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MANUFACTURING METHODS AND TECHNOLOGY
(MANTECH) PROGRAM

CHEM-BRAZE ABRADABLE SEAL ATTACHMENT

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United Technologies Corporation
Pratt & Whitney Aircraft Group
Government Products Division

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An improved Chem-Braze bonding system for attaching sintered abradable seals to compressor blade tip-shrouds was developed. The improved Chem-Braze system incorporates glycerin as an inhibitor to prevent premature evaporation which prolongs working life and allows adequate time to attach seals to engine hardware. Manufacturing guidelines including glycerin concentration, working environment, slurry thickness, bonding pressure, drying and curing parameters, and refurbishing techniques were established. Tooling techniques for attaching abradable seals to engine hardware using this improved system were selected based on a feasibility demonstration which incorporated

20. Abstract *(Continued)*

simulated engine hardware. Nondestructive inspection (NDI) techniques for verifying bond integrity were investigated, but a satisfactory technique was not identified. A preliminary economic analysis indicated significant cost savings for attaching abradable seals to compressor blade tip-shrouds using the improved Chem-Braze system compared to attachment with gold-nickel braze.

SUMMARY

An improved Chem-Braze bonding system for attaching sintered abradable seals such as FELTMETAL® to titanium-, steel- and nickel-base compressor blade tip-shrouds has been developed. The improved Chem-Braze system incorporates glycerin as an inhibitor to prevent premature evaporation thereby increasing the working life of the original Chem-Braze system.

Manufacturing guidelines were established for the Inhibited Chem-Braze (ICB) system. These guidelines include the selection of inhibitor concentration, slurry thickness, bonding pressure, drying technique and curing cycle. Metallography, tensile strength measurements and vibration tests were used to verify the manufacturing guidelines.

A quick and inexpensive chemical stripping technique for refurbishing abradable seals attached with ICB was demonstrated. Tensile strength testing of abradable seals after initial attachment and after stripping and refurbishment showed no decrease in bond strength.

A doctor blade and expandable ring segments were selected as tooling for applying ICB attached abradable seals to engine hardware for a follow-on program. Feasibility of the technique was demonstrated using simulated engine hardware. The demonstrations revealed high quality ICB bonds with a few localized void areas. The voids were caused by inexperience in handling engine-size seals and are not related to the use of the selected attachment composition or tooling technique. Revised handling techniques and seal geometries which should eliminate voids will be investigated in a follow-on program.

Nondestructive inspection (NDI) techniques to identify voids and disbonds in ICB joints were investigated. Two techniques which reveal voids were found, but neither technique is capable of revealing disbonds. Additional NDI techniques will be investigated in a follow-on program.

A preliminary economic analysis demonstrated an appreciable cost savings for attaching abradable seals with the ICB bonding technique compared to attachment with gold-nickel braze. Both materials and labor savings contribute to the economic attractiveness of the ICB system.

FOREWORD

This Final Report covers work performed under Army Contract DAAG46-78-C-0062 by United Technologies Corporation, Pratt & Whitney Aircraft Group, Government Products Division, West Palm Beach, Florida from November 1978 to September 1979.

This project was accomplished as part of the U.S. Army Aviation Research and Development Command 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 material. Comments are solicited on the potential utilization of the information contained herein as applied to present and/or future production programs. Such comments should be sent to: U.S. Army Aviation Research and Development Command, ATTN: DRDAV-EXT, P.O. Box 209, St. Louis, MO 63166.

Work was performed under the technical direction of Mr. Milton Levy of the Army Materials and Mechanics Research Center, Watertown, Massachusetts, and Mr. Fred Reed of the Army Aviation Research and Development Command, St. Louis, Missouri.

Mr. Charles C. McComas, Program Manager for Pratt & Whitney Aircraft Group, Government Products Division, was responsible for the management and execution of the program. Appreciation is extended to Mr. Hal Pettit, P&WA responsible Materials Engineer, and Mr. Steve Narsavage.

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SECTION I

INTRODUCTION

Pratt & Whitney Aircraft Group, Government Products Division (P&WA/Florida) of United Technologies Corporation routinely uses various types of seal attachment methods in the manufacture of gas turbine engine compressors. One system currently in use with the F100/F401 gas turbine engine compressor (stage No. 4 through 13) for blade tip-shroud sealing is metallurgically brazed in place FELTMETAL, a sintered fiber abradable.

This system incorporates a gold-nickel braze and has provided abradability, erosion resistance and reliability in existing F100/F401 engine programs. Because of its advantages, it would be desirable to incorporate sintered abradables throughout the compressor for shroud case alloys of titanium, steel and nickel.

Although effective, the attachment of sintered abradables with metallurgical brazes is relatively expensive and not particularly suited for refurbishment. Removal of the abradable is accomplished by grinding and/or machining, which occasionally causes distortion of lightweight compressor case hardware.

Because of these disadvantages, P&WA/Florida developed the Chem-Braze bonding system for attaching abradable sheet materials like FELTMETAL to compressor case assemblies for blade tip-shroud sealing. The system has demonstrated its viability in preliminary F100 and STAGG engine tests. Attachment involves simple mechanical fixturing and curing, and removal is facilitated by chemical stripping. All operations are relatively fast and inexpensive.

The original Chem-Braze bonding system has one shortcoming. Premature evaporation of the Chem-Braze aqueous slurry occasionally produces substandard bonds. The need for a chemical addition to the Chem-Braze slurry to inhibit premature evaporation, thereby assuring high quality bonds all of the time, was apparent.

Development of the improved attachment scheme was conducted under Contract DAAG46-78-C-0062, "Chem-Braze Abradable Seal Attachment," in three phases. Manufacturing guidelines for 1000°F chemical brazing of sintered abradables to titanium-, steel-, and nickel-base hardware were established during Phase I. Application tooling for a follow-on engine demonstration program was developed during Phase II. The development of preliminary nondestructive inspection (NDI) techniques and standards for verifying Chem-Braze bond integrity was addressed in Phase III. A preliminary economic analysis for attaching abradable seals to compressor case blade tip-shrouds with the improved bonding system completed the program.

SECTION II

TECHNICAL DISCUSSION

Experience with the prior Chem-Braze (Sermabond 481) bond system had shown the need for an improved composition. The prior system did not provide adequate working time to permit easy attachment of abradable seals to full-scale hardware. Premature evaporation of Chem-Braze before abradable seals could be mated to metallic substrates occasionally produced substandard bonding. The requirement for a chemical addition to the existing composition to inhibit evaporation and prolong its useful working life was apparent. Appendix A describes Sermabond 481 Chem-Braze.

PHASE I — ESTABLISHED MANUFACTURING GUIDELINES

Task I — Selection of Suitable Inhibitor

Task I activities were directed at locating a suitable inhibitor and determining its optimum concentration. The preferred working environment and dwell time were also established for the improved composition during Task I. Vibration and tensile strength tests were conducted to verify the selected parameters.

Selection of an inhibitor was based on its miscibility with Chem-Braze and its ability to inhibit evaporation of the existing composition. Candidate inhibitors were mixed with constant volumes of Chem-Braze. The inhibited slurries were placed on glass slides and observed to determine their miscibility and ability to inhibit evaporation. A condensed list of chemicals which were investigated, and the criteria for selection are shown in Table I. The table shows that alcohols, glycols, ketones, hydrocarbons, arenes and other chemicals were investigated, but only glycerin met both criteria. It is the only chemical of the 58 investigated which is miscible and retards evaporation. A complete list of chemicals which were investigated and the specification for the glycerin employed in this program are shown in Appendixes B and C, respectively.

An additional test verified that glycerin inhibits evaporation and prolongs the working life of Chem-Braze. Batches of Chem-Braze which contained 0, 4, 10 and 16 volume percent glycerin additions were applied to glass slides in various thicknesses. The time for excessive evaporation to produce solidified regions on the ICB surface was measured and recorded as that composition's maximum working time. The results of these tests are plotted in Figure 1 and show that as glycerin concentration increases, ICB working life increases.

Initial tensile strength testing of abradable seals attached with ICB revealed the need for an undercoat. The tests showed adhesive failures, that is, failures which occurred at the ICB-substrate interface. It was postulated that the substrates being tested were too smooth. Since P&WA/Florida uses a flame-sprayed nickel aluminide undercoat (Metco 405) in other similar instances, it was logical to investigate the use of the undercoat with ICB seal attachment. Tensile strength test samples with and without the undercoat were prepared and tested, as described in Appendix D. Test results are listed in Table 2 and show that use of the undercoat eliminated adhesive failures and produced higher tensile strengths. Samples which incorporated a Metco 405 undercoat failed cohesively, that is, failure occurred within the abradable seal, not within the bond or at the bond-substrate interface. The desirable cohesive failures are a consequence of the rough surface provided by the undercoat. The use of a 0.001 to 0.003-in.-thick Metco 405 undercoat was selected as part of the preferred manufacturing technique and was employed in the preparation of all samples for the remainder of the program. Appendix E describes Metco 405 nickel aluminide.

TABLE 1. CHEM-BRAZE INHIBITOR ADDITIONS

Inhibitor	Miscible	Inhibits Evaporation
• ALCOHOLS		
• 1-butanol	X	
• Isopropyl alcohol	X	
• Methanol	X	
• 4 Additional alcohols		
• GLYCOLS		
• Glycerin	X	X
• Cellosolve		
• Butyl carbitol		
• Carbowax		
• 15 Additional glycols		
• KETONES		
• Acetone	X	
• MEK	X	
• MIBK	X	
• 2 Additional ketones		
• HYDROCARBONS		
• Chloroform	X	
• Trichloroethylene	X	
• Iso-octane	X	
• ARENES		
• Benzene	X	
• Toluene	X	
• 2 Additional arenes		
• OTHERS		
• Ethyl acetate	X	
• Triethanol amine		
• Varsol		
• 17 Others		

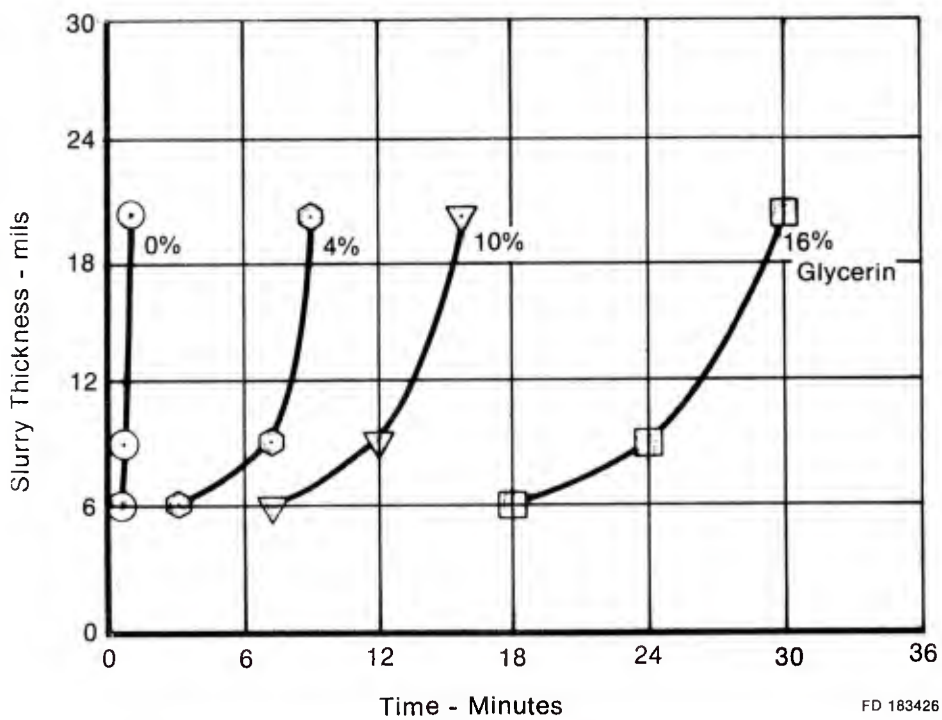

Figure 1. Glycerin Concentration Effect on Working Time

TABLE 2. EFFECT OF UNDERCOAT ON INHIBITED CHEM-BRAZE ADHESION

Glycerin Concentration (vol %)*	*Undercoat*	*Substrate*	*Tensile** Strength (psi)*	*Failure Type*
13	None	AMS 4928	615	Adhesive/ Cohesive
13	Metco 405	AMS 4928	785	Cohesive

* Addition to Sermabond 481.
**Average of four tests per case.

It is reasonable to assume that conditions such as temperature and relative humidity (RH), which are present while attaching abradable seals with ICB, will affect the quality of the bond. Samples were prepared and tensile strength tested to define the preferred working environment. FM515B FELTMETAL abradable seals (Appendix F) were attached to two sets of tensile strength bond bars using a 7 volume percent glycerin addition (7% ICB). The first set was prepared at 60 to 65°F and 60% RH. The second set was prepared at 75 to 80°F and 65% RH. After drying and curing both sets identically, tensile strength tests were conducted as shown in Appendix D. The results of these tests are listed in Table 3 and show tensile strengths of 590 and 480 psi for the first and second sets, respectively. The first set failed cohesively and some adhesive failures were observed in the second set. From these results it was determined that a working environment of 60 to 65°F and 60% RH is preferred. For the remainder of the program steps were taken to assure that these conditions existed while working with ICB.

TABLE 3. EFFECT OF WORKING ENVIRONMENT ON INHIBITED CHEM-BRAZE TENSILE STRENGTH

Glycerin Concentration (vol %)*	*Temperature (°F)*	*Relative Humidity (%)*	*Tensile** Strength (psi)*	*Failure Type*
7	60 to 65	60	590	Cohesive
7	75 to 80	65	480	Cohesive/Adhesive

* Addition to Sermabond 481.
**Average of six tests per case per alloy (AMS 4928 and AMS 5611).

Having selected an effective inhibitor, undercoat and preferred working environment, the optimum inhibitor concentration remained to be defined. FM515B abradable seals were attached to tensile test bars with 0, 4, 7, 10 and 13 volume percent ICB. Tensile strength tests were conducted, as described in Appendix D. The results of these measurements are shown in Table 4 in addition to other characteristics noted for each of the bonding compositions. The table shows that abradable seals bonded with Chem-Braze containing up to 4 volume percent glycerin have tensile strengths of approximately 650 psi, but these compositions do not have acceptable working times. Testing of abradable seals attached with 13% ICB produced an average tensile strength of 730 psi, but the relatively large addition of glycerin significantly reduced the viscosity of the composition. It was judged that the composition is too fluid to attach abradables to engine-size hardware. Abradable seals attached with 7 and 10% ICB failed cohesively at 540 and 630 psi, respectively, and both compositions demonstrated acceptable working lives and viscosities. On the basis of these results, 7 and 10% ICB compositions were selected for additional testing.

Vibration and tensile strength tests were conducted to determine the optimum glycerin concentration. Reverse bending mode vibration test samples were prepared and tested, as described in Appendix G. Test results are shown in Figure 2 and demonstrate that for a given stress, the 10% ICB bonds are capable of surviving more cycles than 7% ICB bonds.

TABLE 4. INHIBITOR CONCENTRATION EFFECT ON CHEM-BRAZE TENSILE STRENGTH AND OTHER CHARACTERISTICS

Glycerin Concentration (vol %)*	*Tensile** Strength (psi)*	*Failure Type*	*Characteristics*
0	643	Cohesive/	Working life
4	655	Adhesive	too short
7	540	Cohesive	Acceptable working
10	630		life and viscosity
13	730	Cohesive	Viscosity too low

* Addition to Sermabond 481.
**Average of six tests per case per alloy (AMS 4928 and AMS 5611).

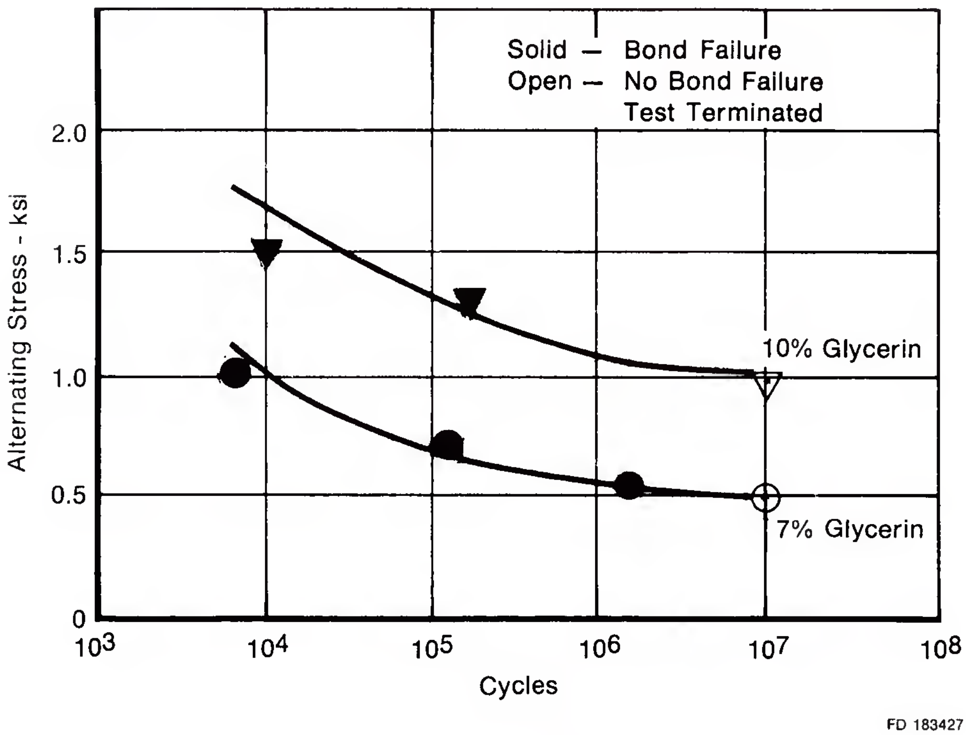

Figure 2. Inhibited Chem-Braze Vibration Test Results

Tensile test samples were prepared by attaching FM515B abradable seals to bond bars with 0, 7, and 10% ICB. Samples were prepared with dwell times (the time between applying bonding cement to components and the actual mating and application of pressure to the assembly) of 0, 5 and 10 minutes. Tensile tests were conducted in accordance with Appendix D, and the results of these tests are listed in Table 5. The table shows decreasing tensile strengths with increasing dwell times for seals attached with 0 and 7% ICB, and no change in tensile strength with increasing dwell time for seals attached with 10% ICB compared to 0% ICB for a 10-minute dwell. All failures were cohesive for 10% ICB attachments, whereas some adhesive failures occurred for 0% ICB attachment. A 10-minute dwell is reasonable for attaching seals to engine hardware using the ICB bonding system. On the basis of the vibration and tensile strength tests, 10% ICB was selected for additional development as the optimum inhibitor concentration.

TABLE 5. EFFECT OF DWELL TIME ON CHEM-BRAZE TENSILE STRENGTH

Glycerin Concentration (vol %)*	*Dwell Time (min.)*	*Tensile** Strength (psi)*	*Failure Type*
	0	550	Cohesive
0	5	488	Cohesive
	10	465	Cohesive/Adhesive
	0	527	
7	5	482	Cohesive
	10	445	
	0	515	
10	5	532	Cohesive
	10	515	

* Addition to Sermabond 481.
**Average of four tests per case per alloy (AMS 4928 and AMS 5611).

Task II — Establish Optimum ICB Slurry Thickness and Bonding Pressure

Attaching porous, abradable seals to compressor case blade tip-shrouds with ICB slurry requires optimizing slurry thickness and bonding pressure. These parameters were established under Phase I Task II.

The quality of ICB bonds was determined by visually inspecting bond joints formed after attaching intentionally deflected FM515B abradable seals to glass slides. Two ICB slurry thicknesses and four bonding pressures for each slurry thickness were investigated. FM515B seals were rolled to permanent deflections of 0.040 to 0.060 in. The deflected seals were attached to 1.5-in.-long glass slides using 10% ICB and the previously established manufacturing parameters. After applying pressure, all samples were dried and cured identically. Figure 3 shows the bonds (as viewed through the glass slides) which were formed for 0.010- and 0.020-in.-thick slurries and bonding pressures of 15, 20, 80 and 200 psi. The figure shows few voids for the 0.010-in.-thick slurry samples, whereas the samples prepared with 0.020-in.-thick slurries show considerably more voids. Apparently a 0.020-in.-thick slurry contains an excessive volume of volatiles which are difficult to evaporate without forming voids. Figure 3 also shows better quality bonds for samples which were fabricated with 0.010-in.-thick slurries and were compressed at 80 or 200 psi compared to samples which were loaded at 15 or 20 psi. Since no appreciable difference in bond quality was observed for the samples compressed at 80 or 200 psi, and prior tests had shown that FM515B seals do not permanently set when compressed at 200 psi, the 200 psi bonding pressure was selected as the more conservative approach. On the basis of these tests, ICB slurry thickness of 0.010-in. and 200 psi bonding pressure were established as preferred manufacturing guidelines.

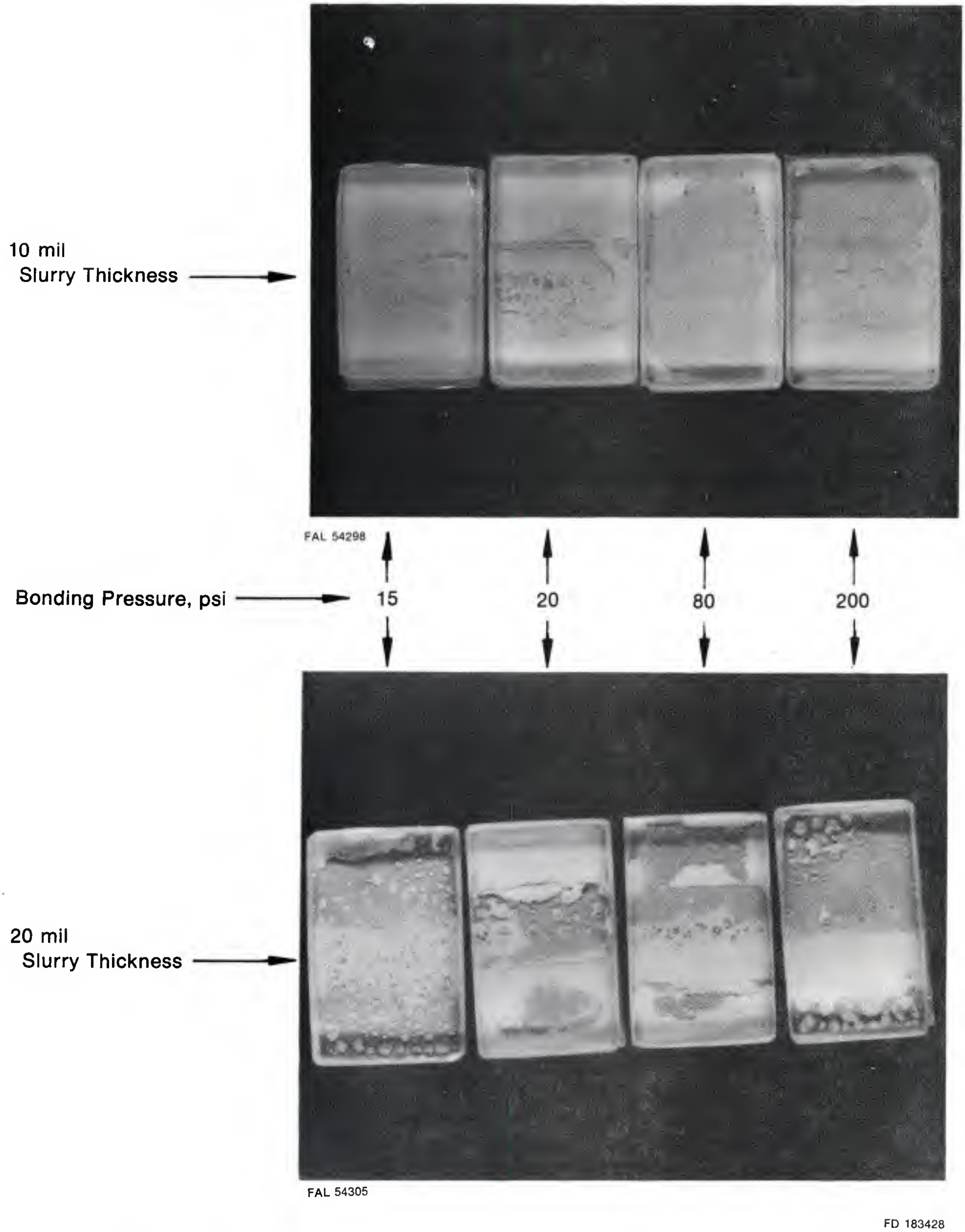

Figure 3. Inhibited Chem-Braze Slurry Thickness and Bonding Pressure Effects

Task III — Establish Drying, Curing and Refurbishment Guidelines

The only manufacturing guidelines remaining to be defined were drying, curing and refurbishment. These parameters were established in Phase I, Task III.

After mating abradable seals to metal alloys with ICB and applying pressure, it is necessary to dry and cure the ICB to complete the bonding process. Metallography was employed to determine that drying for a minimum of 12 hours at ambient temperature followed by 1 hour at 175°F minimizes porosity in ICB bonds.

Abradable seals were attached to metal substrates using 10% ICB and the previously selected manufacturing parameters. After applying pressure, the samples were dried at ambient temperature for 0, 2 or 12 hours before identically curing all samples. Sections of the samples were examined metallographically and are shown in Figure 4. The figure shows less porosity in the ICB bond which was dried at ambient temperature for 12 hours compared to the bonds which were dried for 0 or 2 hours.

Additional samples were dried for 12 hours at 60 to 65°F, and were then dried at 140, 175 or 200°F for 1 hour before identically curing all samples. Figure 5 contains cross section photomicrographs of these samples and shows excessive porosity in the ICB bond which was dried at 200°F. Less porosity is present in the ICB bond which were dried at 140 or 175°F. Since the latter two samples show nearly the same amount of porosity, the more conservative approach of drying at 175°F for 1 hour was selected as the preferred method.

The cure cycle, which had been established for the prior Chem-Braze composition, was selected as a starting point for establishing an improved cycle for the ICB system. The cycle involves accumulative exposure to 200, 360, 450, 700 and 1000°F with 1 hour residence at each temperature. FM515B seals were attached to metal substrates using the selected manufacturing parameters and the previously developed cure cycle. Weight loss measurements for samples which were removed after exposure to each of the previous cure cycle temperatures are shown in Figure 6. The figure shows that little, if any, additional weight loss occurs at 360°F. Therefore, this stage was eliminated resulting in the selected cure cycle; however, all of the selected manufacturing parameters are listed to summarize the entire process.

1. Apply Metco 405 undercoat to metal substrate
2. Add 10 volume percent glycerin to SermaBond 481
3. Apply 0.010-in.-thick ICB slurry
4. Mate seal to substrate and apply 100 to 200 psi load
5. Dry at 60 to 65°F for minimum of 12 hours
6. Dry at 175°F for 1 hr
7. Increase temperature at 1°F/minute to 200°F and hold 1 hour
8. Release load
9. Increase temperature from 200 to 450°F at 5°F/minute and hold 1 hour
10. Increase temperature to 700°F at 10°F/minute and hold 1 hour
11. Increase temperature to 1000°F at 10°F/minute and hold 1 hour.

This procedure was used to prepare tensile test samples. Test results for these seal attachments were previously reported in Table 5 and demonstrate that the procedure produces high quality ICB bonds.

Prior experience demonstrated the suitability of a chemical stripping technique for removing abradable seals which are attached using the original Chem-Braze bonding system. It was shown that the same stripping technique can be used to easily remove seals which are attached with the improved ICB bond and prepare the substrate for refurbishment.

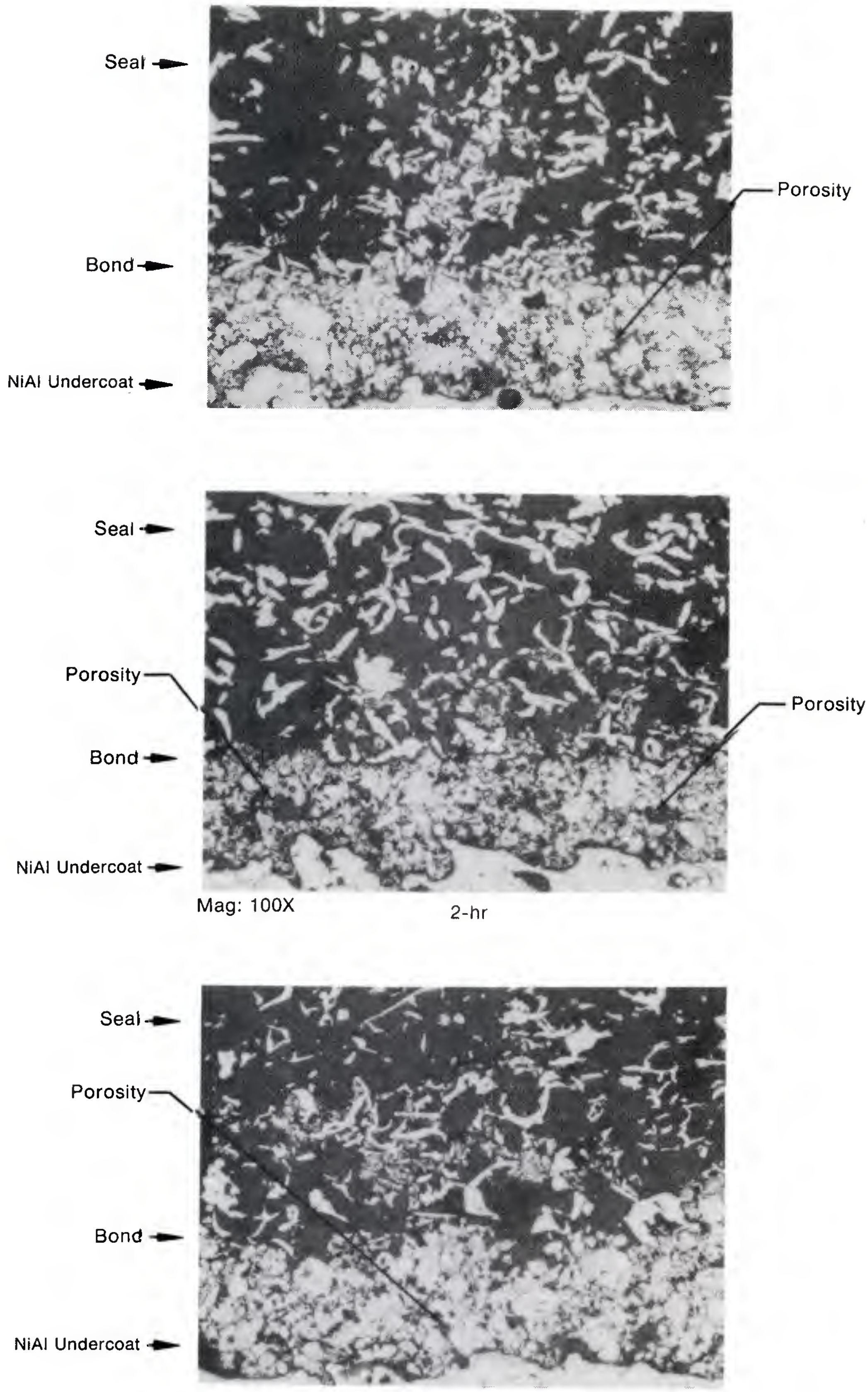

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Figure 4. Effect of Ambient Temperature Drying Time on Inhibited Chem-Braze Porosity

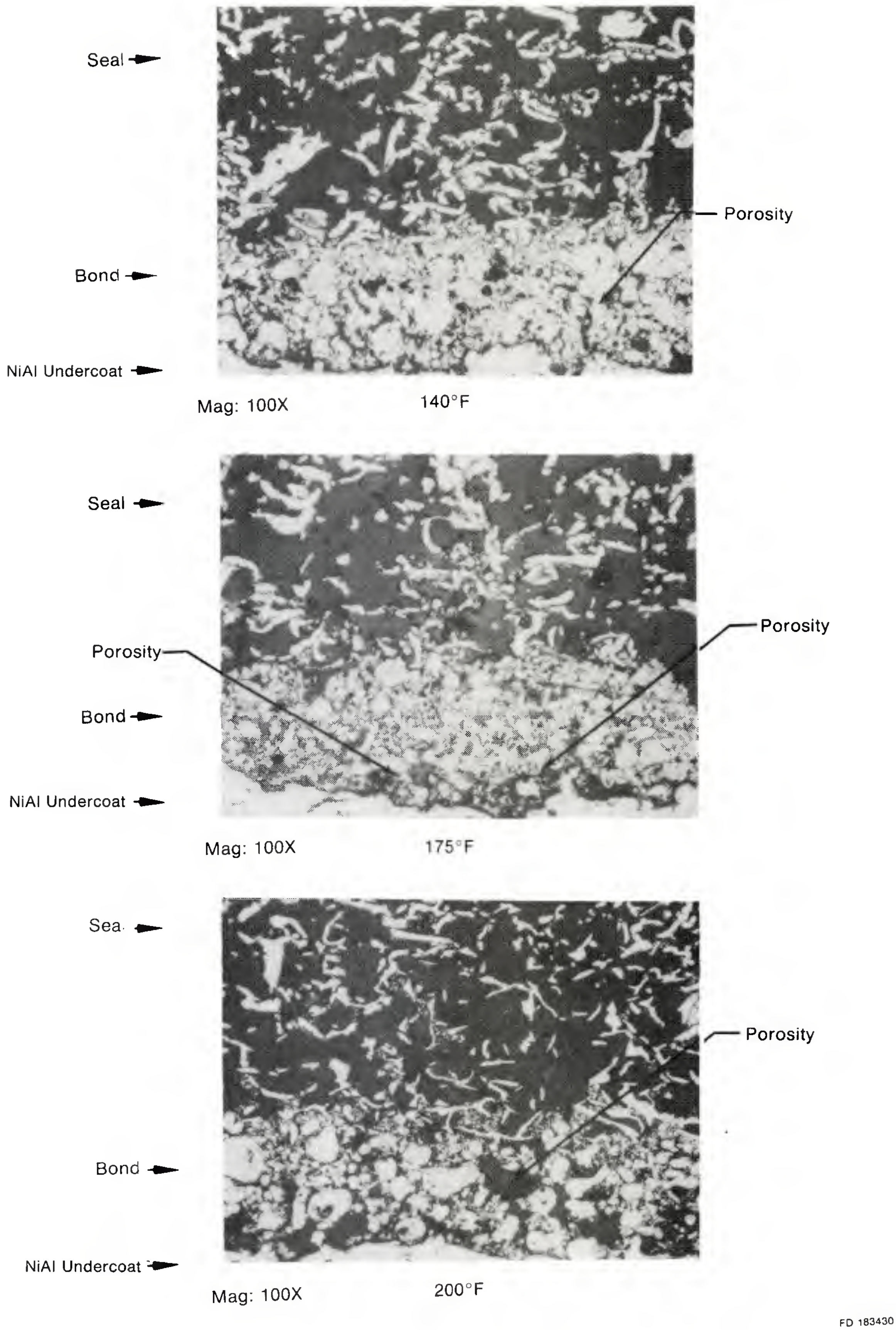

Figure 5. Effect of Drying Temperature on Inhibited Chem-Braze Porosity

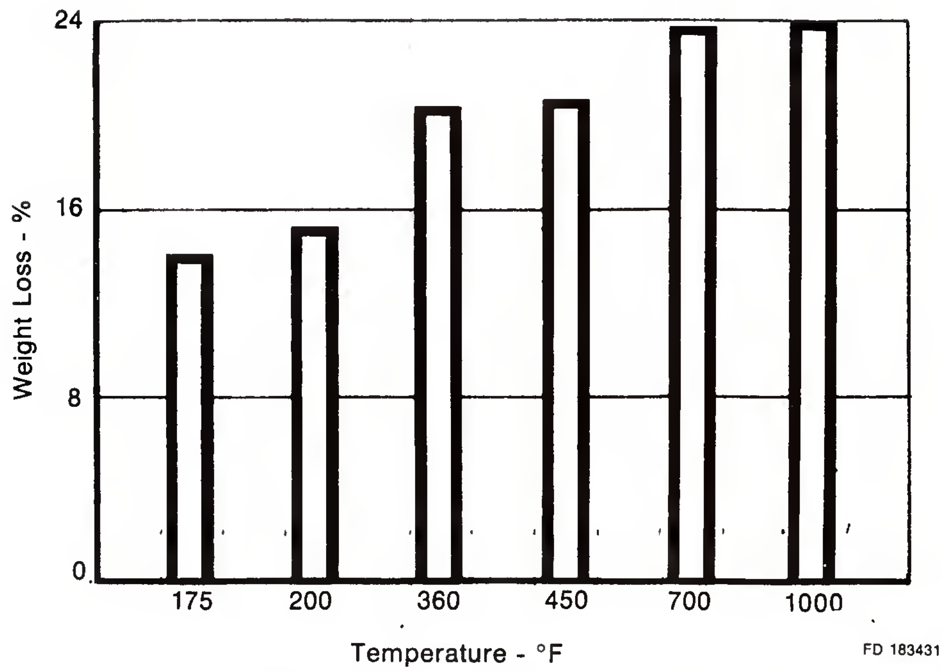

Figure 6. Inhibited Chem-Braze Cure Cycle Weight Losses

FM515B abradable seals were attached to AMS 4928 and AMS 5611 (Appendix H) tensile strength bond bars using the selected manufacturing guidelines. Tensile strength tests were run before immersing the bond bars in 60% aqueous sodium hydroxide (NaOH) at 180°F for 1 hour to remove the seals and ICB. The bond bars were rinsed in tap water and lightly grit blasted with 30-grit SiC to complete the process and fully prepare the surface for refurbishment. The entire process of rebonding virgin abradable seals was repeated using the selected ICB manufacturing process except for the application of a Metco 405 undercoat. It was judged that the original undercoat remained intact and did not need to be replaced. This fact demonstrated just how light the grit blasting operation is and its suitability for use with lightweight compressor hardware. Tensile strength tests were conducted for the refurbished bond bars. Figure 7 compares tensile strength results for original and refurbished seal attachments and shows tensile strengths of 535 and 620 psi, respectively. An increase in strength for the refurbished seal attachment demonstrates that the chemical stripping technique is suited for ICB bonds.

PHASE II — APPLICATION TOOLING AND SIMULATED ENGINE HARDWARE DEMONSTRATION

The manufacture of compressor blade tip-shroud abradable seals attached with ICB requires the definition and demonstration of tooling. Tooling requirements include the means to dispense ICB slurry onto mating components and to apply bonding pressure. These tasks were accomplished during Phase II.

Initial trials involved painting ICB slurry onto metal substrates, but it quickly became apparent that this method was incapable of controlling slurry thickness. Therefore, a doctor blade was selected to dispense controlled slurry thicknesses onto substrates, as shown in Figure 8. Doctor blade tools are inexpensive and eliminate operator technique as a variable. It was also found that painting the surface of the abradable seal with just enough ICB slurry to wet it completely prior to mating components produced higher quality bonds. These techniques were developed early in the program, therefore, they were employed throughout Phase I.

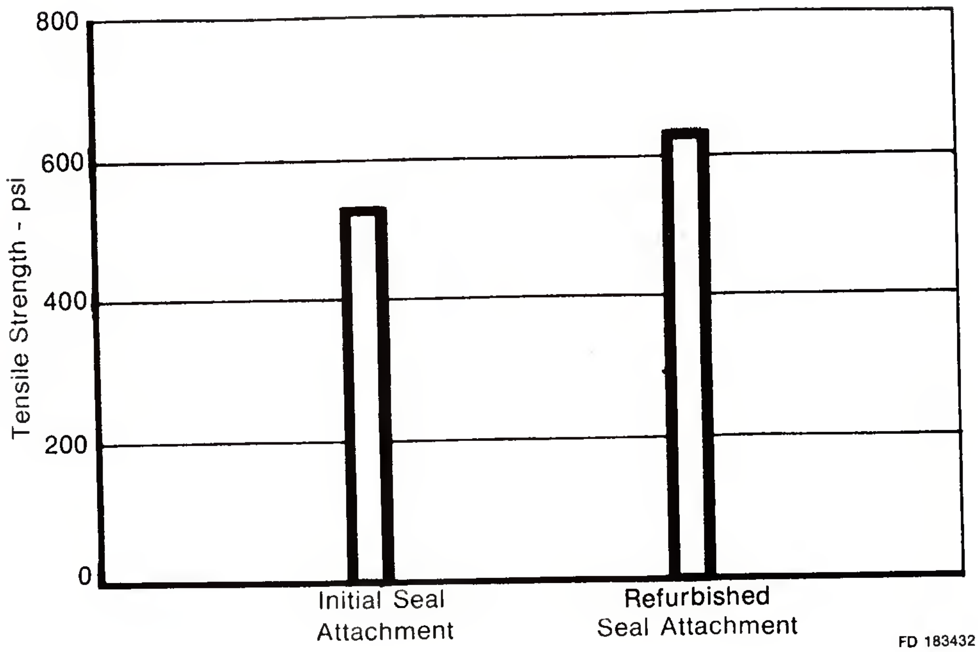

Figure 7. Tensile Strengths of Initial and Refurbished Seal Attachments

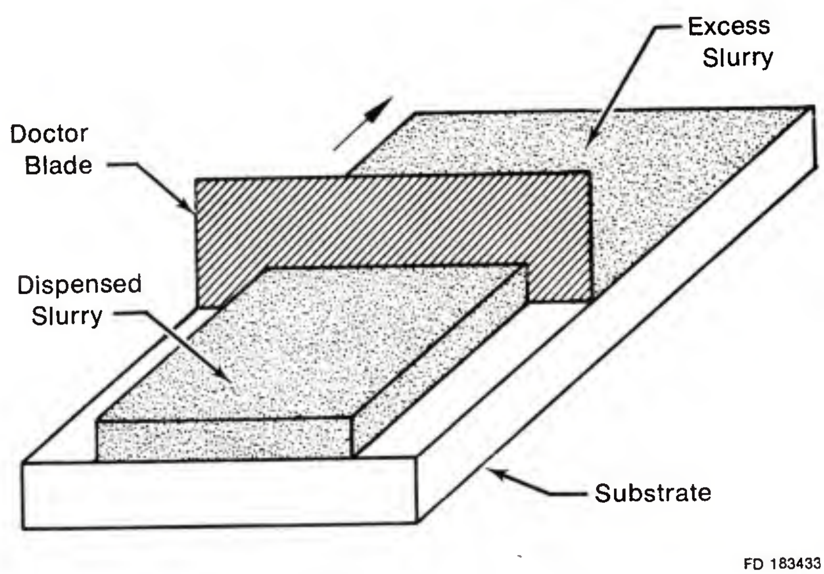

Figure 8. Doctor Blade Technique for Dispensing Inhibited Chem-Braze Slurry

Use of relatively small components during Phase I permitted the use of C-clamps to fixture components and to apply pressure. Scale-up to engine-size hardware during this phase of the program required development of an improved technique to uniformly apply fixturing and bonding pressure. After investigating three tooling schemes, the use of expandable ring segments was selected as the preferred method.

The use of liquid nitrogen shrink fit tooling was rejected since a metal tool with an appropriate thermal expansion coefficient could not be located, and critical tool tolerances required by this process would make the cost prohibitive. The use of air bag tooling was also rejected after realizing that uniform pressure would have to be maintained during ambient and elevated temperature drying cycles. The use of this technique would require a means of compensating for expansion of gases while heating the air bag.

Pratt & Whitney Aircraft/Florida routinely uses expandable ring segment tooling to apply pressure during other bonding operations. Since ICB seal attachment only involves application of pressure up to 200°F, it seemed apparent that inexpensive tooling could be constructed. Wooden expandable ring segments with neoprene rubber inserts were fabricated, as shown in Figure 9. The segments were used to apply fixturing and bonding pressure while attaching FM515B abradable seals to simulated engine hardware. An assembled view of the expandable ring segments, abradable seals and simulated engine hardware is shown in Figure 10. Use of the rubber inserts permitted application of a uniform load and compensated for dimensional variations in tooling, seals and hardware. This fact was substantiated by strain gage measurements, which demonstrated that the selected bonding pressure range was maintained throughout the drying cycle. The strain gages monitor hoop stresses which are converted to bonding pressures using the technique described in Appendix I.

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Figure 9. Expandable Ring Segments

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Figure 10. Abradable Seals Fixtured in Simulated Engine Hardware

The simulated engine hardware demonstration involved attachment of FM515B seals to 6-in. ID by 1-in.-wide metal alloy rings using selected tooling and manufacturing guidelines. Two rings each of AMS 4928, AMS 5536 and AMS 5504 alloys were employed. Visual inspection revealed high quality bonds for each of the base metals investigated except for a few localized void areas as shown in Figure 11. The voids were caused by inexperience in handling full-size hardware and are not related to the use of the selected attachment composition or tooling technique. Two 180-deg abradable seal segments with right angle butt-joints were used in each of the demonstrations. The use of this seal geometry caused excessive handling and operator contact with the ICB composition. Three 120-deg abradable seal segments with mitered joints will be easier to assemble and should alleviate void areas. This approach will be investigated in a follow-on program.

The simulated engine hardware demonstration was also significant in that it involved ICB attachment of abradable seals to a nickel-base alloy (AMS 5536) for the first time in the program. Manufacturing guidelines were established in Phase I using titanium and steel alloys, assuming that guidelines which worked with steel alloys would also be acceptable for nickel alloys. The validity of this assumption was demonstrated by the fact that bond quality proved to be identical for each of the alloys employed in the simulated engine hardware demonstration.

Figure 11. Simulated Engine Hardware Demonstration

PHASE III — ESTABLISH NDI TECHNIQUES AND STANDARDS

Establishing an effective nondestructive means of inspecting the finished chemical bond is necessary to ensure reliability. The task of identifying an NDI technique and standards was undertaken during Phase III.

ICB bond joints with defects were intentionally fabricated and evaluated using X-ray radiographic and sonic NDI techniques. It was found that both techniques are capable of identifying voids, but neither technique is capable of identifying disbonds. Disbonds, or areas which have failed to chemically bond but are not physically separated, occur if the working life of ICB is exceeded before mating components. This situation was simulated by spraying ICB bond areas with a release agent before mating, drying and curing. Neither of the NDI techniques identified these areas. NDI testing of the abradable seals, which were attached to the simulated engine hardware, will be conducted after an acceptable technique is developed in a follow-on program.

Economic Analysis

A preliminary economic analysis shows a 74% cost savings for attaching abradable seals with the ICB bonding technique compared to attachment with gold-nickel braze. The comparison, which is shown in Figure 12, was based on the attachment of FM515B abradable seals to a common compressor stage which contains three separate seals. The comparison includes materials and labor costs for the two braze techniques only. It does not include the cost of abradable seals, tooling and processing equipment. Since seal costs are identical in both cases, and the ICB technique involves relatively low temperature processing, it is reasonable to assume that inclusion of these items in a thorough comparison will result in the ICB technique being even more economically attractive. Details of the economic comparison are shown in Appendix J.

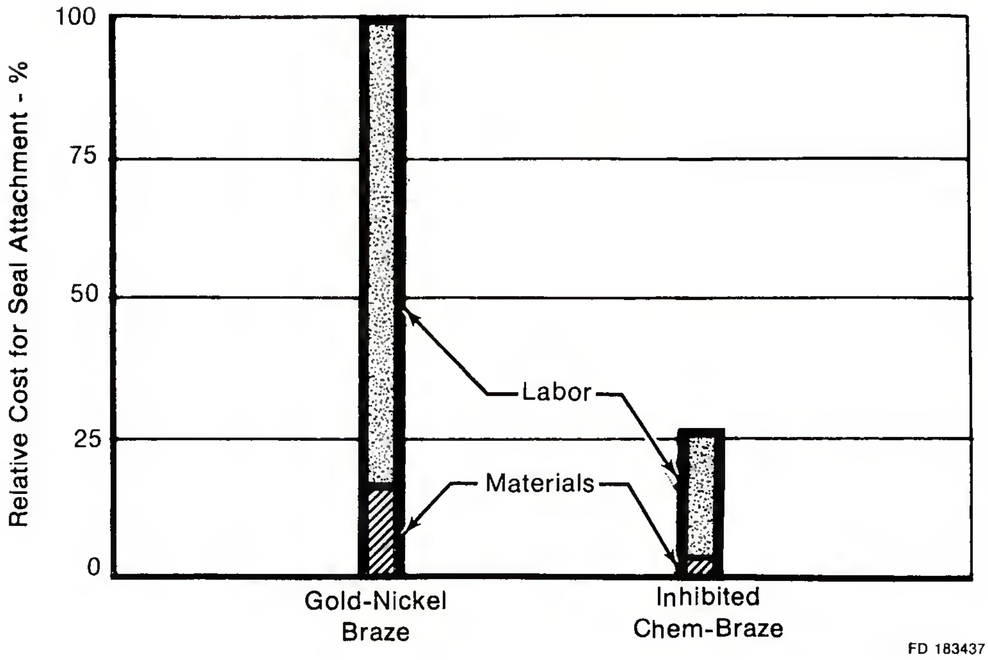

Figure 12. Preliminary Economic Comparison of Brazing Techniques for Common Compressor Stage Seal Attachment

SECTION III
CONCLUSIONS

An improved Chem-Braze bonding system for attaching sintered abradable seals, such as FELTMETAL, to titanium-, steel-, and nickel-base compressor blade tip-shrouds has been developed. The improved Chem-Braze system incorporates glycerin as an inhibitor to prevent premature evaporation which prolongs working life and allows adequate time to attach abradable seals to engine hardware.

Manufacturing guidelines were established for the Inhibited Chem-Braze (ICB) bond system. An addition of 10 volume percent glycerin to SermaBond 481 Chem-Braze is the optimum inhibitor concentration and application of 0.001 to 0.003-in.-thick undercoat of Metco 405 nickel-aluminide eliminates adhesive failures. A doctor blade is the preferred method for applying 0.010-in. thick ICB, the optimum slurry thickness for attaching FM515B abradable seals.

The selected procedure for drying and curing ICB bonds is a two-stage operation. Drying is accomplished by subjecting an assembly to 60 to 65°F for a minimum of 12 hr followed by controlled heating to 200°F while maintaining 100 to 200 psi pressure. After drying, pressure is released, and the bond is cured by subjecting it to incremental temperature increases up to 1000°F.

A quick and inexpensive chemical stripping technique for refurbishing abradable seals attached with ICB was successfully demonstrated. Immersion in aqueous sodium hydroxide at 180°F for up to 1 hour followed by water rinsing and light grit blasting completely prepares hardware for refurbishment.

A doctor blade and expandable ring segments are the selected tooling techniques for applying ICB attached abradable seals to engine hardware for a follow-on program. The doctor blade easily dispenses ICB in the preferred slurry thickness, and expandable ring segments are inexpensive and apply a uniform load to bond joints.

The feasibility of the selected tooling method was demonstrated by attaching abradable seals to simulated engine hardware. Generally, high quality bonds were produced in the demonstrations. Voids which are attributable to inexperience in handling engine-size seals were present in a few localized areas. The voids are not directly related to the use of the selected composition, manufactuirng guidelines or tooling techniques. An improved seal geometry and revised handling techniques which should eliminate voids will be investigated in a follow-on program.

Ultrasonic analysis and X-ray radiography are NDI techniques which can be used to identify voids within ICB bond joints. However, neither technique is capable of locating disbonds. Other NDI techniques will be investigated in a follow-on program.

Significant cost savings can be realized by attaching abradable seals to compressor blade tip-shrouds using ICB. A preliminary economic analysis indicated a 74% cost savings for attaching seals to a single compressor stage with ICB compared to attachment with gold-nickel braze.

SECTION IV
RECOMMENDATIONS

Considerable progress has been made in the attachment of abradable seals to compressor case shrouds utilizing the improved Chem-Braze bonding system. Additional effort is required to determine bonding efficiency for attachment to other compressor case alloys, to develop acceptable NDI techniques and standards, and to attach abradable seals to an Army-supplied compressor case element for future demonstration tests. Continuing work initiated under this contract, these tasks will be accomplished during a follow-on program.

Attachment of abradable seals to compressor case alloys other than the three investigated in this program is desirable. Therefore, manufacturing guidelines and refurbishing techniques for ICB seal attachment to aluminum and magnesium alloys will be established and verified.

Development of an acceptable NDI technique and standards for verifying the integrity of ICB bonds is required. Candidates which will be investigated include scanning laser acoustic microscopy, vibrathermography and a modified C-scan ultrasonic technique.

Tooling for seal attachment to a full-size compressor section will be fabricated and demonstrated by Chem-Brazing abradable seals to an Army-supplied compressor section. The full-size hardware will be utilized in a future demonstration engine program. Refurbishment and NDI inspection techniques will be demonstrated for full-size components also.

APPENDIX A
CHEM-BRAZE (SERMABOND 481)

GENERAL DESCRIPTION

SermaBond 481 is an inorganic ceramic metallic compound that matures to an insoluble, machinable, tenaciously bonded cement. The coating is a two-part mix which consists of aluminum powder in a chromium modified alkali silicate binder and zinc oxide powder. When mixed together and cured to 1000°F, the cement is unaffected by hot or cold water, mineral spirits, jet fuel, hydraulic oils, or hot degreasing vapors up to 1000°F temperatures.

SOURCE

Sermetel Incorporated, Limerick, Pennsylvania

SURFACE PREPARATION

Parts shall be thoroughly cleaned and free from dirt, grit, oil and grease. Superior results are obtained by abrasive cleaning either wet or dry. Coat parts as soon as possible after cleaning.

PREPARATION OF CEMENT

SermaBond 481 is shipped in a two-part mix and has a six-month shelf life. However, when the powders are mixed with the liquid, the shelf life is limited to two weeks. The contents of the two containers should be thoroughly mixed by mechanically stirring at a rate adjusted to keep trapped air to a minimum, (entrapped air causes voids in the cured compound). The mixed material should be allowed to stand 18 to 20 hours before using; this allows time for the reaction of the activator to take place. If less than the total contents are to be mixed, the following quantities should be used:

To 100 ml of Part I by volume
add 4.35 gm of Part II

To 100 gm of Part I by weight
add 2.35 gm of Part II

PRODUCT DATA

481-2 PART I

Weight Per Gallon	14.5 lb minimum
Viscosity	Paste
Principal Pigment	Aluminum
Solids	70% Minimum
Color	Grey

481-2 PART II

Color	White
Specific Gravity	5.6
Structure	Crystalline Powder

TOXICITY

Although SermaBond 481 is of low toxicity, care should be taken to avoid ingestion. Skin contact may produce irritation. In case of skin contact, immediately rinse with running water.

APPENDIX B
CHEM-BRAZE ADDITIVES INVESTIGATED

- Alcohols
  - 1-Butanol
  - Isopropyl Alcohol
  - Methanol
  - Iso-Amyl Alcohol
  - Iso Butanol
  - Allyl Alcohol
  - Cyclohexonal
- Glycols
  - Glycerin
  - Cellosolve
  - Butyl Carbitol
  - Carbowax
  - Ethylene Glycol Monomethyl — Ether
  - Ethylene Glycol Monomethyl — Ether Acetate
  - Diethylene Glycol Monobutyl — Ether
  - Diethylene Glycol Monoethyl — Ether
  - Ethylene Glycol
  - Diethylene Glycol
  - Propylene Glycol
  - Polypropylene Glycol
  - 1, 3 - Butanediol
  - 1, 4 - Butanediol
  - 1, 6 - Hexanediol
  - 1, 5 - Pentanediol
  - 1, 3 - Propanediol
  - Glycidol
- Cyclic Glycols
  - 1, 4 - Cyclohexanediol
  - Inositol
- Ketones
  - Acetone
  - MEK
  - MIBK
  - 25-Hexanedione
  - 4-Hydroxy-4-Methyl-2-Pentanone
- Hydrocarbons
  - Chloroform
  - Trichloroethylene
  - Iso-Octane

- Arenes
  - Benzene
  - Toluene
  - Xylenes

- Phenols

  - Phenol
  - Cresol

- Cyclic Ethers

  - 1, 4-Dioxane
  - Tetrahydrofuran

- Acetates

  - Ethyl Acetate
  - N-Butyl Acetate

- Amines

  - Triethanol Amine
  - Ethanolamine
  - 2-Dimethylaminoethanol
  - Benzylamine

- Acetamide

  - N-Ethylacetamide

- Aldehydes

  - Crotonaldehyde

- Polynuclear Aromatics

  - Tetrahydronaphthalene (Tetralins)
  - 1, 2-Dihydroxyanthraquinone (Alizarin)

- Dicarboxylic Aromatic

  - Dinonyl Phthalate

- Others

  - Varsol
  - Titration Solvent
  - Mineral Spirits

APPENDIX C

GLYCERIN SPECIFICATION

Reagent Grade Glycerin	99.5 vol %
Residuals After Ignition	0.005
Chlorinated Compounds	0.003
Sulfate	0.001
Fatty Acid Esters	0.05
Heavy Metals; e.g., Pb	2 ppm

APPENDIX D

TENSILE STRENGTH TEST SAMPLE PREPARATION AND TEST PROCEDURE

Tensile strength test samples were prepared by assembling 0.9-in. dia abradable seals, as shown in Figure D-1. Abradable seals were attached to bond bars using the manufacturing guidelines, as described in the Technical Discussion (Section II). After completing attachment to the bond bar, the free surface of the abradable seal was bonded to a mating bond bar using 3M Co. EC2186 Scotchweld epoxy. Completed bond bar assemblies were then tensile tested in a Tinius Olsen Testing Machine at a strain rate determined as crosshead speed maintained at 0.005 ±0.002-in. per inch per minute.

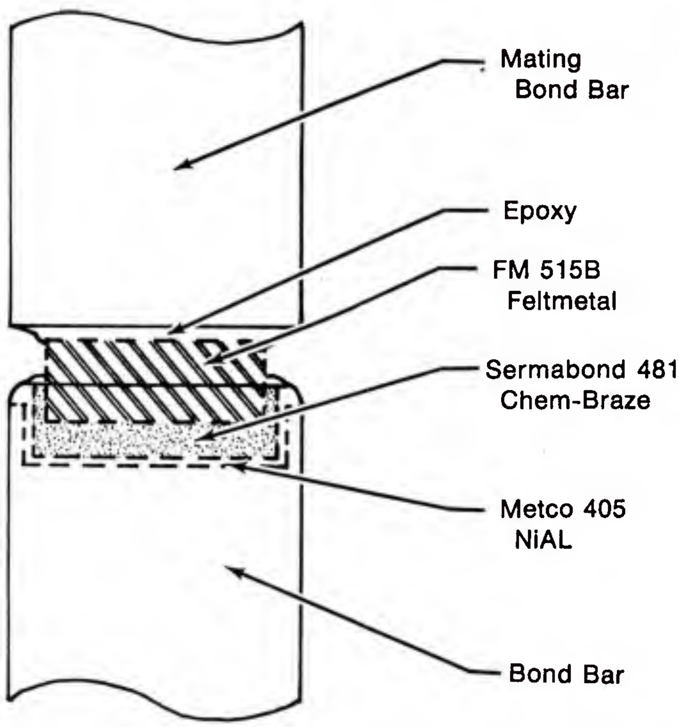

Figure D-1. Tensile Test Schematic

APPENDIX E

METCO 405 NICKEL ALUMINIDE SPECIFICATION

COMPOSITION:

Nickel	80%
Aluminum	20%

EQUIPMENT:

METCO 405 Wire can be sprayed with most METCO Flame Spray Guns. It cannot be sprayed with the METCO Types 5E and 7E Guns, since these high-speed units cannot be slowed down to the 2½ to 3½ feet-per-minute feed rate required. Whenever a Type KT or Type XT Extension is used, a special angular air cap, Cat. No. KT 6-1/8T or XT 6-1/8T, is required.

SPRAYING:

Because of the bright flame and loud noise, eye and ear protection should always be worn when spraying METCO 405 Wire.

Gun	Fuel Gas	Wire Size+ (in.)	Air Cap Size	Air Pres. psi	Lighting Pressure Oxy.	Lighting Pressure Fuel Gas	Flowmeter Readings Oxy.	Flowmeter Readings Fuel Gas	Air	Consumption Metal lb	Consumption Oxy. Cu Ft	Consumption Fuel Gas Cu Ft
4E	Acet	1/8	H	65	41	12	34	29	49	5	75	27
	Prop	1/8	H	55	35	30	49	20	45	5	107	19
	MAPP	1/8	H	55	40	35	40	23	46	5	89	23
8E	Acet	1/8	C*	65	26	8	46	33	49	5	90	29
	Prop	1/8	C*	55	43	35	68	30	47	5	170	30
	MAPP	1/8	C*	55	41	39	69	30	46	5	170	31
K	Acet	1/8	C	60	38	12	42	34	45	5	92	32
	Prop	1/8	D	50	46	37	62	28	38	5	155	28
	MAPP	1/8	D	50	40	40	59	31	38	5	146	32
Y	Acet	1/8	C	65	42	15	48	39	61	5	112	41
	Prop	1/8	D	60	40	37	69	29	59	5	169	29
	MAPP	1/8	D	60			65	33		5		

* Do *not* use the "EC" Air Cap.
+ Use special rear wire guide Catalog No. 8E 162 when using METCO 4E and 8E Guns.

NOTE: Use adapter fittings for MAPP and Propane Gases.

Recommended bond coat thickness for optimum bond: 0.004 to 0.006 in.

Approximate Deposit Efficiency: 75%

Coverage: 119 sq. ft./hr, 0.001 in. thick.

Wire Required: 0.042 lb/sq. ft./0.001 in. thick.

Coating Weight: 0.0312 lb/sq. ft./0.001 in. thick.

Spraying Distance: The spraying distance should be from 4 to 6 in. for the best results. The spraying distance is not as critical with METCO 405 Wire as it is with METCO 404 Powder. Good bond strengths have been achieved at 2 in., as well as 8 in.

Wire Spraying Speed: 3 ± ½ ft/min. is recommended. This rate is slightly lower than that for 1/8 in. dia SPRASTEEL and METCOLOY Wires.

PRECAUTIONS:

There is no tendency for spontaneous initiation of the exothermic reaction. Precautions should be taken when starting to spray METCO 405 Wire. Any excess tip that flies off remains red hot slightly longer than usual. It may be a potential fire hazard.

APPENDIX F

FM 515B ABRADABLE SEAL SPECIFICATION

FM515B seals are manufactured by producing a uniform felt or mat of metal fibers, then sintering and compressing the felt to the required thickness and density. Sintering is carried out at very high temperatures under a reducing atmosphere to produce metallic bonds at all inter-fiber contact points. The seals are manufactured by Brunswick Corporation (Technetics Division, DeLand, Florida) with a nominal thickness of 0.125 in. Typical mechanical properties for FM515B seals are shown in Table F-1, and the seal's fiber alloy composition is listed in Table F-2.

TABLE F-1. TYPICAL MECHANICAL PROPERTIES

Product No.	*Alloy*	*Percent Density*	*Compressive Modulus**	*Compressive Strength*** *at 5% Strain*	*Tensile Modulus**	*Ultimate Tensile*** *Strength*
FM515B	Hastelloy X	19.0	1.3 (0.9)	330 (227)	2.9 (2.0)	1400 (965)

* Modulus values are in psi $\times 10^4$ — numbers in ( ) are in newtons/m^2 $\times 10^8$.
** Strength values are in psi — numbers in ( ) are in newtons/m^2 $\times 10^4$.

TABLE F-2. FIBER ALLOY COMPOSITION

Alloy	*Ni*	*Co*	*Cr*	*Mo*	*W*	*Fe*	*C*	*Si*	*Mn*
*Hastelloy X**	Bal	1.5	22	9	0.6	18	1.10	1.0 max	1.0 max

*Trademark of Cabot Corporation.

APPENDIX G

VIBRATION TEST SAMPLE PREPARATION AND TEST PROCEDURE

Samples were prepared by bonding two metal plates together, as shown in Figure G-1, using ICB manufacturing guidelines specified in Section II (Technical Discussion).

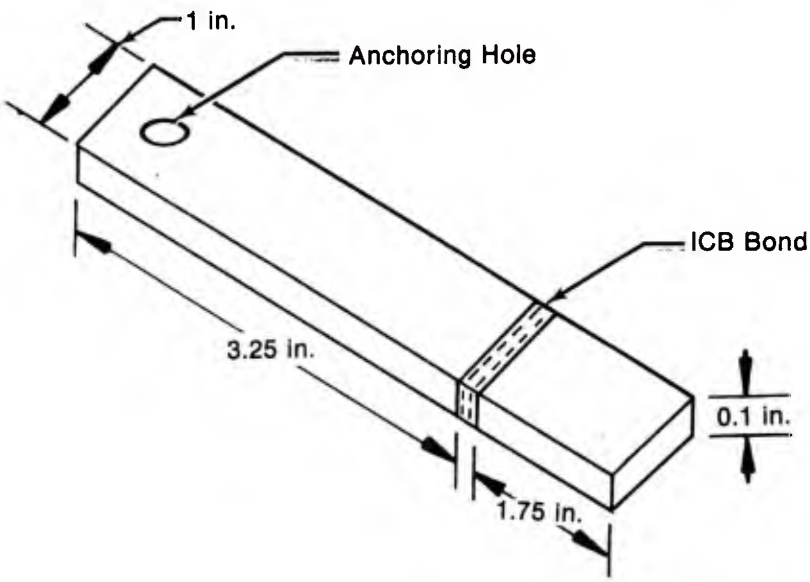

Figure G-1. Vibration Test Sample

The shorter metal segment (1.75 in.) of each sample was clamped at a point approximately 0.100 in. from the bond joint to form a cantilever beam. After attaching ferrous plates to anchoring holes located at the free end of each sample, room temperature tests were conducted by electromagnetically vibrating to failure or 10 million cycles in the first bending mode at resonance.

Each sample was calibrated and loaded to determine test deflection limits which were calculated using the equation:

$S = Mc/I$

where, S = bending stress, $lb/in.^2$
M = applied moment, lb/in.
C = distance from neutral axis, in.
I = moment of inertia, $in.^4$

All samples which failed fractured at the bond joint.

These tests were conducted to rank the relative fatigue strengths of two candidate bonding compositions using an established test technique which has been employed at P&WA/GPD to determine relative fatigue strengths of metal components.

Gas turbine compressor case assemblies typically experience trinodal vibration modes in service. This vibration mode is equivalent to the second bending mode of a flat plate geometry. Second bending mode vibration testing of ICB bond joints will be conducted under a follow-on program.

APPENDIX H
AMS SPECIFICATIONS

Condensed AMS specifications for the three alloys employed in this program follow. Condensed specifications are shown below due to the length of the complete specifications which are readily available from the Society of Automotive Engineers, Inc.

AMS 4928G
TITANIUM ALLOY BARS AND FORGINGS
6Al-4V
Annealed, 120,000 psi (827 MPa) Yield

1. *SCOPE.*

1.1 *Form:* This specification covers a titanium alloy in the form of bars, wire, forgings, flash welded rings, and stock or flash welded rings.

1.2 *Application:* Primarily for parts requiring strength up to 750°F (399°C) where response to heat treatment is not required.

2. *APPLICABLE DOCUMENTS:* The following publications form a part of this specification to the extent specified herein. The latest issue of Aerospace Material Specifications (AMS) shall apply. The applicable issue of other documents shall be as specified in AMS 2350.

2.1 *SAE Publications:* Available from Society of Automotive Engineers, Inc., Two Pennsylvania Plaza, New York, New York, 10001.

2.1.1 *Aerospace Material Specifications:*

AMS 2241 — Tolerances, Corrosion and Heat Resistant Steel Bars and Wire and Titanium and Titanium Alloy Bars and Wire
AMS 2249 — Chemical Check Analysis Limits, Titanium and Titanium Alloys
AMS 2350 — Standards and Test Methods
AMS 2375 — Approval and Control of Critical Forgings
AMS 2808 — Identification, Forgings
AMS 7498 — Rings, Flash Welded, Titanium and Titanium Alloys

2.2 *ASTM Publications:* Available from American Society for Testing and Materials, 1916 Race Street, Philadelphia, Pennsylvania, 19103.

ASTM E8 — Tension Testing of Metallic Materials
ϕ ASTM E120 — Chemical Analysis of Titanium and Titanium-Base Alloys
ASTM E292 — Conducting Time-for-Rupture Notch Tension Tests of Materials

2.3 *Government Publications:* Available from Commanding Officer, Naval Publications and Forms Center, 5801 Tabor Avenue, Philadelphia, Pennsylvania, 19120.

2.3.1 *Federal Standards.*

Federal Test Method Standard No. 151 — Metals; Test Methods

3. *TECHNICAL REQUIREMENTS.*

3.1 *Composition:* Shall conform to the following percentages by weight, determined by wet chemical methods in accordance with ASTM E120, by spectrographic methods in accordance with Federal Test Method Standard No. 151, Method 112, or by other approved analytical methods:

	Minimum	Maximum	
Aluminum	5.50	—6.75	
Vanadium	3.50	—4.50	
Iron	—	0.30	
Oxygen	—	0.20	
Carbon	—	0.10	
Nitrogen	—	0.05	(500 ppm)
Hydrogen (3.1.1)	—	0.0125	(125 ppm)
Other Elements, total (3.1.2)	—	0.40	
Titanium	Remainder		

3.1.1 Hydrogen content of forgings may be as high as 0.0150 (150 ppm).

3.1.2 Determination not required for routine acceptance.

3.1.3 *Check Analysis:* Composition variations shall meet the requirements of AMS 2249.

3.2 *Condition:* The product shall be supplied in the following condition:

3.2.1 *Bars:* Hot finished, with or without subsequent cold reduction, annealed, and descaled.

3.2.2 *Wire:* Cold drawn, annealed, and descaled.

3.2.3 *Forgings and Flash Welded Rings:* Annealed and descaled.

3.2.3.1 Flash welded rings shall not be supplied unless specified or permitted on purchaser's part drawing. When supplied, they shall be manufactured in accordance with AMS 7498.

3.2.4 *Stock for Forging or Flash Welded Rings:* As ordered by the forging or flash welded ring manufacturer.

3.3 *Annealing:* Bars, wire, forgings, and flash welded rings shall be annealed by heating to a temperature within the range 1300-1450°F (704.4-787.8°C), holding at the selected temperature within ±25°F (±14°C) for not less than 1 hr, and cooling at a rate which will produce products meeting all requirements of this specification and capable of meeting the requirements of 3.4.1.1 and 3.4.1.2 after heating to any temperature up to 1200°F (649°C), holding at heat for 20 min., cooling in air, and descaling.

3.4 *Properties:*

3.4.1 *Bars, Wire, Forgings, and Flash Welded Rings:*

3.4.1.1 *Tensile Properties:* Shall be as specified in Table I, determined in accordance with ASTM E8 with the rate of strain maintained at 0.003-0.007 in. per in., per min.

(0.003-0.007 mm/mm/min.) through the yield strength and then increased so as to produce failure in approximately one additional minute. When a dispute occurs between the purchaser and vendor over the yield strength values, a referee test shall be performed on a machine having a strain rate pacer, using a rate of 0.005 in. per in., per min. (0.005 mm/mm/min.) through the yield strength and a minimum cross head speed of 0.10 in. per min. (2.5 mm per min.) above the yield strength.

3.4.1.1.1 Yield strength and reduction of area requirements do not apply to wire under 0.125 in. (3.18 mm) in diameter.

3.4.1.1.2 Tests in the longitudinal direction are not required if tests in the transverse direction are made.

3.4.1.2 ϕ *Room Temperature Notched Stress-Rupture Test:* Specimens shall be capable of meeting the following requirements; tests shall be conducted in accordance with ASTM E292.

AMS 5611
STEEL BARS, FORGINGS, AND TUBING, CORROSION AND MODERATE HEAT RESISTANT
12CR
Ferrite Controlled
Premium Quality, Consumable Electrode Melted

1. *ACKNOWLEDGMENT:* A vendor shall mention this specification number in all quotations and when acknowledging purchase orders.

2. *FORM:* Bars, wire, forgings, mechanical tubing, and forging stock.

3. *APPLICATION:* Primarily for pressure vessels or structural parts requiring uniformly high room temperature tensile properties, and having resistance to moderately corrosive environments.

4. *COMPOSITION:*

	Minimum		*Maximum*
Carbon	0.12	—	0.15
Manganese	—		0.60
Silicon	—		0.50
Phosphorus	—		0.025
Sulfur	—		0.025
Chromium	11.50	—	12.50
Nickel	—		0.75
Molybdenum	—		0.20
Aluminum	—		0.05
Copper	—		0.50
Tin	—		0.05
Nitrogen	—		0.18

4.1 *Check Analysis:* Composition variations shall meet the requirements of the latest issue of AMS 2248.

5. *CONDITION:* Unless otherwise ordered, the product shall be supplied in the following condition:

5.1 *Bars:* Annealed, in a machinable condition, having hardness not higher than Brinell 241 or equivalent.

5.1.1 Round bars shall be turned or ground.

5.1.2 Hexagons shall be cold finished.

5.1.3 Other bars 2.75 in. and under in distance between parallel sides shall be cold finished and those over 2.75 in. in distance between parallel sides shall be hot finished.

5.2 *Wire:* Annealed and cold finished having tensile strength not higher than 115,000 psi.

5.3 *Forgings:* Normalized and tempered having hardness not higher than Brinell 241 or equivalent.

5.4 *Mechanical Tubing:* Cold finished, having hardness not higher than Brinell 241 or equivalent.

5.5 *Forging Stock:* As ordered by the forging manufacturer.

AMS 5536G
ALLOY SHEET AND PLATE, CORROSION AND HEAT RESISTANT
Nickel Base — 22 Cr — 1.50Co — 9.0Mo — 0.60W — 18.5Fe

1. *ACKNOWLEDGEMENT:* A vendor shall mention this specification number and its revision letter in all quotations and when acknowledging purchase orders.

2. *APPLICATION:* Primarily for parts such as welded nozzle diaphragm assemblies, burner liner parts, tail pipes, exhaust cone assemblies, and other parts requiring oxidation resistance up to 2200°F (1204°C) and relatively high strength above 1500°F (816°C).

3. *COMPOSITION:*

	Minimum		*Maximum*
Carbon	0.05	—	0.15
Manganese	—		1.00
Silicon	—		1.00
Phosphorus	—		0.040
Sulfur	—		0.030
Chromium	20.50	—	23.00
Cobalt	0.50	—	2.50
Molybdenum	8.00	—	10.00
Tungsten	0.20	—	1.00
Boron	Present but not exceeding		0.010
Iron	17.00	—	20.00
Nickel	Remainder		

3.1 *Check Analysis:* Composition variations shall meet the requirements of the latest issue of AMS 2269.

4. *CONDITION:* Unless otherwise ordered, the product shall be supplied in the following condition:

4.1 *Sheet and Strip:* Hot or cold rolled, solution heat treated, and descaled unless
φ solution heat treatment is performed in an atmosphere yielding a bright finish, having a surface appearance as close as possible to a commercial corrosion resistant steel No. 2D finish; standards for acceptance and rejection shall be as agreed upon by purchaser and vendor.

4.2 *Plate:* Hot rolled, solution heat treated, and descaled.

5. *TECHNICAL REQUIREMENTS:* When ASTM methods are specified for determining conformance to the following requirements, tests shall be conducted in accordance with the issue of the ASTM method listed in the latest issue of AMS 2350.

5.1 *HEAT TREATMENT:* Material shall be solution heat treated by heating to
φ 2150°F ±25 (1176.7°C ±14), except that sheet and strip up to 0.030 in. thick may be heated to temperatures as low as 2100°F ±25 (1148.9°C ±14), holding at heat for a time commensurate with the thickness, and rapidly cooling.

APPENDIX I

CONVERSION OF HOOP STRESS TO BONDING PRESSURE

The relationship between hoop stress and internal pressure for thin walled pressure vessels is shown below in Equation (1) (*Formulas for Stress and Strain*, fifth edition, Roark, R. J., and W. C. Young, McGraw-Hill Book Co., 1975) and Figure I-1.

$$S = \frac{pR}{t} \tag{1}$$

where:

S = hoop stress, psi
p = internal pressure, psi
R = internal radius, in.
t = wall thickness, in.

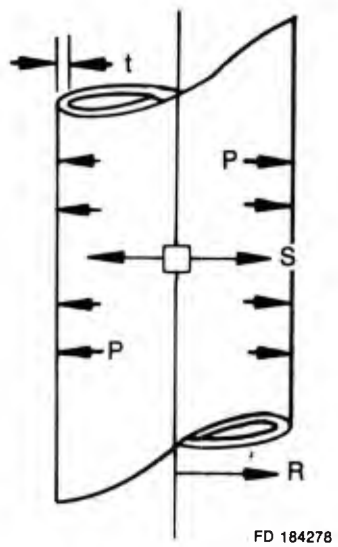

Figure I-1. Thin Walled Pressure Vessel

Changing Equation (1),

$$p = \frac{St}{R} \tag{2}$$

and, $S = \sigma$

from Hooke's Law, $\sigma = E\epsilon$

where

E = Modulus of Elasticity, psi
ϵ = strain, in./in.

therefore, $S = E\epsilon$

substituting $E\epsilon$ for S in Equation (2),

$$p = \frac{E\epsilon t}{R} \qquad (3)$$

Since strain gaging produces strain data (ϵ) and E is known, Equation (3) was used to calculate pressure exerted by expandable ring segments while attaching abradable seals to simulated engine hardware.

APPENDIX J

PRELIMINARY ECONOMIC ANALYSIS

A preliminary economic analysis for attaching abradable seals with ICB was conducted and compared to gold-nickel braze attachment of seals to a common compressor stage. The comparison, which involves attachment of three seals within the common compressor stage, is shown in Table J-I. Labor cost estimates for ICB attachment were based on our experience in this program, and material costs were derived from actual purchase orders. Material and labor costs for gold-nickel braze attachment were supplied by P&WA/GPD Process Material Control group. The relative costs for the two procedures expressed as a percentage of the total cost for gold-nickel braze attachment is shown in the figure.

TABLE J-1. RELATIVE COSTS FOR SEAL ATTACHMENT TO A COMMON COMPRESSOR STAGE

• Materials		• Materials	
• Chem-Braze	0.1	• Gold	15.9
• Glycerin	0.2	• Nickel	0.1
• Nickel Aluminide	1.0		
	1.3		16.0
• Labor		• Labor	
• Undercoat	16.8	• Plating and Flashing	63.0
• Dispense Slurry and Fixture	3.9	• Heat Treatments	21.0
• Dry and Cure	4.0		
	24.7		84.0
• Total	26.0%	• Total	100.0%

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