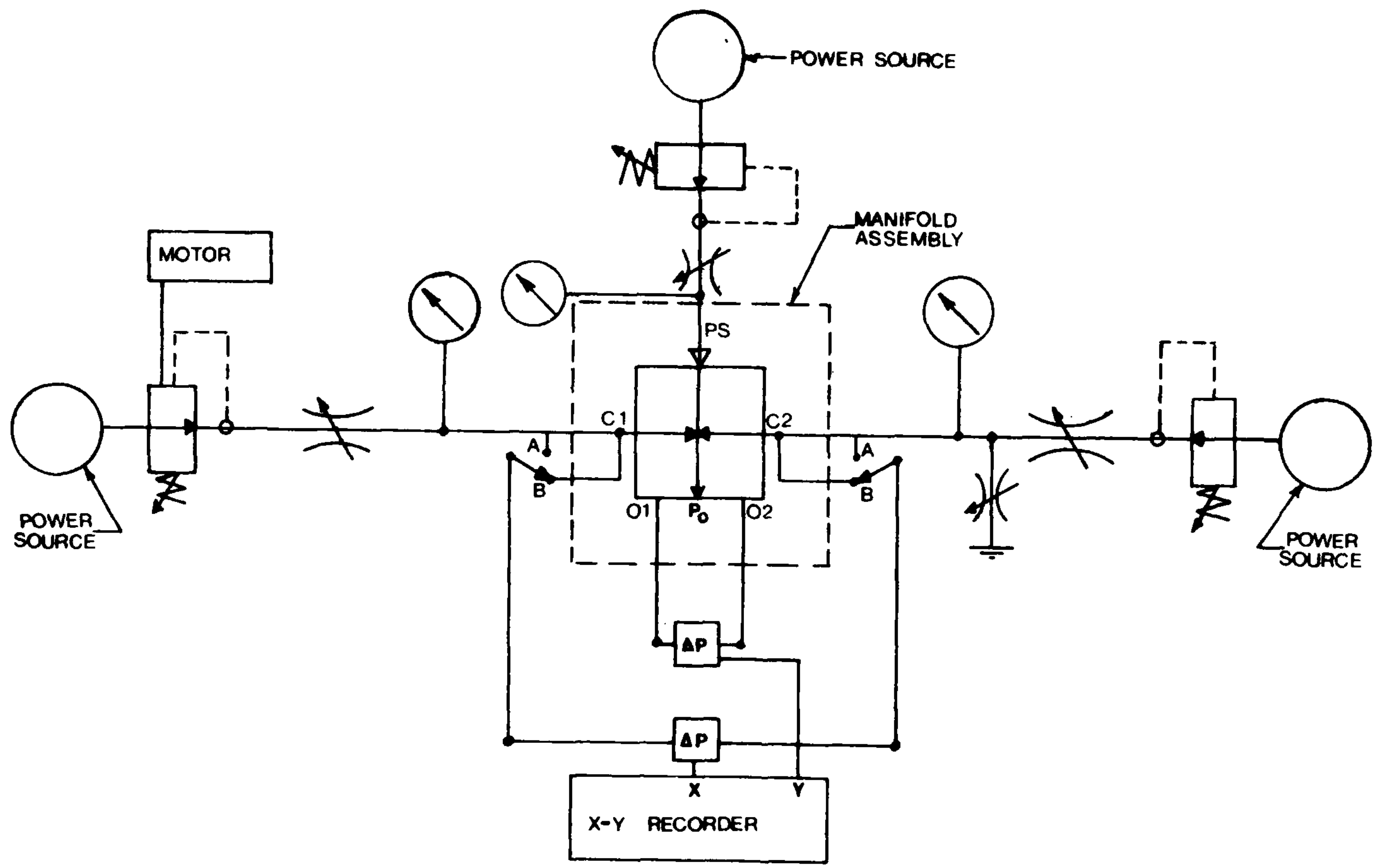

Figure B1. Gain test schematic.

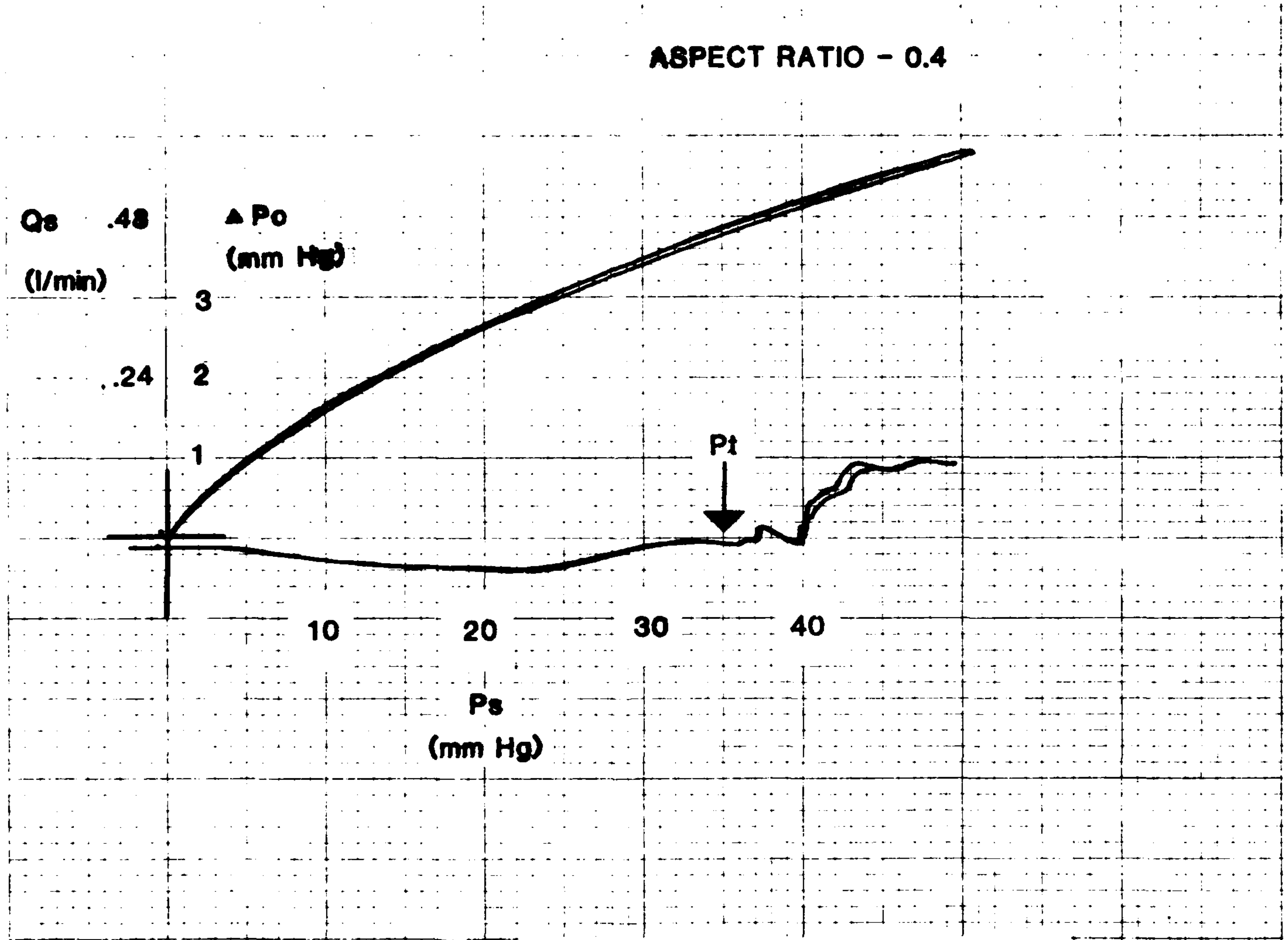

Figure B2. Null offset curve, module # 1.

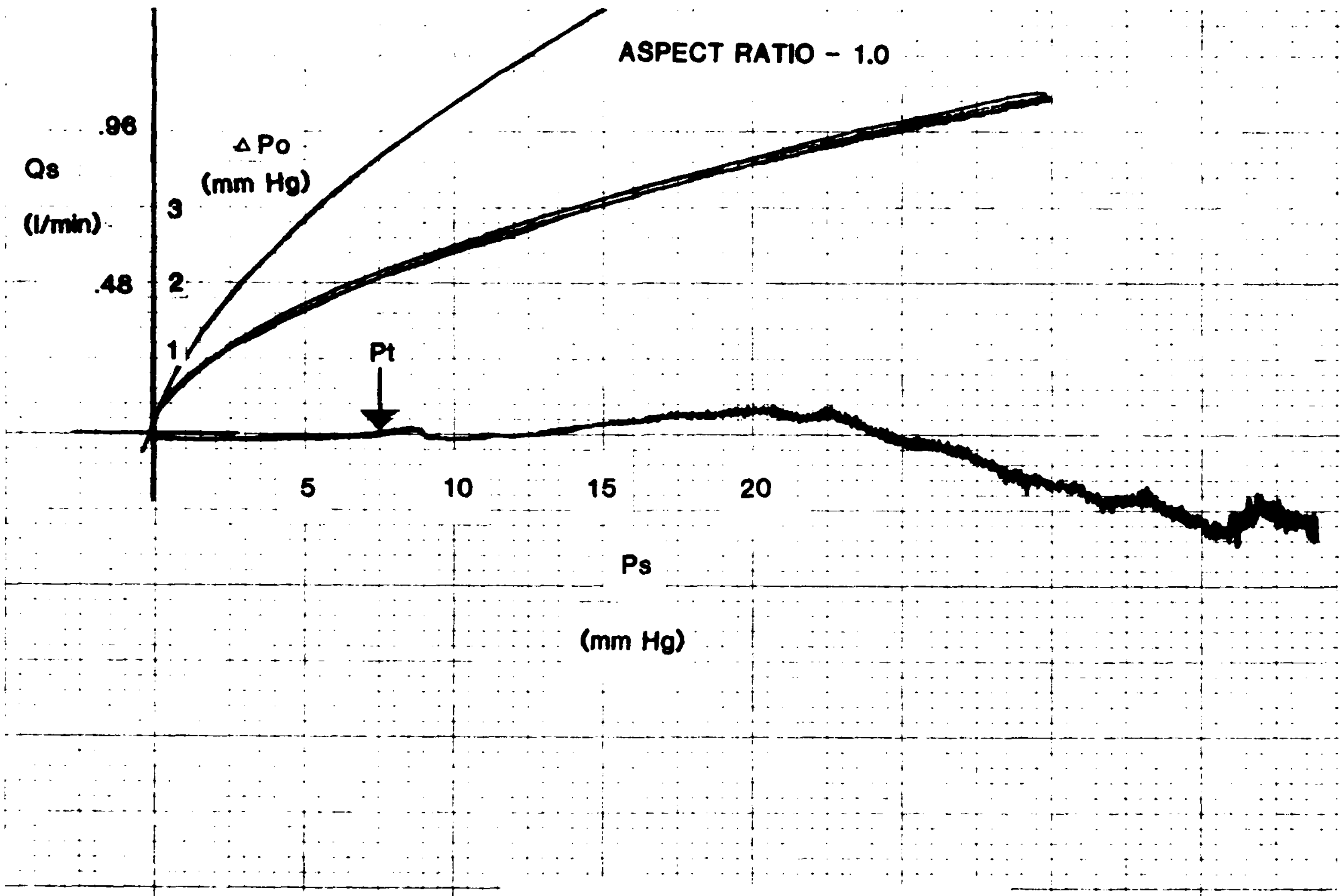

Figure B3. Null offset curve, module #4.

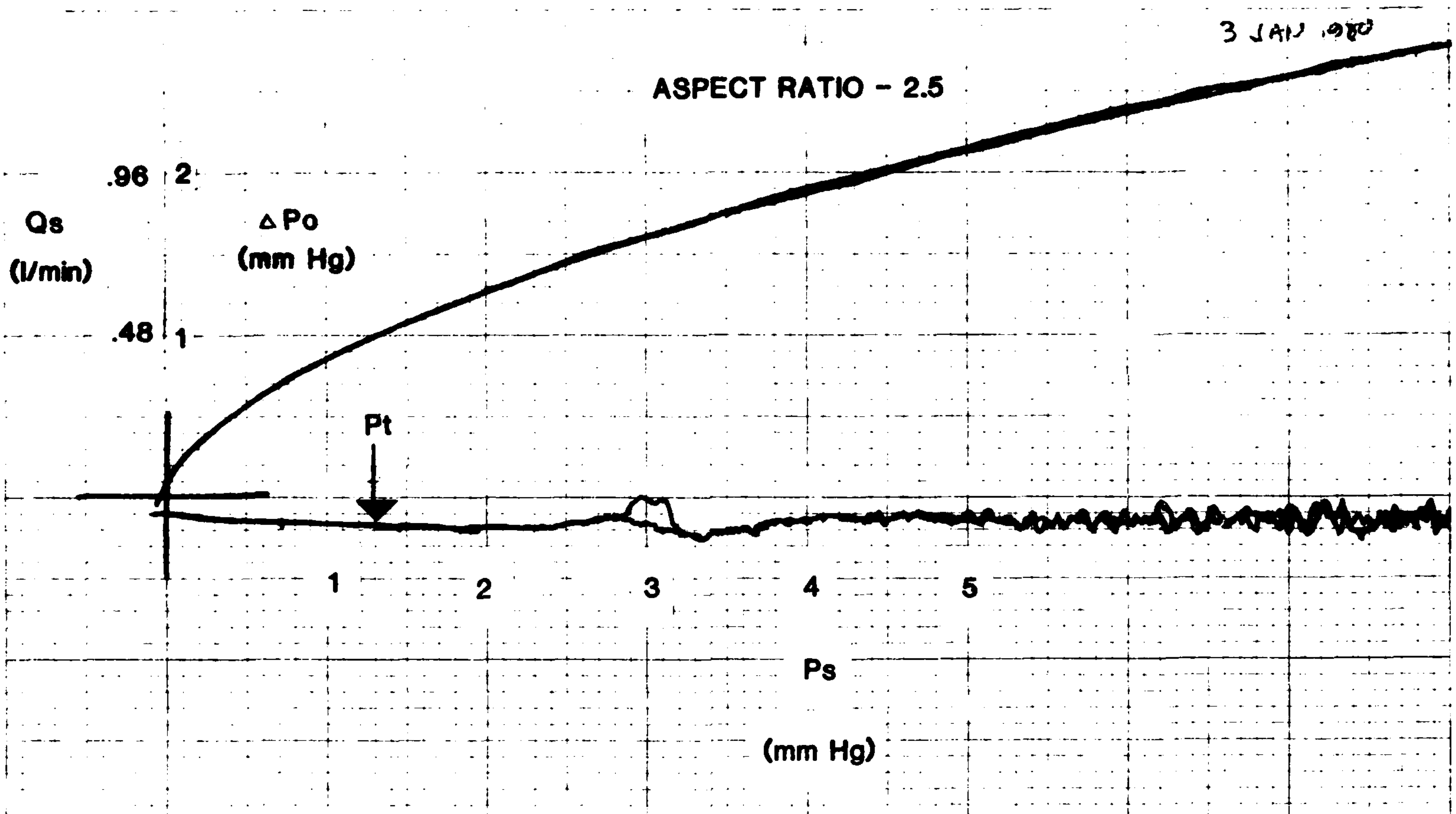

Figure B4. Null offset curve, module #7.

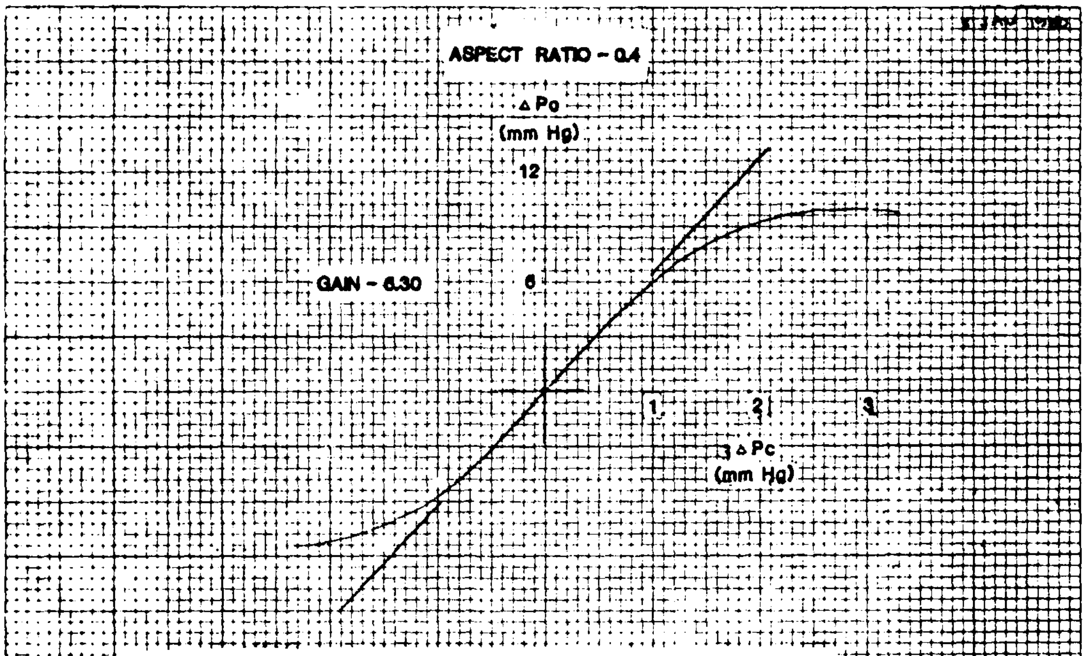

Figure B5. Pre-bond gain curve, module #1.

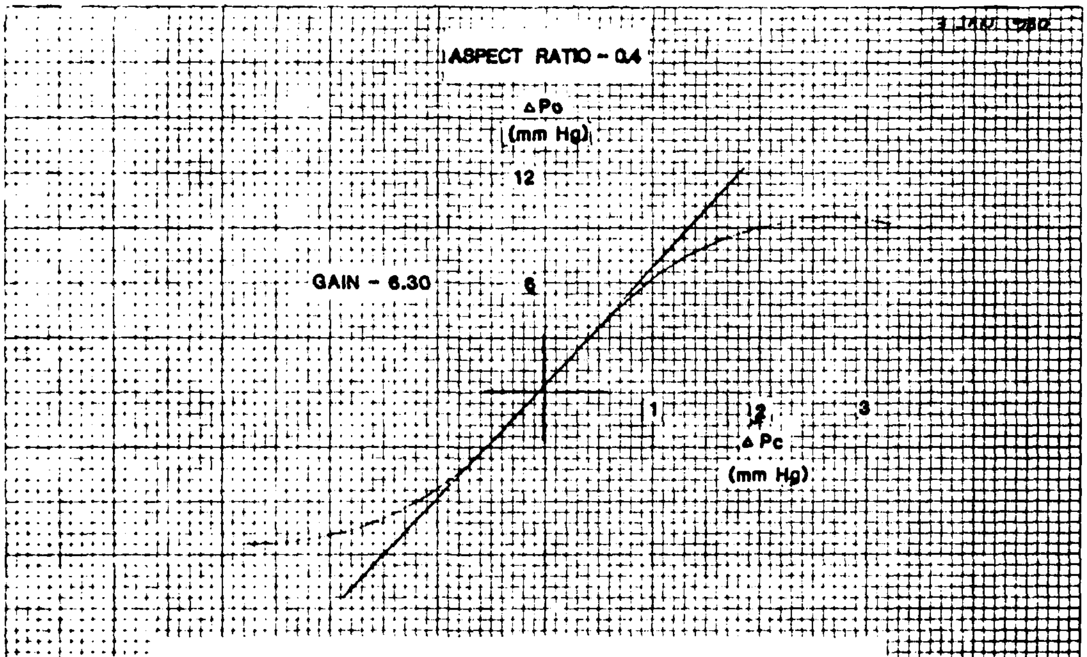

Figure B6. Pre-bond gain curve, module #2.

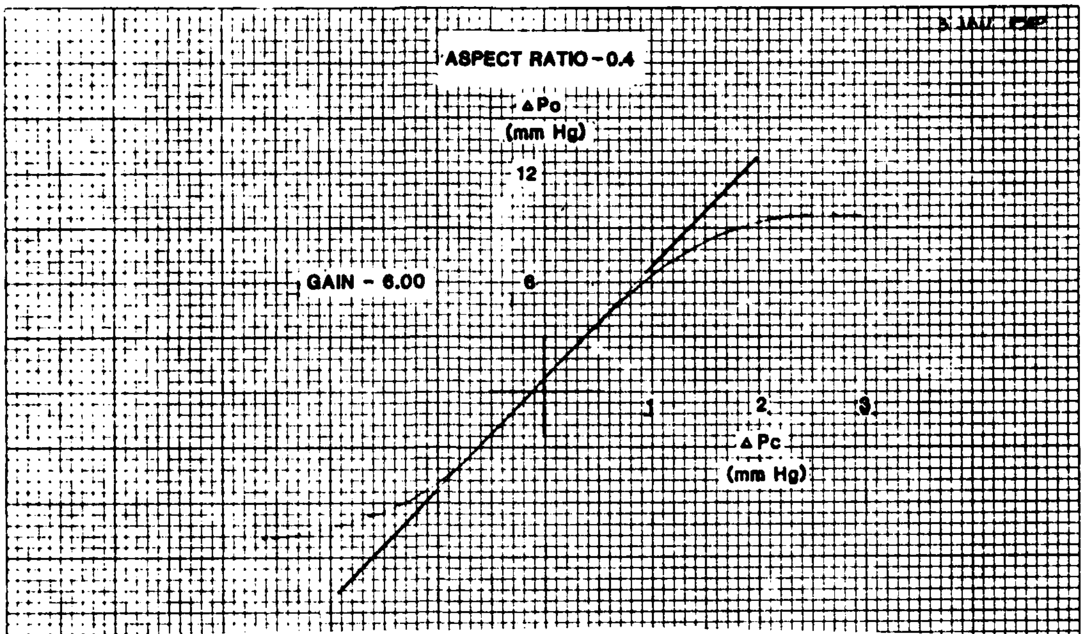

Figure B7. Pre-bond gain curve, module #3.

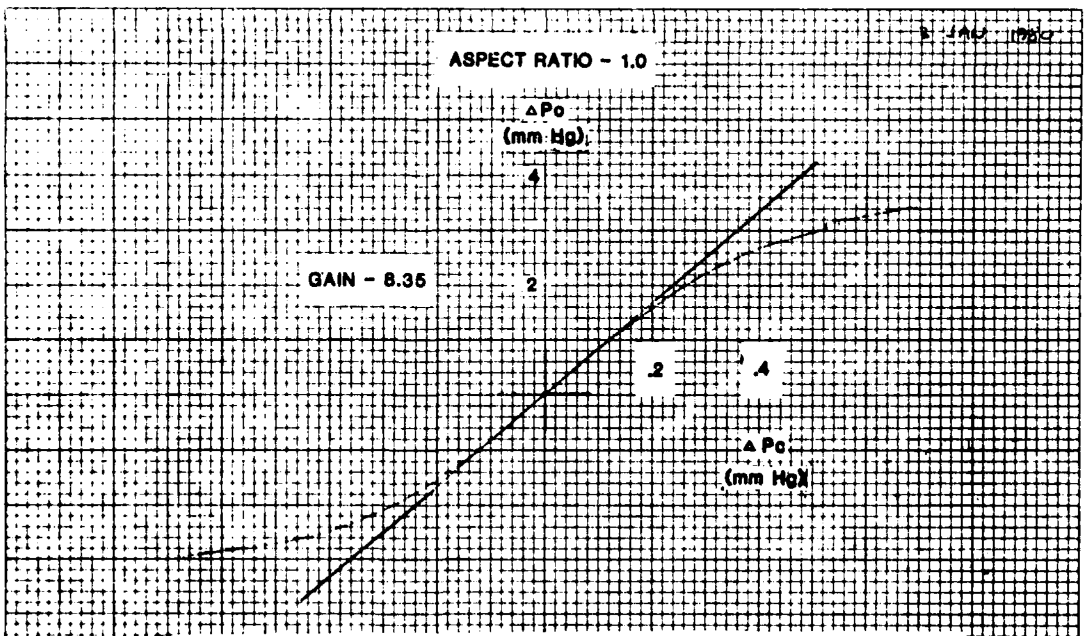

Figure B8. Pre-bond gain curve, module #4.

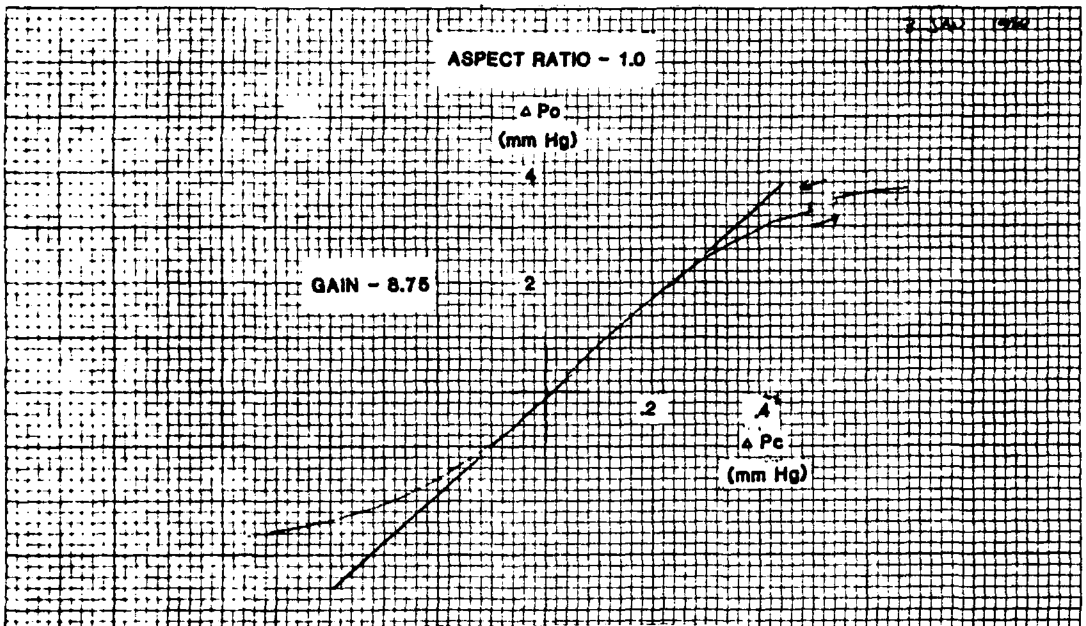

Figure B9. Pre-bond gain curve, module #5.

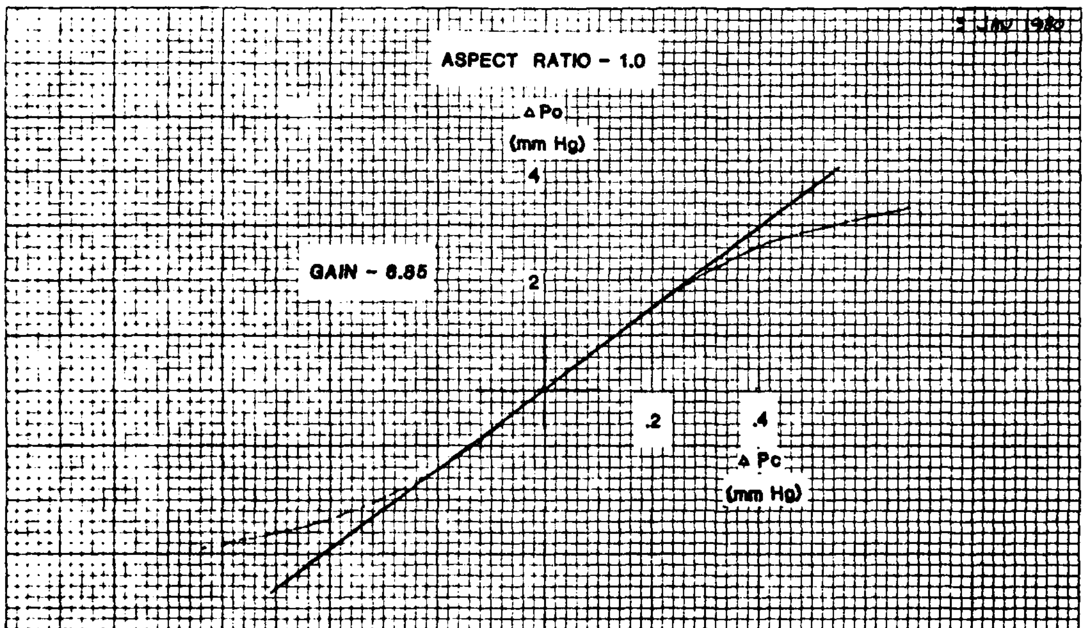

Figure B10. Pre-bond gain curve, module #6.

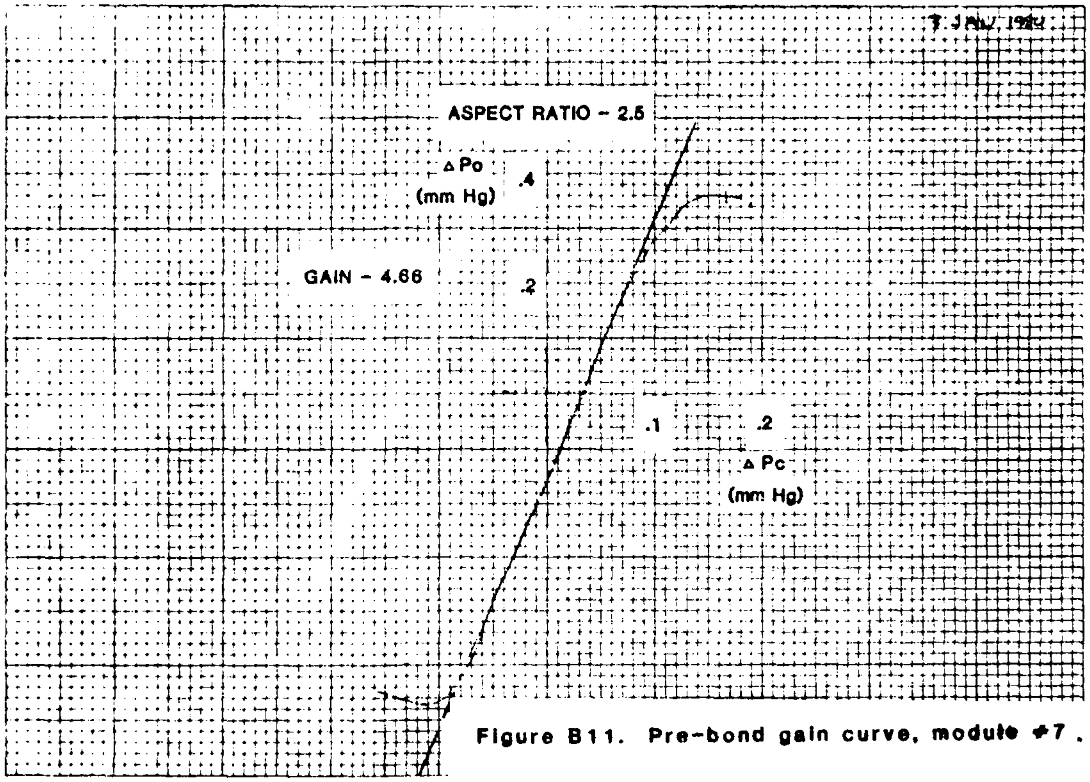

Figure B11. Pre-bond gain curve, module #7.

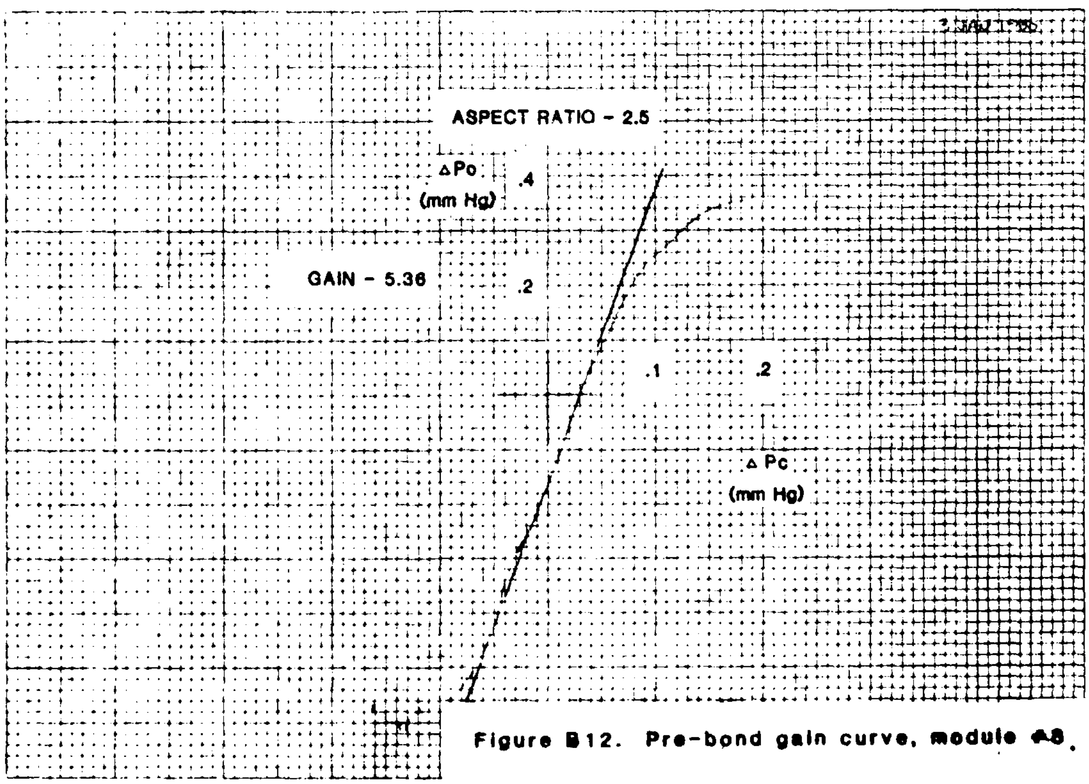

Figure B12. Pre-bond gain curve, module #8.

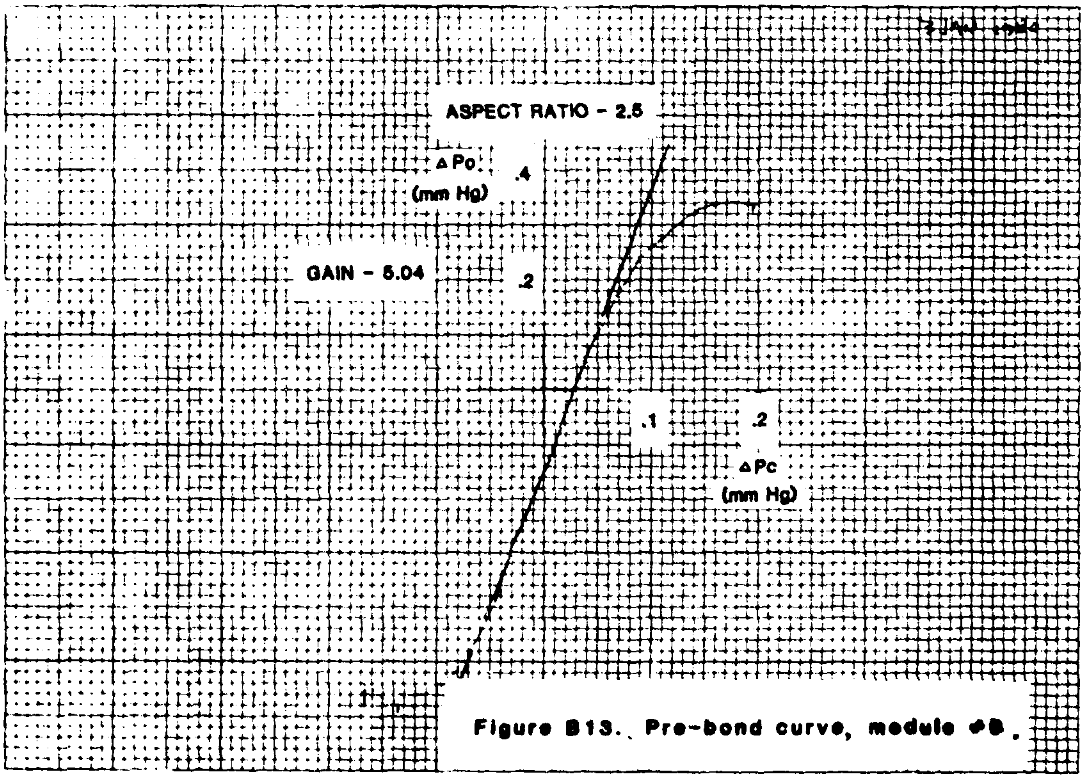

Figure B13. Pre-bond curve, module #B.

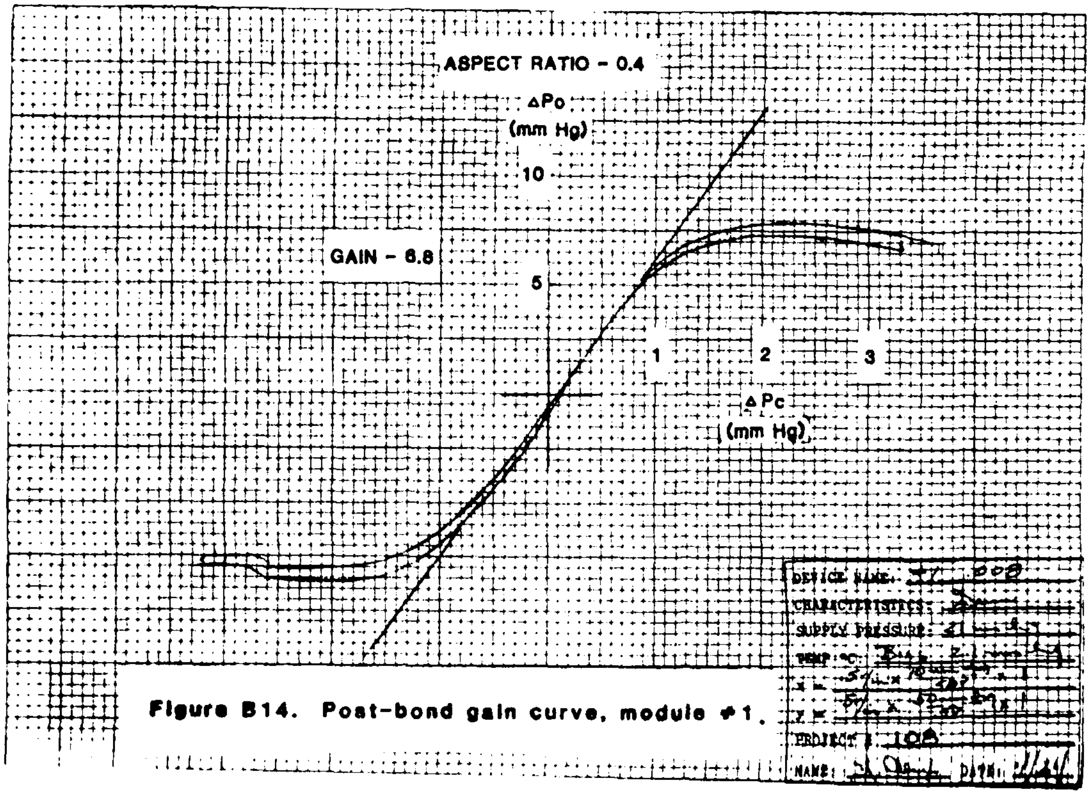

Figure B14. Post-bond gain curve, module #1.

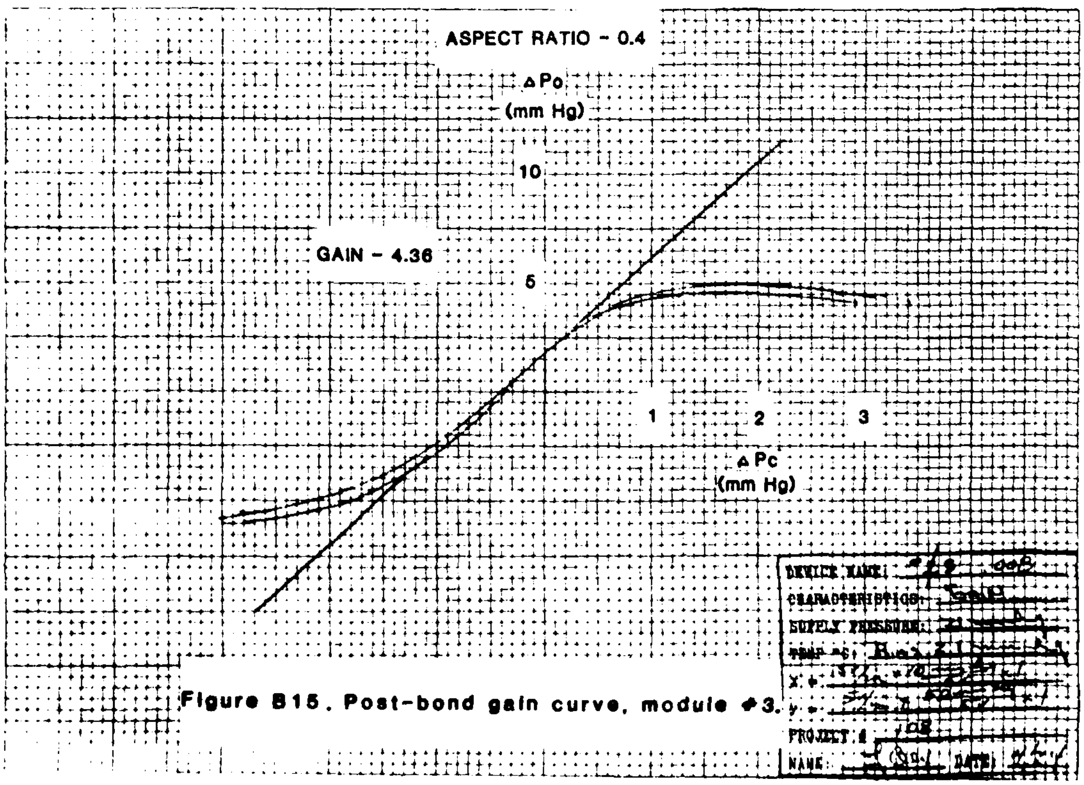

Figure B15. Post-bond gain curve, module #3.

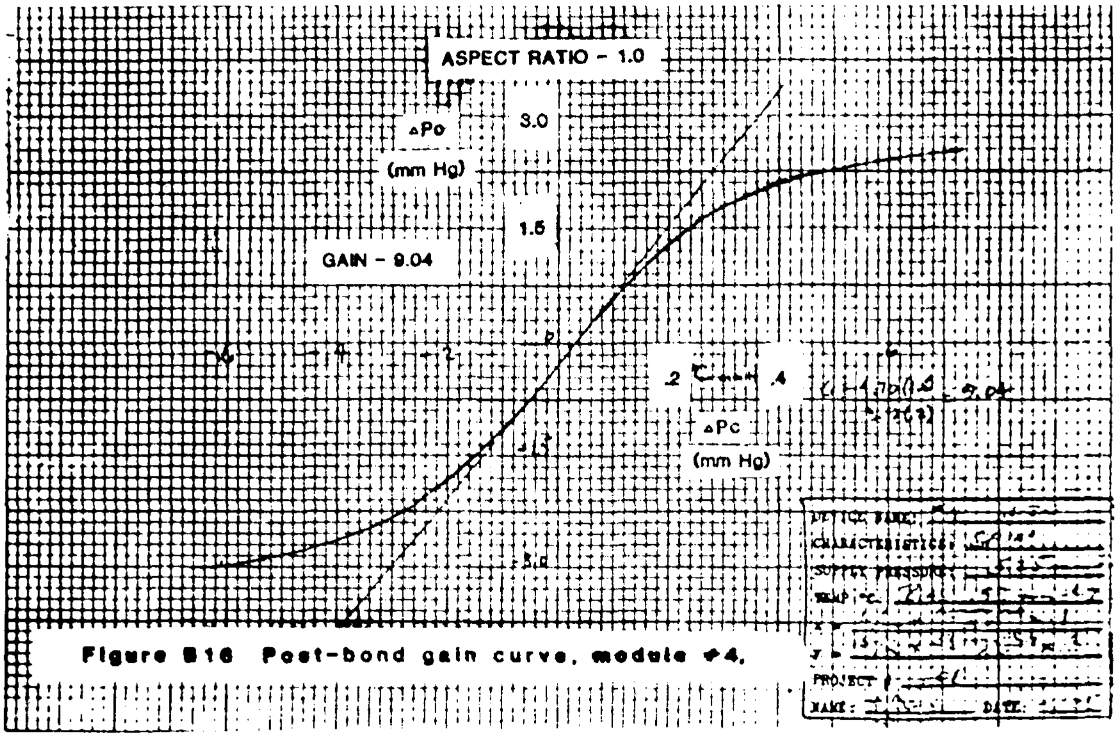

Figure B16 Post-bond gain curve, module #4.

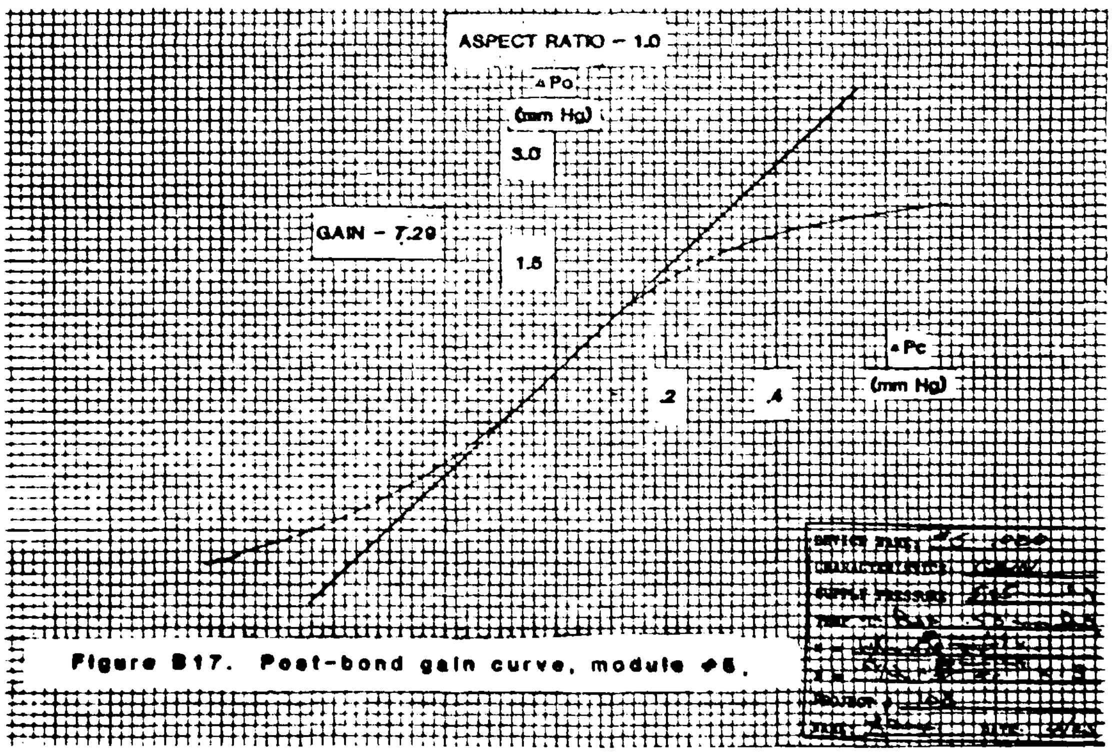

Figure B17. Post-bond gain curve, module #5.

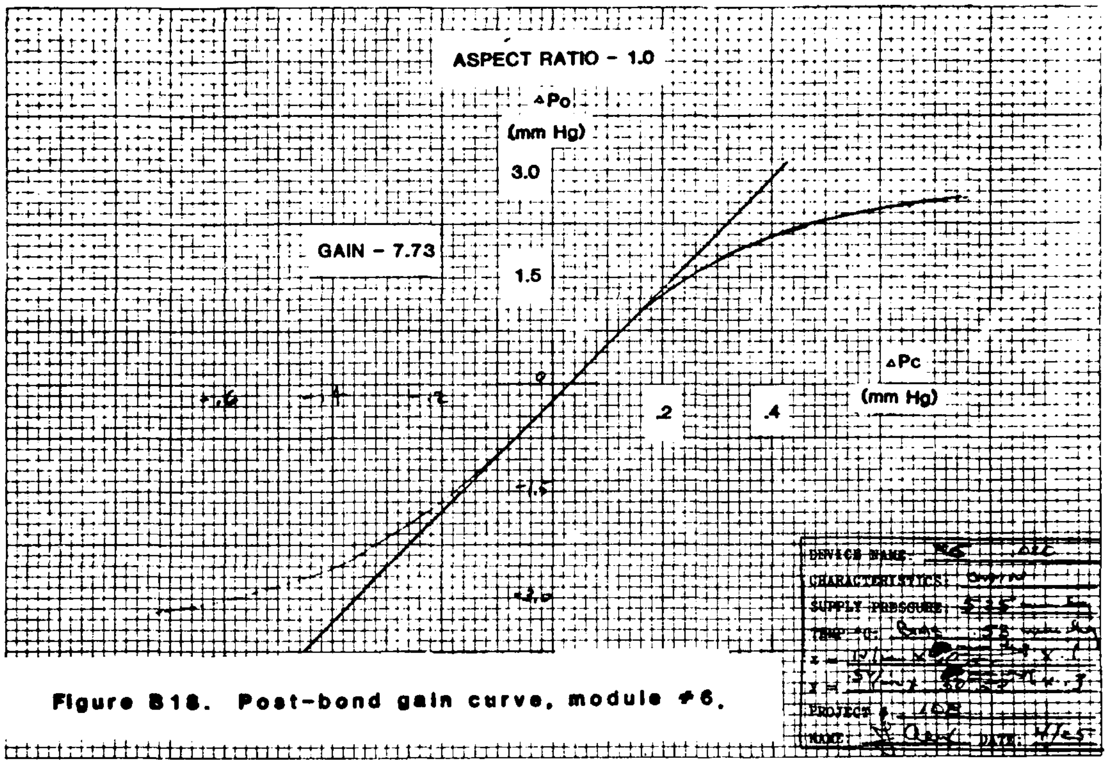

Figure B18. Post-bond gain curve, module #6.

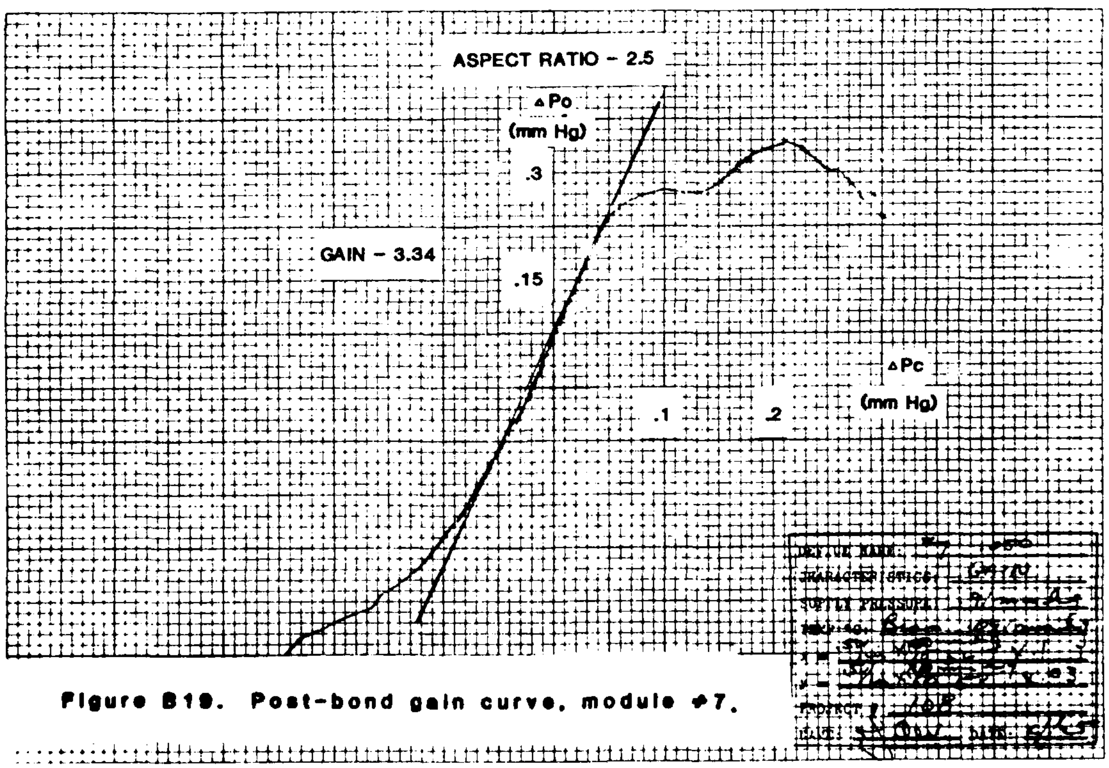

Figure B19. Post-bond gain curve, module #7.

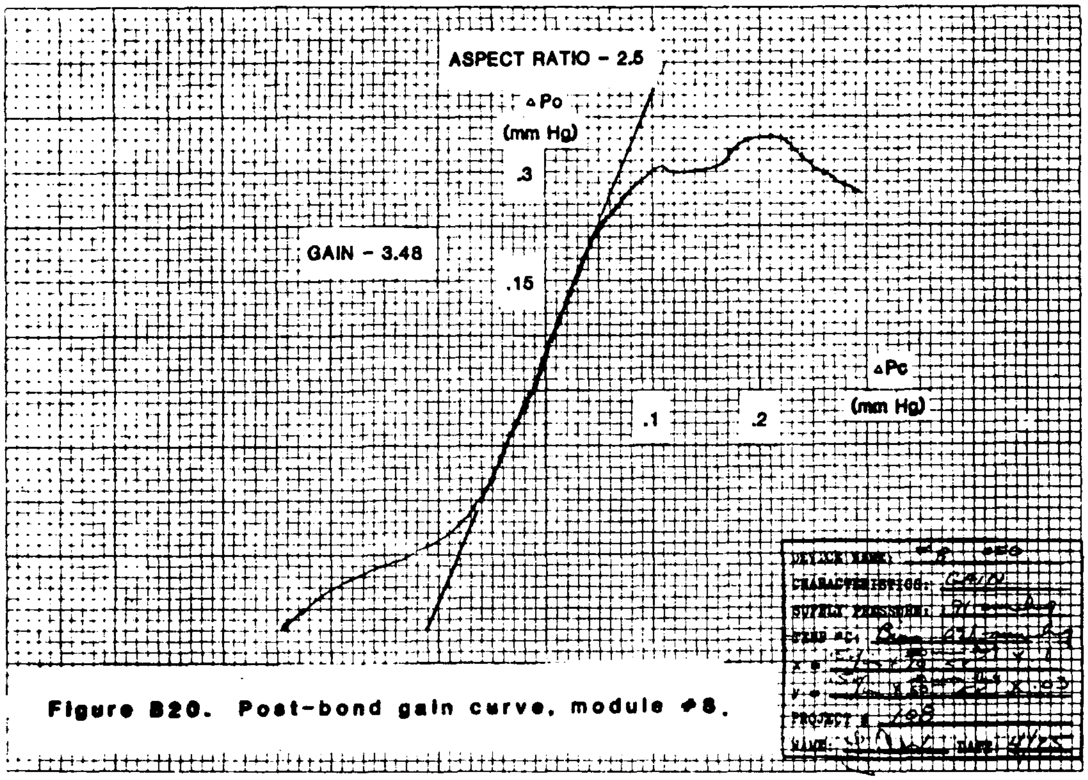

Figure B20. Post-bond gain curve, module #8.

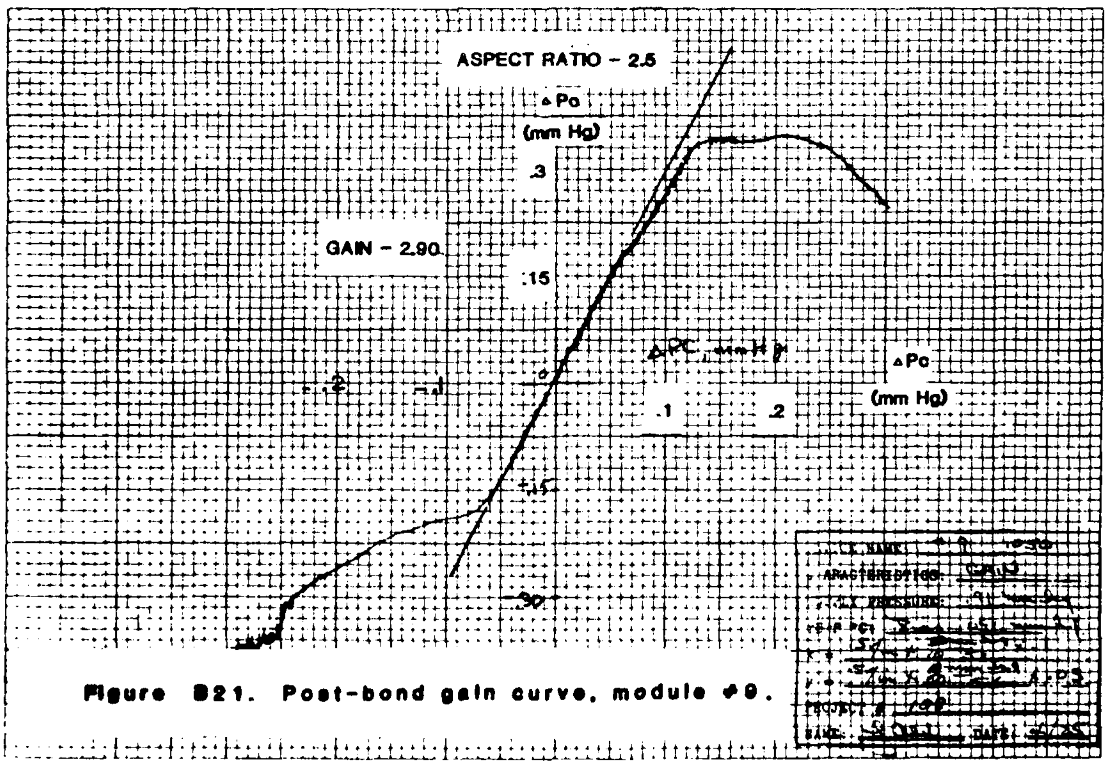

Figure B21. Post-bond gain curve, module #9.

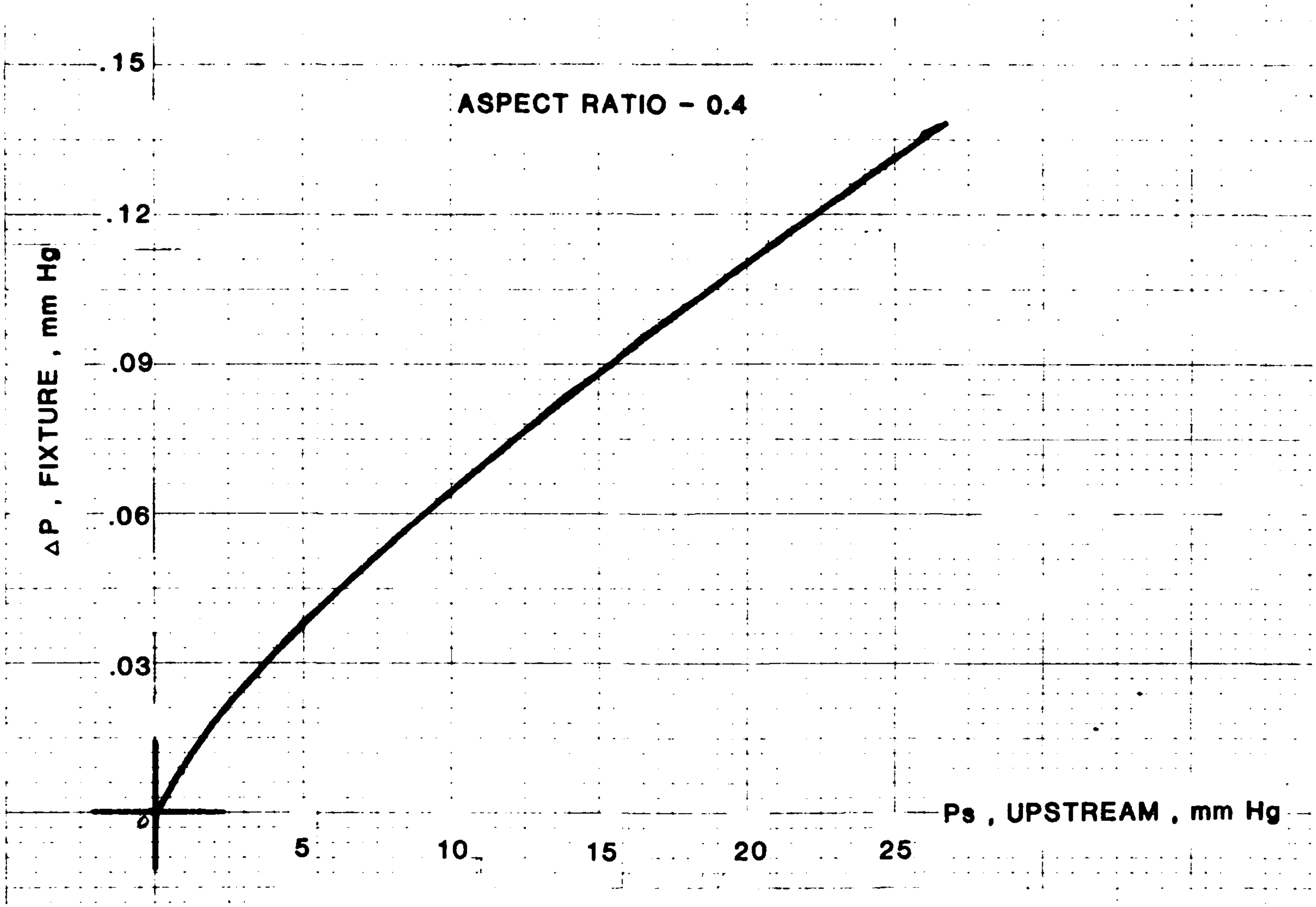

Figure B22. Fixture pressure drop, upstream to inlet port, module #1

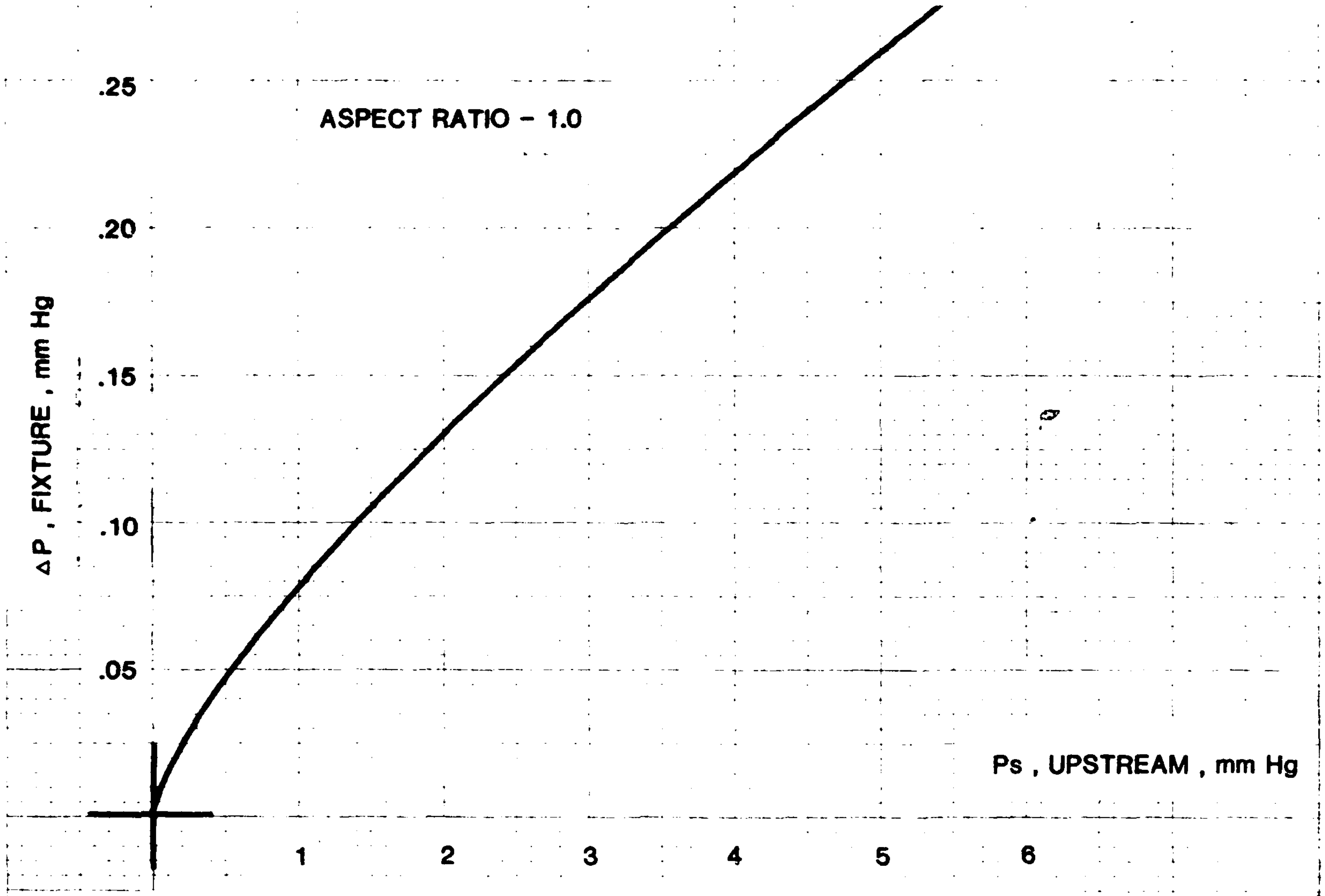

Figure B23. Fixture pressure drop upstream to inlet port, module #4

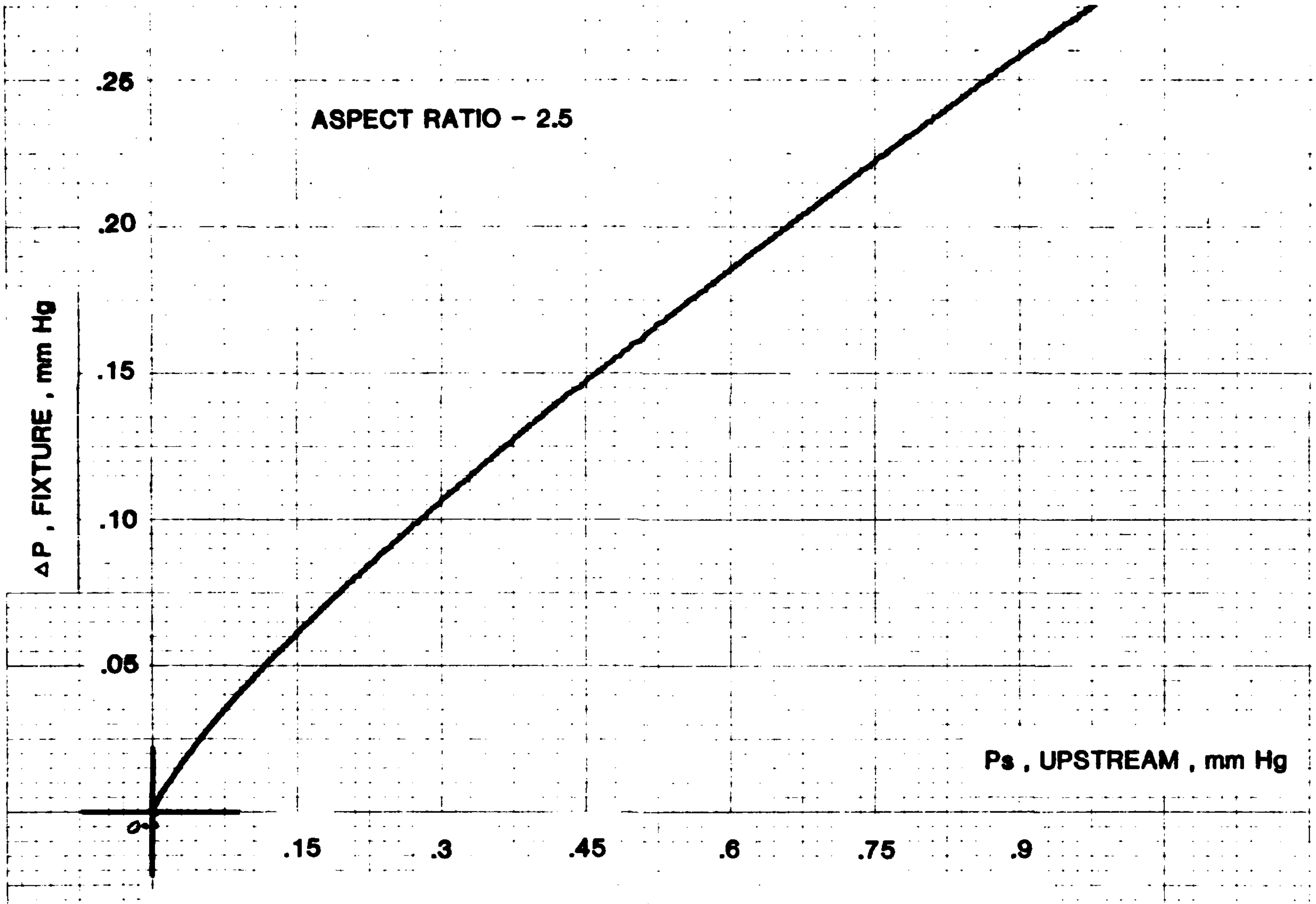

Figure B24. Fixture pressure drop, upstream to inlet port, module #9

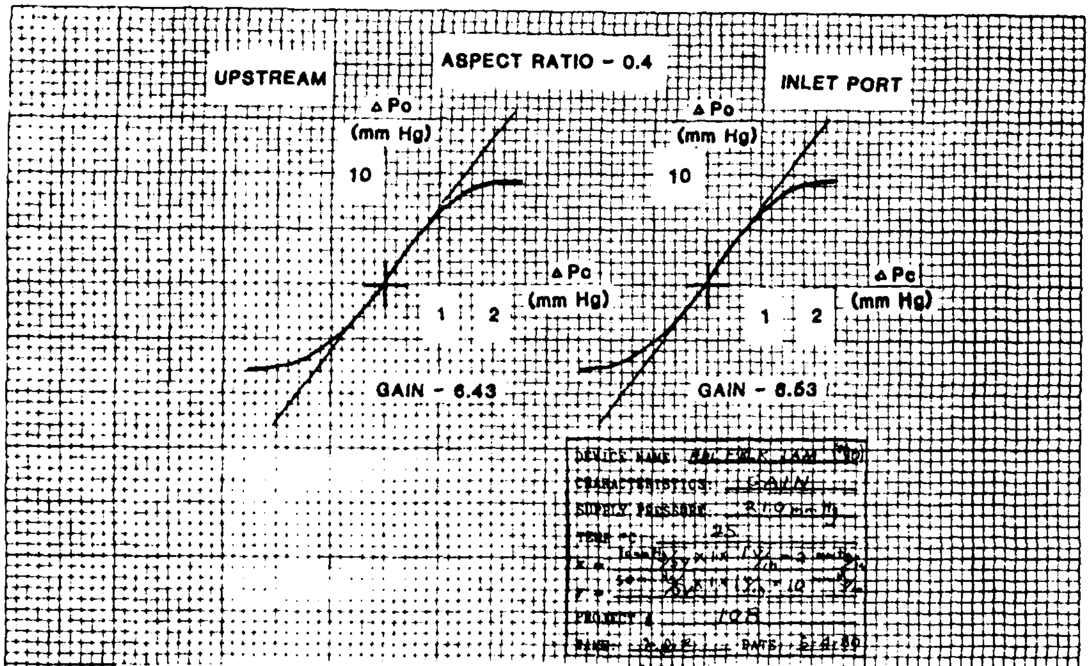

Figure B25. Upstream & inlet port gain curves, module #10.

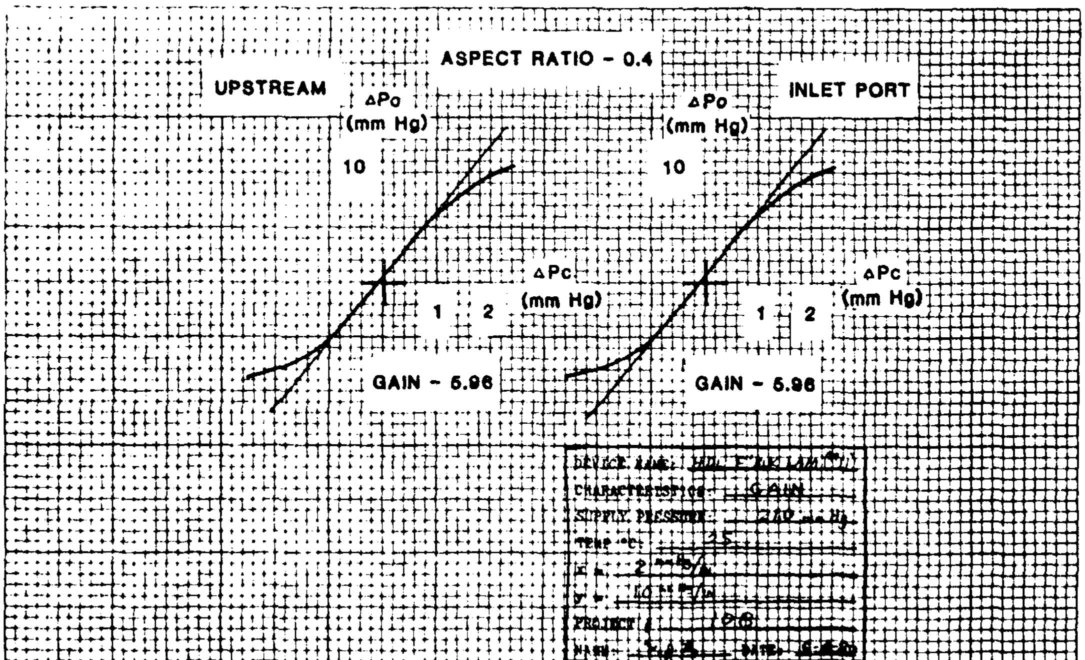

Figure B26. Upstream & inlet port gain curves, module #11.

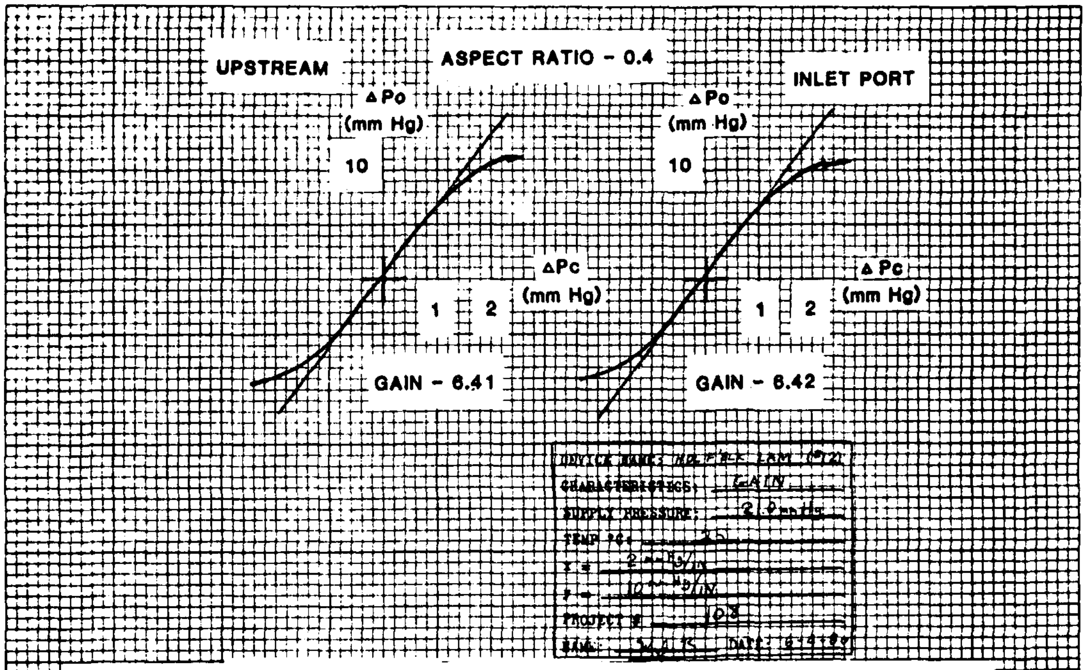

Figure B27. Upstream & inlet port gain curves, module #12 .

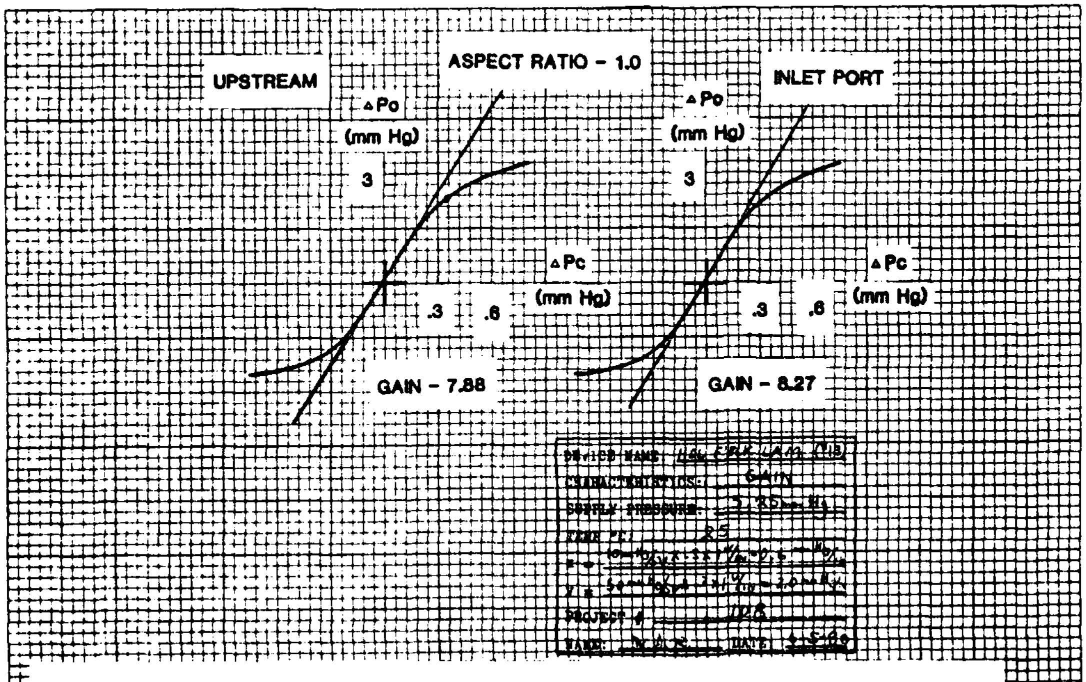

Figure B28. Upstream & inlet gain port gain curves, module #13.

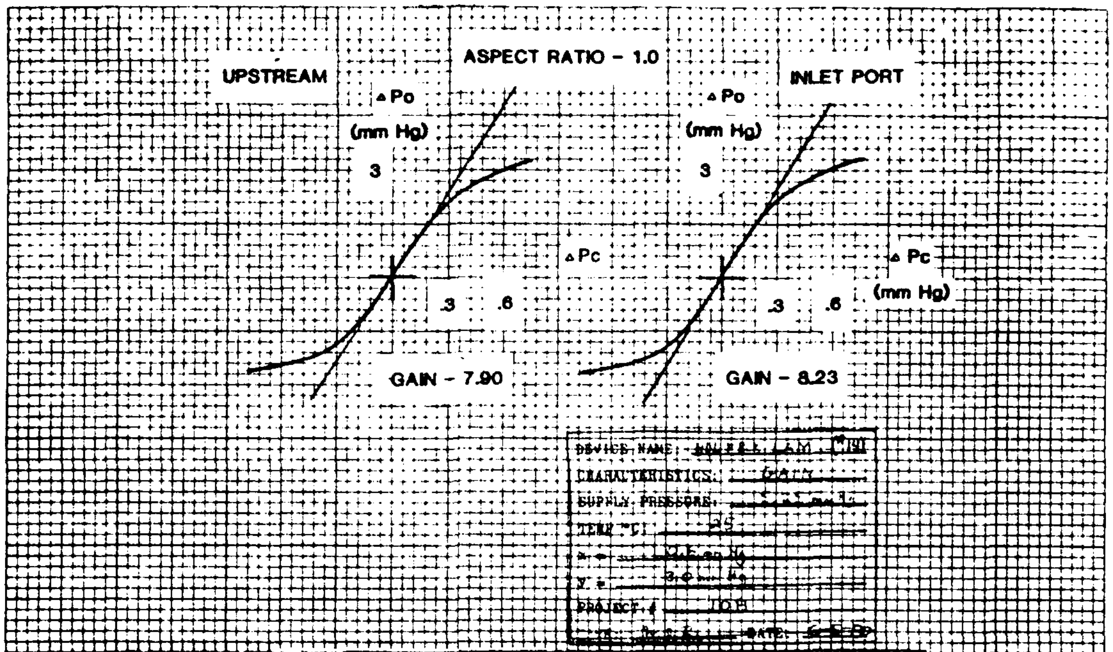

Figure B29. Upstream & Inlet port curves, module #14.

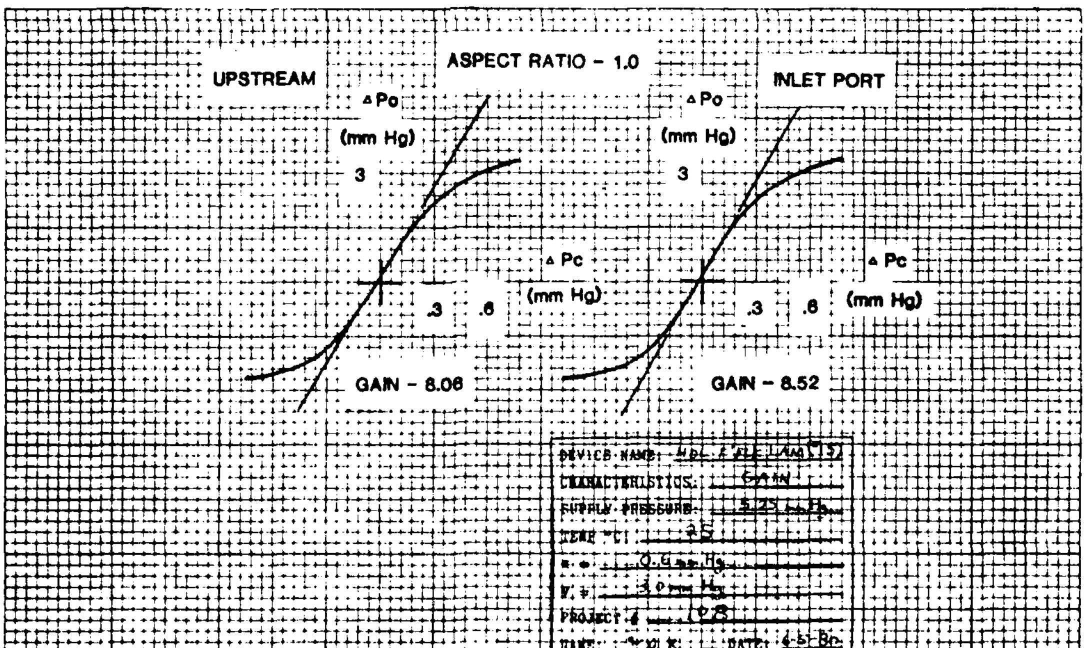

Figure B30. Upstream & Inlet port gain curves, module #15.

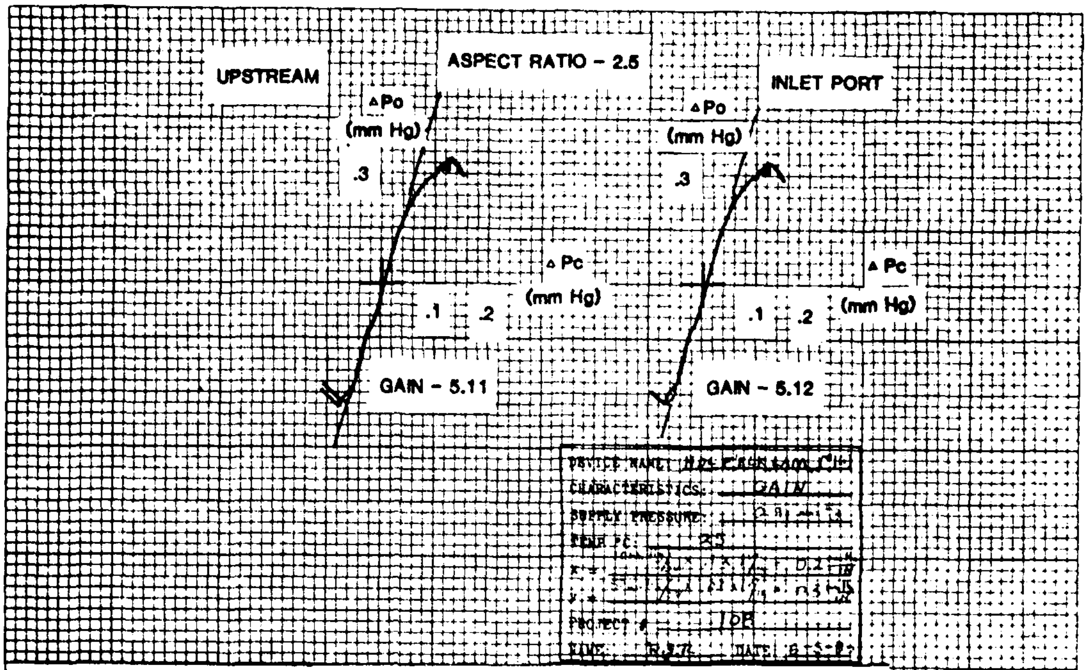

Figure B31. Upstream & inlet port gain curves, module #16.

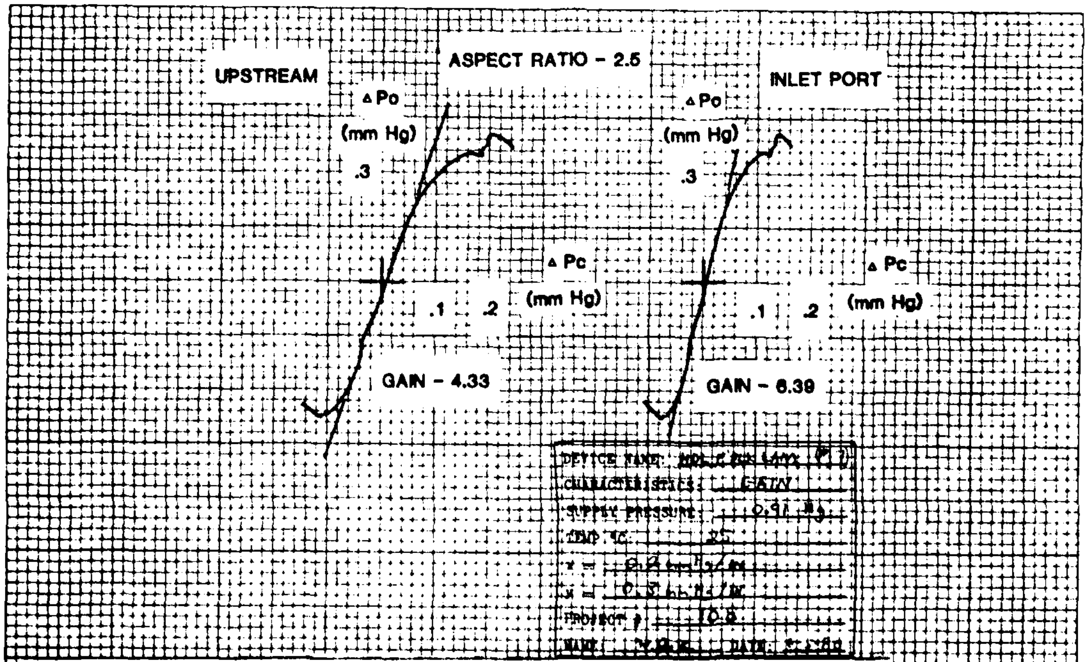

Figure B32. Upstream & inlet port curves, module #17.

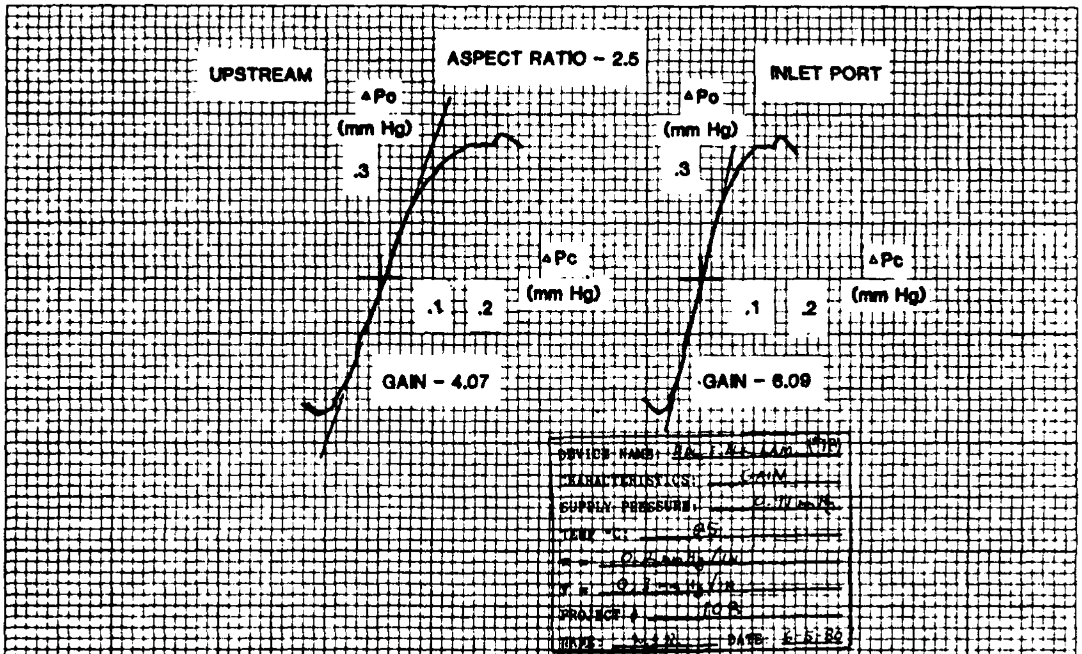

Figure B33. Upstream & inlet port gain curves, module #18.

TABLE B1. GAIN FIXTURE PRESSURE CORRECTION

Laminate No.	Aspect Ratio	Supply Pressure (Upstream) (mmHg)	Gain (Upstream)	Gain (Inlet Ports)
10	0.4	21.0	6.43	6.53
11	0.4	21.0	5.96	5.96
12	0.4	21.0	6.41	6.42
			6.27	6.30 AVERAGES
13	1.0	5.25	7.88	8.27
14	1.0	5.25	7.90	8.23
15	1.0	5.25	8.06	8.52
			7.95	8.34 AVERAGES
16	2.5	0.91	5.11	5.12
17	2.5	0.91	4.33	6.39
18	2.5	0.91	4.07	6.00
			4.57	5.84 AVERAGES
CORRECTION FACTOR (σ = 0.4) = 6.30/6.27 = 1.00 CORRECTION FACTOR (σ = 1.0) = 8.34/7.95 = 1.05 CORRECTION FACTOR (σ = 2.5) = 5.84/4.57 = 1.28				

B1.2 Modified Reynolds Number

A comparison criterion frequently used in the modified Reynolds Number as derived by Drzewiecki[1] and as used by Phillipi[2], is defined:

$$N_{Ra} = \frac{b_s}{\nu}\left(\frac{2P_s}{\rho}\right)^{\frac{1}{2}} \bigg/ \left[\left(\frac{\ell_{th}}{b_s} + 1\right)\left(1 + \frac{1}{\sigma}\right)^2\right] = \frac{N_R}{\left(\frac{\ell_{th}}{b_s} + 1\right)\left(1 + \frac{1}{\sigma}\right)^2}$$

where

N_{Ra} = modified Reynolds number,

b_s = amplifier supply-nozzle width,

ν = fluid kinematic viscosity,

1 Drzewiecki, T.M., A Fluid Amplifier Reynolds Number, II. Proceedings of the 1974 Fluidic State-of-the-Art Symposium, Harry Diamond Laboratories, (October 1974).

2 Phillipi, R. Michael, "A Study of Fineblanking for the Manufacture of Flueric Laminar Proportional Amplifiers," Report No. HDL-TM-77-8, U.S. Army Material Development and Readiness Command, Harry Diamond Laboratories, Adelphi, Maryland, May 1977.

P_s = amplifier supply pressure,

ρ = fluid density,

ℓ_{th} = amplifier supply-nozzle throat length,

σ = amplifier supply-nozzle aspect ratio, and

N_R = Reynolds number.

For the amplifiers used in this program, the parameters are:

b_s = 0.508 mm

ν = 0.1505 cm^2/s

ρ = 1.2046 x $10^{-3} g/cm^3$

ℓ_{th} = 0.508 mm

Using these values

$$N_{Ra} = 251.4 \left(P_s\right)^{\frac{1}{2}}/\left(1 + \frac{1}{\sigma}\right)^2 , \; P_s \text{ in mmHg.}$$

This expression, evaluated for the three aspect ratios of interest, is plotted as a function of P_s in Figure B34.

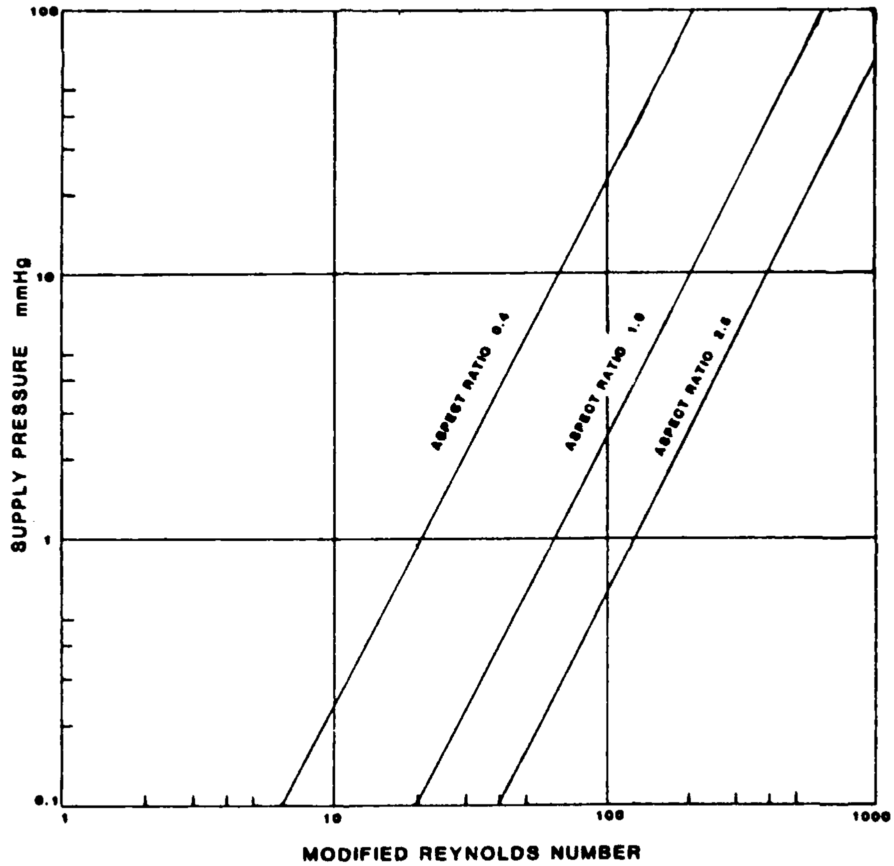

Figure B34. Modified reynolds number

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