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AFML-TR-78-84

# EXPLORATORY DEVELOPMENT OF AN OVERHAUL COATING PROCESS FOR GAS TURBINE COMPONENTS

Detroit Diesel Allison
Division of General Motors Corporation

June 1978

TECHNICAL REPORT AFML-TR-78-84

Final Report for Period May 1976 to March 1978

AIR FORCE MATERIALS LABORATORY
AIR FORCE WRIGHT AERONAUTICAL LABORATORIES
Air Force Systems Command
Wright-Patterson Air Force Base, Ohio 45433

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The purpose of this program was to demonstrate the feasibility of a single diffusion coating process which may be used for re-application of aluminide protective coatings to various superalloy turbine components during overhaul of Air Force aircraft gas turbine engines. The electrophoretic coating process developed by Detroit Diesel Allison Division, General Motors Corporation was chosen as the program coating procedure for the five task

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20. ABSTRACT (Cont)

development effort. An Al, Cr, Mn coating, identified as AEP 32, was successfully applied to four program alloys, C1023, B1900, Rene' 80 and Alloy 713C. In addition, a comprehensive test program was conducted to comparatively evaluate the environmental performance and mechanical properties of the program alloys coated with AEP 32 and their respective production coatings.

The AEP 32 coating on all alloys demonstrated excellent environmental performance without degradation of mechanical properties as compared to production coatings. A chemical stripping procedure was developed for removing the service coatings without significant substrate attack. A variety of engine components were stripped and recoated as demonstration parts. In addition, documentation for recoating overhaul turbine components is given.

## FOREWORD

This technical report covers all work performed under U. S. Air Force Contract Number F33615-76-C-5130 from May 1976 to March 1978. This program, AFML Project 7312, "Exploratory Development of an Aluminide Coating Process for Turbine Component Overhaul" was conducted by the Materials Development Laboratory, Detroit Diesel Allison Division of General Motors Corporation, Indianapolis, Indiana. The project was accomplished under the technical direction of J. J. Crosby, AFML/LLM, Air Force Materials Laboratory, Wright-Patterson Air Force Base, Ohio.

K. H. Ryan was program manager for Detroit Diesel Allison from May 1976 to May 1977. T. Pacala was the program manager from May 1977. J. O. Hodshire and Q. O. Shockley were the principal investigators.

The authors wish to acknowledge the contribution provided by the following individuals:

| | |
|---|---|
| G. L. Vonnegut | Preparation of cast test specimens |
| R. R. Mucho | Mechanical properties testing |
| M. J. Barber | Metallographic assistance |
| R. C. Bourke | Environmental assessment of the AEP coating process |
| G. R. Sippel | Provided technical monitoring of the program and assistance in analysis of test data |
| F. C. Flowers | Electron microprobe evaluations |

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# LIST OF TABLES

# SECTION I

# INTRODUCTION

The objective of the program is to demonstrate the feasibility of using a single diffusion coating process suitable for re-application of aluminide protective coatings to various superalloy components during overhaul of Air Force aircraft gas turbine engines. Further, the process shall be applicable to single blades and multiple vane segments producing a uniform coating which is comparable in protection properties to the variety of coatings presently applied by pack cementation, fused slurry, hot dipping and electrophoretic deposition. Several versions (some proprietary) of each of these processes are used to coat various original equipment Air Force turbine engine parts. Likewise, similar processes are used to re-apply coatings to refurbish the parts during overhaul.

The development of a single, non-proprietary process for applying performance equivalents of the various coatings now used in Air Force overhaul operations offers a cost and time effective opportunity for recoating engine service hardware at the AFLC overhaul facilities. It was necessary to demonstrate the suitability of the coating for the various alloys and components used in Air Force turbine engines.

In addition to being non-proprietary the coating process must be amenable to installation and employment at an Air Force overhaul facility. Also, demonstration and validation of the coatings as qualified alternatives for specific hardware for each particular engine was required.

To achieve the objectives of the program, Detroit Diesel Allison proposed the utilization of their electrophoretically applied coating identified as AEP 32. The process is licensed for use by the U. S. Government per Contract DAAJ-69-C-0412. Facilities required for the AEP processes are relatively simple and costs less than for most conventional aluminide processes. Allison Electrophoretic Process (AEP) facility has been operational in production at DDA for more than four years applying AEP 32 coating to Model TF 41 turbine blades. Also, the coating has been utilized on turbine components of other developmental gas turbine engines such as the Model XT 701 with good success.

An AEP aluminide coating can be tailored to meet a variety of specific turbine component requirements. The AEP 32 (Al-Cr-Mn) composition was developed to overcome thermal cracking problems encountered with the DDA pack cementation coating (Alpak) and at the same time hot corrosion resistance was improved. The AEP 32 coating has shown excellent performance and applicability to a variety of superalloy substrates in an AFML(1) evaluation program which included the coating on five nickel base and one cobalt base alloy.

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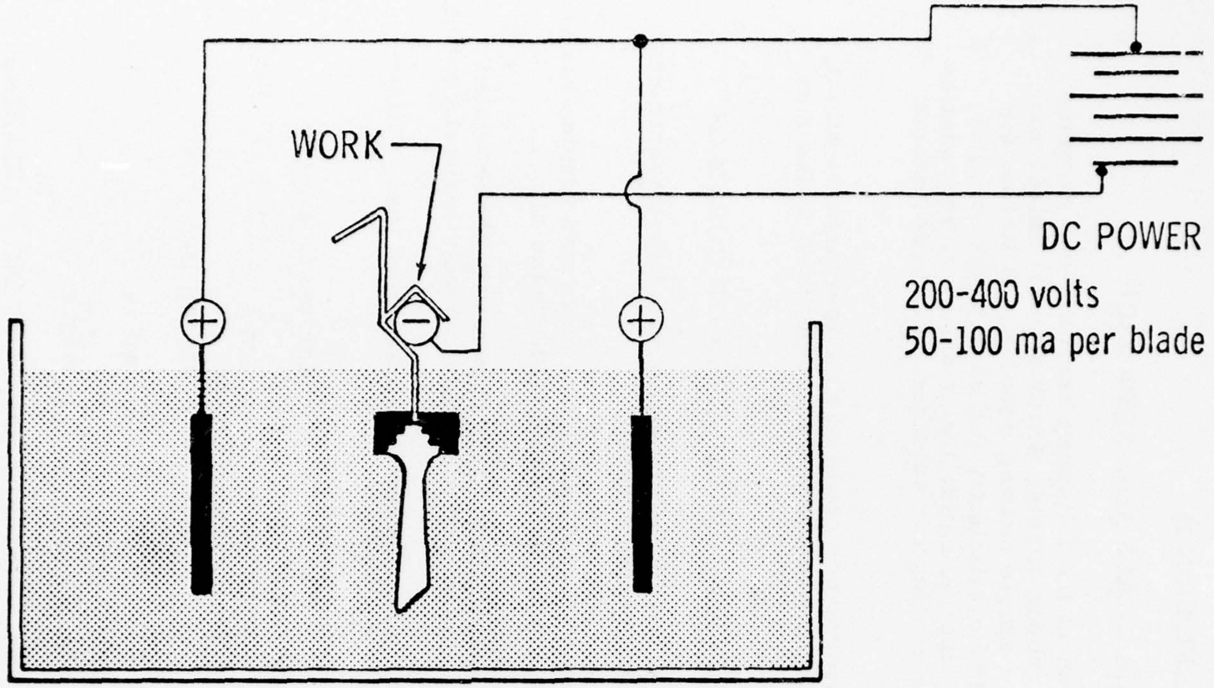
(1) AFML TR-71-173, Volume II, Comparative Evaluation of Coated Alloys for Turbine Components of Advanced Gas Turbine Engines, K. H. Ryan, January 1972.

The AEP Coating Process is based on the principle that migration is observed when an electrical potential is applied to two electrodes immersed in a dispersion of charged particles. An electrophoretic cell is shown in Figure 1-1. When the dispersion is properly formulated, the suspended particles will deposit upon one of the electrodes. Electrophoretic deposition differs from electroplating in that particles of any composition rather than ions are deposited. As compared with physical vapor deposition, electroplating, spraying, or dipping, the electrophoretic, procedure is particularly suited to applying coatings to non-uniform geometries, because, as the coating deposits on external areas and edges they become insulated and the effective deposition shifts to uncoated areas. The AEP procedures utilize fine particles dispersed in a low viscosity polar liquid. Empirically determined coating weights are electrophoretically deposited upon turbine components. The coated articles are then subjected to thermal treatments in a suitable environment (hydrogen, vacuum and argon have been used successfully) for times necessary to produce substrate coatings with the desired structure.

# ELECTROPHORETIC CELL



Electrolyte: A liquid media, usually a dielectric plus electrostatically dispersed particles of coating material (s).

Electrolytes for AEP coatings generally use mixtures of isopropanol and nitro-methane.

Figure 1-1

# SECTION II

## PROGRAM GOALS AND APPROACH

The development effort described in the following sections was directed toward meeting three program requirements, which are: (1) Select and evaluate a suitable cost effective single coating process; (2) Refine the coating process and demonstrate its efficiency for each program alloy; and (3) Verify equivalence in protective capability and lack of degradation in component performance after coating for selected Air Force turbine components.

To reach the objectives and performance goals of this development effort, a comprehensive five task program was conducted as outlined in the subsequent paragraphs.

### TASK I SELECTION AND SCREENING EVALUATION OF COATINGS

- Apply AEP 32 and baseline coatings to program alloy test specimens for the initial screening evaluation.
- Perform hot corrosion tests and creep rupture on coated turbine blade alloys and stress rupture test on the coated C1023 vane alloy.
- Compare results from the AEP coated specimens with those coated with the baseline test coatings (current production and overhaul coatings).
- The alloys selected for the program and their baseline test coatings are as follows:

| Alloys | Baseline Coatings |
|---|---|
| B1900 (PWA 663) | PWA 73 |
| Rene 80 (GE C50T48-58) | Codep B-1 |
| C1023 (EMS 73669) | Alpak |
| Alloy 713C (EMS 73632) | Alpak |

### TASK II OPTIMIZATION AND REFINEMENT OF COATING VARIABLES

- Optimize and refine, as required, the AEP 32 processing parameters, coating compositions and thicknesses as dictated from results of Task I.

### TASK III EVALUATION OF SELECTED ALLOY/COATING COMBINATIONS

- Select and apply alloy/coating combination from Tasks I and II.

- Compare the AEP 32 coating and the baseline coatings results on the following:

  Tensile properties
  Oxidation/Erosion
  Thermal fatigue (vane alloy)
  High cycle fatigue (blade alloy)
  Low cycle fatigue (blade alloy)

### TASK IV COATING OF TURBINE COMPONENT HARDWARE

- Coat designated turbine components supplied by AFML by the demonstrated AEP 32 coating process from Task III.
- Evaluate the following:

  Masking and Fixturing Techniques
  Coating Thickness and Uniformity
  Coating Inspection Techniques

### TASK V DOCUMENTATION OF OVERHAUL RECOATING PROCEDURES

- Prepare documentation of the coating process development and draft process specifications suitable for use by Air Force Logistics Center.
- Make recommendations for scaleup to production level.

# SECTION III

# EXPERIMENTAL PROGRAM

## 3.1 TASK 1 SELECTION AND SCREENING EVALUATION OF COATINGS

### 3.1.1 Cast Test Specimens

- Material Qualification The materials used in this program were vacuum cast into various specimen configurations by Detroit Diesel Allison foundry. Chemical composition and mechanical properties data which qualified the various heats of alloys are listed in Tables 3-I through 3-IV.

Table 3-I

Heat Qualification Data for C1023 Alloy

| Material Specification | Vendor | Heat No. |
|---|---|---|
| EMS 73669 (DDA) | Central Foundry Div. | NK 554 |

| Composition | Analysis | Specification |
|---|---|---|
| Carbon | 0.12 | 0.12-0.18 |
| Manganese | <0.05 | 0.20 max. |
| Chromium | 15.73 | 14.5-16.5 |
| Molybdenum | 8.4 | 7.6-9.0 |
| Silicon | <0.1 | 0.2 max. |
| Iron | 0.24 | 0.5 max. |
| Aluminum | 4.25 | 3.9-4.4 |
| Titanium | 3.50 | 3.4-3.8 |
| Cobalt | 9.20 | 9.0-10.5 |
| Boron | 0.007 | 0.004-0.008 |
| Sulfur | <0.01 | 0.015 max. |
| Nickel | Bal. | Bal. |

| Cast Test Specimen Properties | Test Results | Specification |
|---|---|---|
| Stress Rupture (1800°F, 19.0 ksi): | | |
| Rupture life (hours) | 44.8 | 30 min. |
| Elongation, 4D (%) | 4.0 | 3 min. |
| Structure: | fine, equiax | no columnar grains |

## Table 3-II

## Heat Qualification Data for 713C Alloy

| Material Specification | Vendor | Heat No. |
|---|---|---|
| EMS 73632 (DDA) | Certified Alloy Product | V1186 |

| Composition | Analysis | Specification |
|---|---|---|
| Carbon | 0.12 | 0.08-0.20 |
| Manganese | 0.05 | 0.25 max |
| Chromium | 14.10 | 13.0-15.0 |
| Molybdenum | 4.30 | 3.8-5.2 |
| Silicon | 0.50 | 0.50 max |
| Iron | 1.48 | 2.5 max |
| Aluminum | 6.10 | 5.5-6.5 |
| Titanium | 1.09 | 0.5-1.25 |
| Columbium + Tantalum | 2.20 | 1.8-2.8 |
| Cobalt | 0.50 | 1.0 max |
| Zirconium | 0.117 | 0.05-0.15 |
| Boron | 0.012 | 0.005-0.015 |
| Nickel | Bal | Bal |

| Cast Test Specimen Properties | Test Results | Specification |
|---|---|---|
| Tensile Properties (Room Temperature): | | |
| Ultimate (ksi) | 136 | 110 min. |
| Yield, 0.2% Offset (ksi) | 112 | 100 min. |
| Elongation (4D), % | 10 | 3 min. |
| Stress Rupture (1800$^\circ$F, 22 ksi): | | |
| Rupture life (hours) | 33.3 | 30min. |
| Elongation (4D), % | 13 | 5 min. |
| Hardness (RC): | 39 | 42 max. |
| Structure | Equiax, fine grain 0.062" max. | 0.062" max. |

## Table 3-III

## Heat Qualification Data for Rene' 80 Alloy

| Material Specification | Vendor | Heat No. |
|---|---|---|
| C50TF28-S8, Class A (GE) | Howmet | 101C4866 |

| Composition | Analysis | Specification |
|---|---|---|
| Carbon | 0.16 | 0.15-0.19 |
| Manganese | 0.01 | 0.10 max |
| Chromium | 14.06 | 13.7-14.3 |
| Molybdenum | 3.90 | 3.70-4.30 |
| Silicon | 0.07 | 0.10 max. |
| Iron | 0.28 | 0.35 max. |
| Aluminum | 2.88 | 2.8-3.2 |
| Titanium | 4.96 | 4.8-5.2 |
| Columbium | 0.03 | 0.10 max. |
| Cobalt | 9.42 | 9.0-10.0 |
| Tungsten | 3.84 | 3.7-4.3 |
| Zirconium | 0.06 | 0.02-0.10 |
| Tantalum | 0.05 | 0.10 max. |
| Boron | 0.015 | 0.01-0.02 |
| Vandium | 0.01 | 0.10 max. |
| Hafnium | 0.01 | 0.10 max. |
| Sulfur | 0.002 | 0.0075 max. |
| Phosphorous | 0.005 | 0.015 max. |
| Magnesium | 0.0035 | 0.01 max. |
| Copper | 0.02 | 0.10 max. |
| Nickel | Bal. | Bal. |
| $N_{V3}$ | 2.27 | 2.32 max. |
| Trace Elements | conform to spec. per Accu-Labs ALR No. 90-2520-14-8 | |

| Cast Test Specimen Properties | Test Results | Specification |
|---|---|---|
| Tensile Properties (1600°F) | | |
| Ultimate (KSI) | 107.9 | 90 min. |
| Yield, 0.2% offset (KSI) | 77.9 | 70 min. |
| Reduction of area (%) | 16.1 | 15 min. |
| Stress Rupture (1800°F, 27.5 KSI): | | |
| Rupture life (hours) | 34.1 | 23 min. |
| Reduction of area (%) | 7.8 | 5 min. |
| Grain Size: | Equiax, 0.062" max. | 0.015-0.062" |

## Table 3-IV

## Heat Qualification Data for B1900 Alloy

| Material Specification | Vendor | Heat No. |
|---|---|---|
| PWA 663 | Howmet | 54C5666 |

| Composition | Analysis | Specification |
|---|---|---|
| Carbon | 0.10 | 0.08-0.13 |
| Manganese | 0.01 | 0.20 max. |
| Chromium | 7.90 | 7.5-8.5 |
| Molybdenum | 6.03 | 5.75-6.25 |
| Silicon | 0.02 | 0.25 max. |
| Iron | 0.10 | 0.35 max. |
| Aluminum | 5.95 | 5.75-6.25 |
| Titanium | 1.00 | 0.80-1.20 |
| Columbium | 0.04 | 0.10 max. |
| Cobalt | 10.09 | 9.5-10.5 |
| Tungsten | 0.02 | 0.10 max. |
| Zirconium | 0.08 | 0.05-0.10 |
| Tantalum | 4.10 | 4.0-4.5 |
| Boron | 0.016 | 0.01-0.02 |
| Sulfur | 0.002 | 0.015 max. |
| Lead | 0.0001 | 0.0005 max. |
| Bismuth | 0.00001 | 0.00005 max. |
| Selenium | 0.00005 | 0.0003 max. |
| Thallium | 0.00005 | To be reported |
| Tellurium | 0.00005 | To be reported |
| Nickel | Bal. | Bal. |

| Cast Test Specimen Properties | Test Results | Specification |
|---|---|---|
| Creep Rupture (1400°F, 94 KSI): | | |
| Rupture life (hours) | 33.1 | 23 min. |
| Elongation, 4D (%) | 2.0 | 2 min. |
| Stress Rupture (1800°F, 29 KSI): | | |
| Rupture life (hours) | 41 | 30 min |
| Elongation, 4D (%) | 7.5 | 3 min |
| Hardness (RC): | 41 | 34-44 |
| Grain Size: | Equiax, 0.062" max | Equiax, uniform |

- Casting inspection The cast specimens were cleaned of mold material by the foundry by blasting with 120 grit aluminum oxide. After cleaning, the castings were macroetched followed by visual, fluorescent penetrant (ZL 22) and radiographic inspection. The critical areas of the acceptable castings conformed to the following quality standards:

  (1) Uniform equiaxed grains which did not exceed approximately 0.062 inch diameter

  (2) Castings were sound and free of foreign materials, surface and internal defects detrimental to the fabrication, coating or to performance of the specimens.

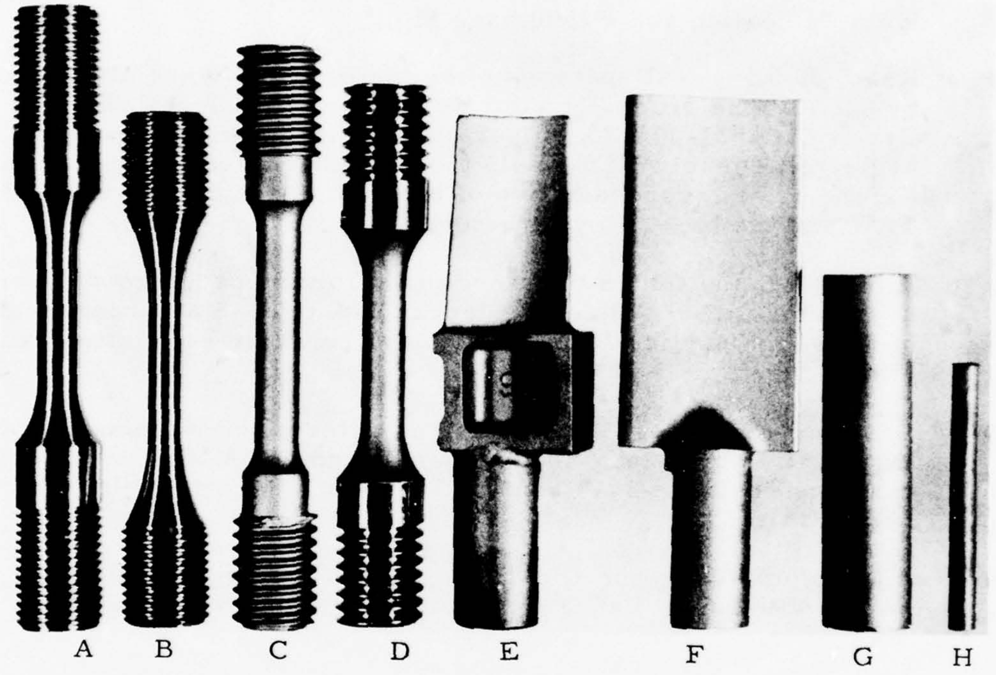
  (3) Castings had smooth clean surfaces.

  Following inspection procedures the castings were again cleaned by blasting with 120 grit aluminum oxide.

- Pre-coating heat treatment Following inspection, the test specimen castings were heat treated as follows:

  - B1900 alloy castings were heat treated in argon per Pratt and Whitney Aircraft Specification PWA 663
  - Rene' 80 alloy specimens were heat treated in vacuum with argon backfill cooling per General Electric Aircraft Engine Group Specification C50TF28-S8, Class A.
  - Alloy 713C specimens were heat treated in vacuum per Detroit Diesel Allison Specification EPS 333-6.
  - C1023 alloy specimens did not require a pre-coating heat treatment

- Specimen Configuration Typical configurations of the various cast test specimens used throughout the program are shown in Figure 3-1. Approximately twenty five cylindrical specimens, 1/2" x 2", were cast for each alloy/coating combination and were used for coating development.



| | | | |
|---|---|---|---|
| A | Low Cycle Fatigue | E | Hot Corrosion |
| B | High Cycle Fatigue | F | Thermal Fatigue |
| C | Tensile | G | Coating Development |
| D | Stress Rupture | H | Oxidation Erosion |

Figure 3-1 Test specimen configuration

### 3.1.2 Baseline Coated Test Specimens

- B1900 alloy test specimens for the program were coated by TRW Jet Ordnance Division per Pratt and Whitney Aircraft Specification PWA 73 with the exception of the post-coating heat treatment which was performed at Detroit Diesel Allison with the AEP 32 coated test specimens. Figure 3-2 illustrates typical structures for the PWA 73 coating and B1900 base alloy.

- Rene' 80 alloy test specimens for the program were also coated by TRW. The process conformed to General Electric Engine Group T.O. 2J-J79-43. Post-coating heat treatment was performed at Detroit Diesel Allison with the AEP 32 coated test specimens. Figure 3-3 is representative of the Codep B-1 coating applied by TRW and the base alloy structures.

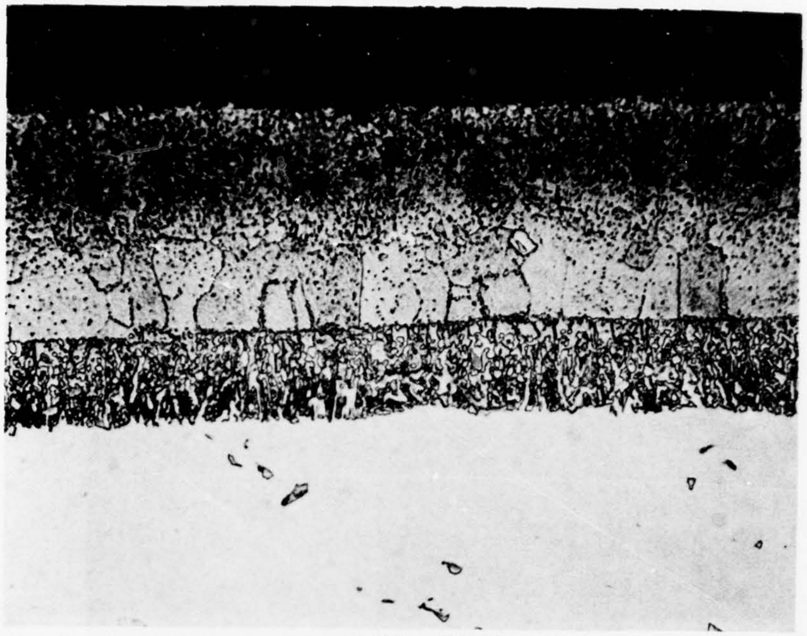
- Alloy 713C and C1023 test specimens for the program were coated by Detroit Diesel Allison. Figures 3-4 and 3-5 are representative of the Alpak coatings applied by DDA and their respective base alloys.

- Baseline coated test specimens, as determined by metallographic examination of coating load control samples, had coating thicknesses as shown in Table 3-V (control samples - 1/2" diameter x 2" cylinders).

- All photomicrographs illustrating alloy/coating combinations were etched with $HCl + FeCl_3$ + methanol.

Table 3-V

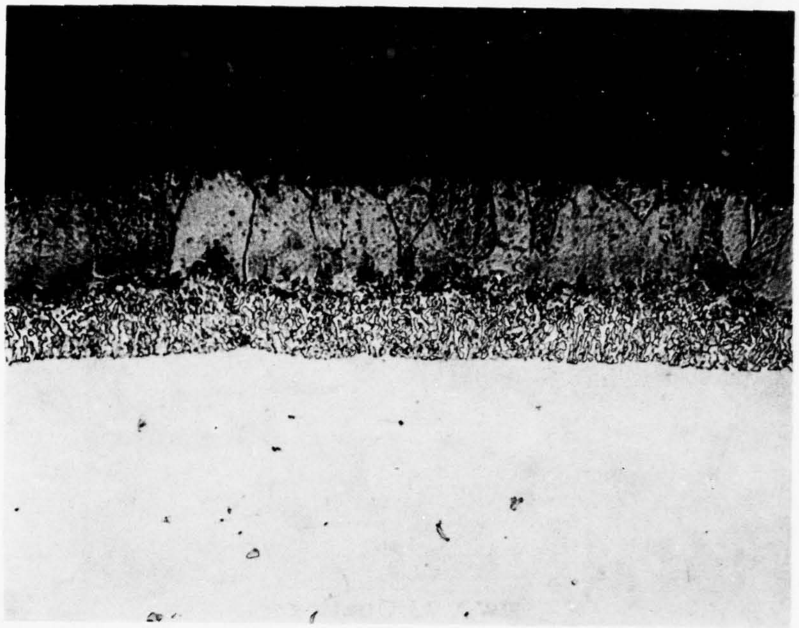
| Alloy | Coating | Average Coating Thickness (mils) | Coating Thickness Range (mils) |
|---|---|---|---|
| B1900 | PWA 73 | 3.5 | 3.0-4.0 |
| Rene' 80 | Codep B-1 | 2.2 | 2.0-2.5 |
| IN 713C | Alpak | 3.6 | 3.0-4.2 |
| C1023 | Alpak | 3.1 | 2.3-3.8 |



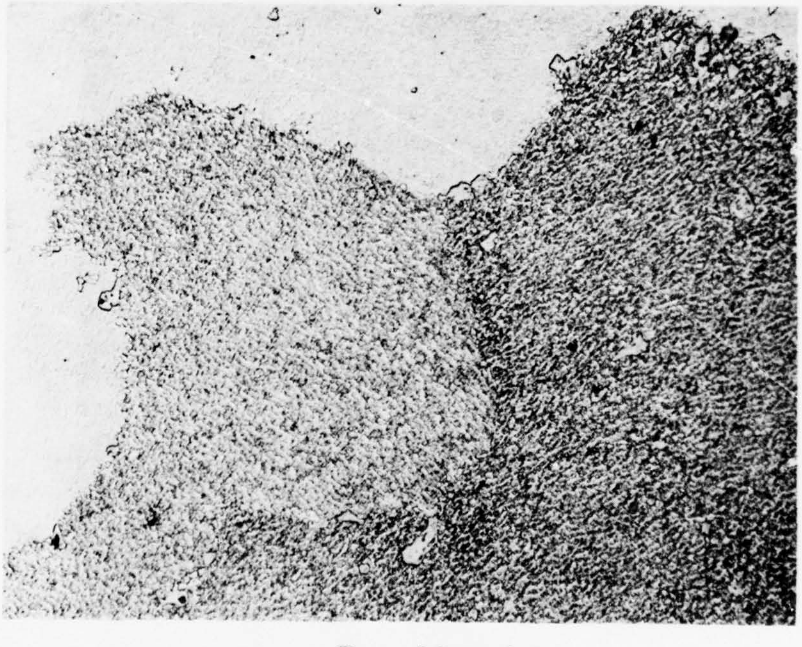
PWA 73 Coating

Base Material

Figure 3-2 PWA 73 coated B1900 alloy - cylindrical cast test specimens (500X)

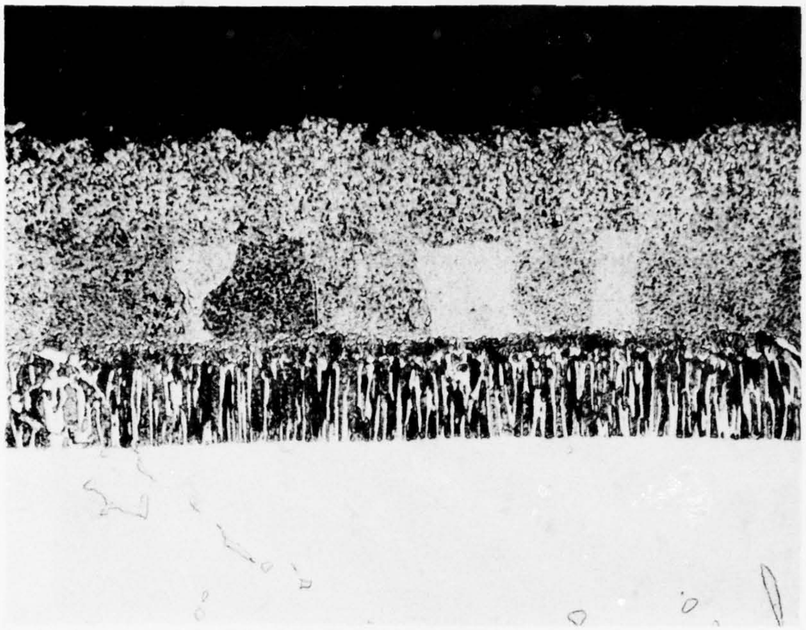


Codep B-1 Coating

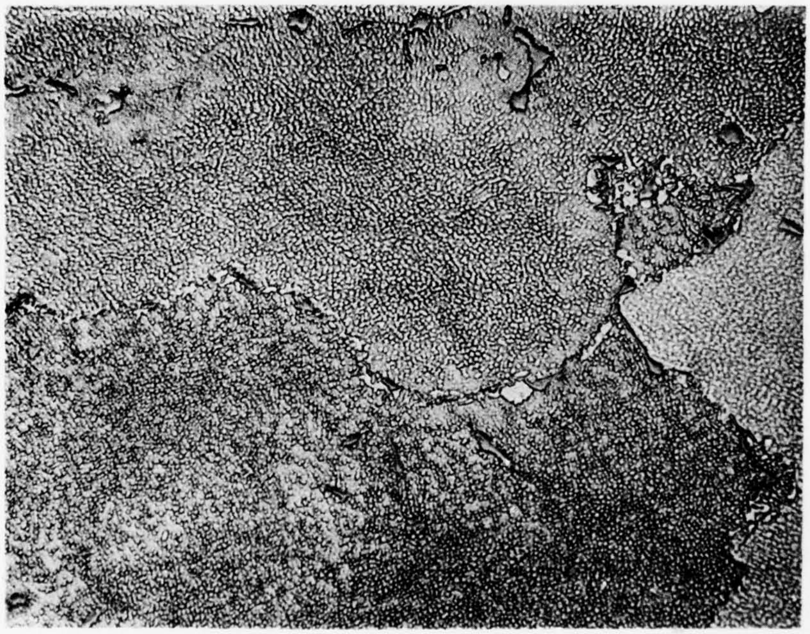


Base Material

Figure 3-3 Codep B-1 coated Rene' 80 alloy - cylindrical cast test specimens (500X)

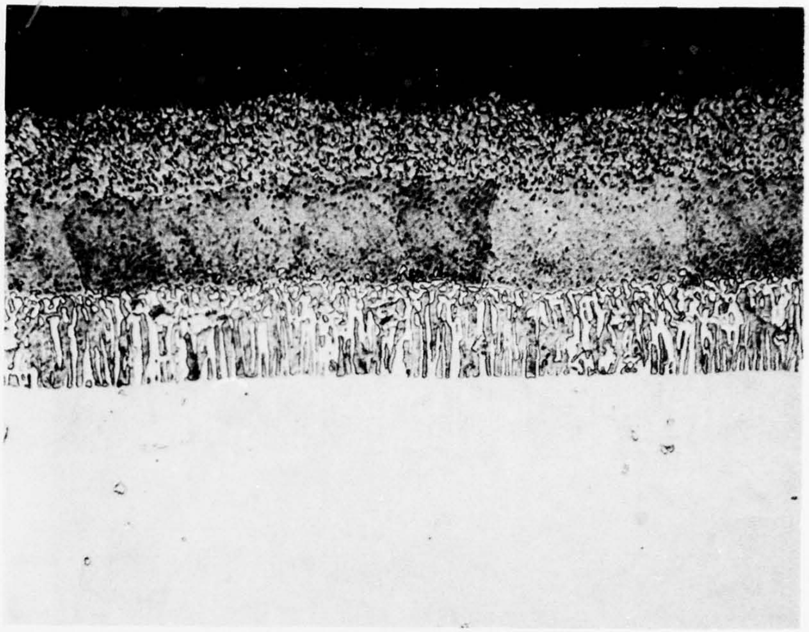


Alpak Coating

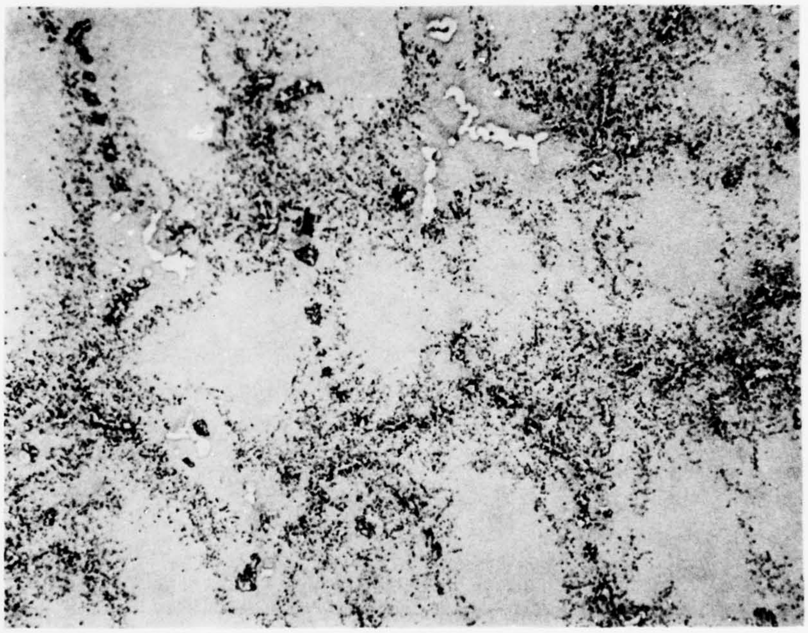


Base Material

Figure 3-4 Alpak coated alloy 713C - cylindrical cast test specimens (500X)



Alpak Coating



Base Material

Figure 3-5 Alpak coated C1023 alloy - cylindrical cast test specimens (500X - etched)

### 3.1.3 AEP 32 Coated Test Specimens

- <u>AEP 32 Coated Bath Composition</u> Through the exploratory development program, the AEP coating bath composition was maintained within the limits of DDA Specification PCI 2740 as described in the following paragraphs. The details for the preparation of the AEP 32 coating bath are presented in the section Documentation, Task V of this report. The bath constituents, specification limits and actual bath analysis range used throughout this program are shown below.

| Bath Constituent | Specification Limits | Bath Analysis |
|---|---|---|
| Dispersing media: | | |
| Isopropanol (99% grade) | 55-65% | --- |
| Nitromethane | 35-45% | --- |
| Water (contaminant) | 20 gm/l max. | 2.7-12.3 gm/l |
| Soluble additives | | |
| Zein | 2.0-3.0 gm/l | 2.7-2.8 gm/l |
| Cobalt nitrate hexahydrate | 0.09-0.15 gm/l | 0.11-0.13 gm/l |
| Insoluble dispersants | (15-33 gm/l total) | |
| Chromium powder | 40 ± 7% | 38-42% |
| Aluminum powder | 40 ± 12.5% | 38-47% |
| Manganese powder | 20 ± 5% | 16-18% |
| Particle Size (Coulter Counter) | | |
| Chromium powder | 90% < 25 microns | 95% < 25 microns (2-3 micron mean) |
| Aluminum powder | 10 micron max | < 6.5 microns |
| Manganese powder | 90% < 30 microns | 99% < 30 microns (4-5 micron mean) |

- <u>"Green" Coating Composition</u> Cylindrical control specimens 1/2" x 2", were coated along with program test specimens and then stripped of its green coating. The green coating was then chemical analyzed to determine if it conformed to the specification limits. The green coating specification and range for various chemical analysis throughout the program are as follows:

| Coating Metal | Specification | Analysis |
|---|---|---|
| Aluminum | 44 ± 10% | 43-41% |
| Chromium | 38 ± 10% | 38-40% |
| Manganese | 18 ± 8% | 12-14% |

- Diffusion Time and Temperature Variations In an effort to optimize the application of AEP 32 coating to the four program alloys, variations in diffusion times and temperatures were performed. Cylindrical 2 inch x 1/2 inch diameter test specimens of the alloys were coated with AEP 32 (1 minute depositions) providing test specimens with "green" coating deposits of 0.030 ± 0.002 gram/cm$^2$. The test specimens were diffused in hydrogen (-80F dewpoint) for the times and temperatures shown in Table 3-VI. Each diffusion treatment also included a one (1) hour dwell at 1300-1350°F before increasing the temperature. Specimens were retort cooled. It was recognized that some of the temperatures and times were deviations from the engine manufacturer's specification limits employed for diffusion of the baseline coatings; however, the investigation was considered to be a viable evaluation of possible increases in coating thicknesses and the applicability of a diffusion cycle which would be common to all the program alloys. Metallographic evaluations of specimens from the various diffusion treatments provided basis for the conclusion that the diffusion treatments specified for the baseline coatings were applicable to the AEP 32 coated alloys.

- AEP 32 Coating of Task I Test Specimens

  - Clean surfaces to be coated by blasting with 220-240 grit aluminum oxide at 45-50 psig. Mask machined threaded areas. Blow residual abrasive from surfaces and cavities with filtered compressed air.
  - Mask and fixture, as required.
  - Immerse in AEP 32 solution.
  - Cathodically deposit "green" coating at 200 volts dc for 60 seconds.
  - Air dry for 30 to 60 seconds.
  - Remove masking and fixturing.

  Diffuse "green" coating deposits on the various alloys as described in Table 3-VII.

## Table 3-VI

## Effect of Diffusion Temperature and Time on AEP 32 Deposits

| Alloy | Temperature (°F) | Time (Hrs.) | Average Coating Thickness (Mils) |
|---|---|---|---|
| B1900 | 1975* | 4 | 1.7 |
| B1900 | 1975* | 11 | 2.1 |
| B1900 | 2000 | 4 | 1.8 |
| Rene' 80 | 1925* | 6** | 1.6 |
| Rene' 80 | 1925* | 11 | 1.6 |
| Rene' 80 | 2000 | 4 | 1.7 |
| 713C | 2000 | 2 | 2.0 |
| 713C | 2000 | 4 | 2.1 |
| 713C | 2080* | 2** | 2.6 |
| C1023 | 2000 | 2 | 1.6 |
| C1023 | 2000 | 4 | 2.0 |
| C1023 | 2080* | 2** | 2.0 |

*Baseline coating specified diffusion temperature.

**Baseline coating specified diffusion time; TRW diffusion time for PWA 73 coating is 8 hours.

## Table 3-VII

### Diffusion Treatments of AEP 32 Coatings on Task I Test Specimens

| Alloy | Diffusion Treatment |
|---|---|
| B1900 | 1325 ± 25F/1 hr., 1975 ± 25/8 hrs. |
| Rene' 80 | 1325 ± 25F/1 hr., 1925 ± 25F/6 hrs. |
| 713C | 1325 ± 25F/1 hr., 2080 ± 25F/2 hrs. |
| C1023 | 1325 ± 25F/1 hr., 2080 ± 25F/2 hrs. |

Note 1: Hydrogen atmosphere (-80F dewpoint) during heating and cooling. All specimens were retort cooled.

- Relationship of "Green" Coating to Diffused Coating Thickness

  A significant number of Task I cylindrical test specimens (ten each alloy) were weighed before and after coating to determine the weight uniformity of "green" coating deposited. Following diffusion treatment and cleaning, metallographic measurements of the coating thicknesses were performed. Table 3-VIII summarizes the data from the above investigation which aided in establishing green coating control procedures.

## Table 3-VIII

### Comparison of AEP 32 "Green" Coating Weight with Diffused Coating Thickness on Task I Test Specimens

| Alloy | Average "Green" Coating Weight (gm/Cm$^2$) | Average Coating Thickness (mils) |
|---|---|---|
| B1900 | 0.0298 | 3.2 |
| Rene' 80 | 0.0297 | 2.0 |
| 713C | 0.0343 | 2.9 |
| C1023 | 0.0313 | 2.6 |

- Post Diffusion Heat Treatments In conformance with their applicable coating specification requirements, the AEP 32 and baseline coated, diffused and cleaned test specimens were heat treated as shown in Table 3-IX.

## Table 3-IX

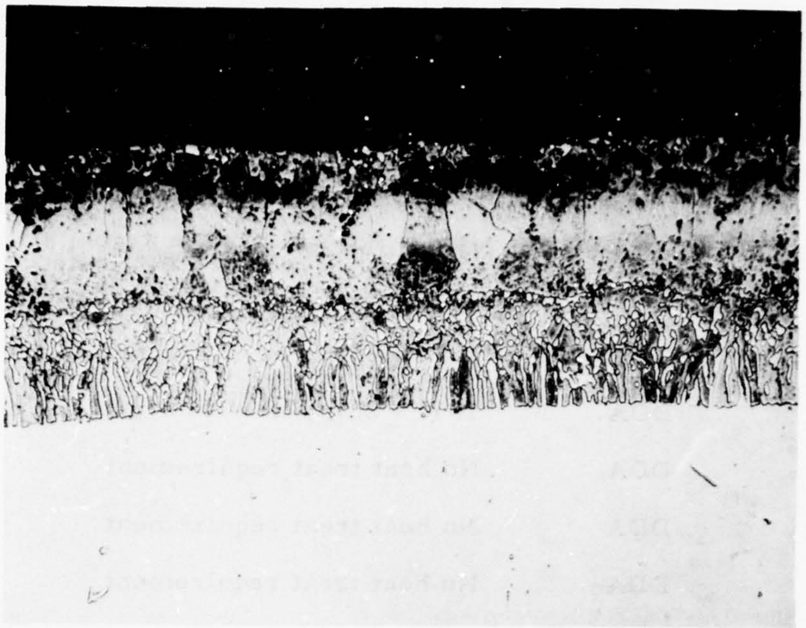
### Post-Diffusion Heat Treatments of AEP 32 and Baseline Coated Test Specimens

| Alloy | Coating | Coating Source | Heat Treatment |
|---|---|---|---|
| B1900 | PWA 73 | TRW | 1650 ± 25F/10 hrs. in argon; air cool |
| B1900 | AEP 32 | DDA | 1650 ± 25F/10 hrs. in argon; air cool |
| Rene' 80 | Codep B-1 | TRW | 1550 ± 25/16 hrs. in argon; air cool |
| Rene' 80 | AEP 32 | DDA | 1550 ± 25/16 hrs. in argon; air cool |
| 713C | Alpak | DDA | No heat treat requirement |
| 713C | AEP 32 | DDA | No heat treat requirement |
| C1023 | Alpak | DDA | No heat treat requirement |
| C1023 | AEP 32 | DDA | No heat treat requirement |

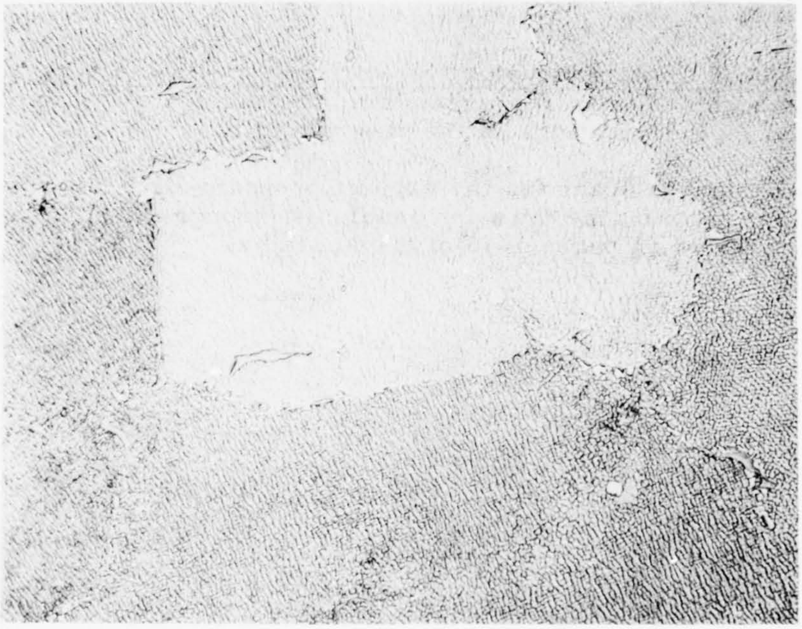
Note: AEP 32 and PWA 73 coated B1900 test specimens were post-diffusion heat treated together as were the AEP 32 and the Codep B-1 coated Rene' 80 test specimens.

- <u>AEP 32 Coating Structure on Various Program Alloys</u> Figures 3-5a through 3-8 show representative structures of the base material and AEP 32 coatings on the program alloys.

  Microprobe scans for the various program alloy/coating combinations, showing the diffusion gradients through the coating, are presented on pages 1-13 of the Appendix.

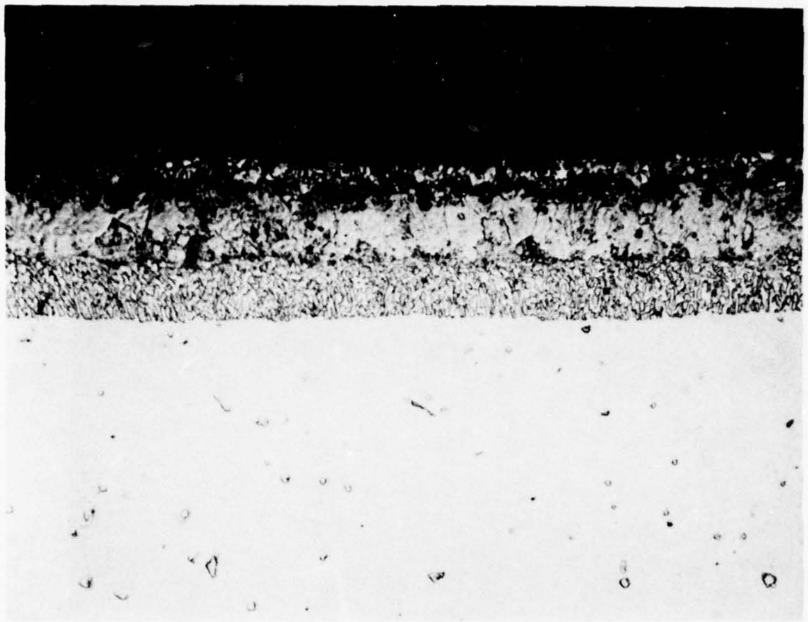


AEP 32 Coating

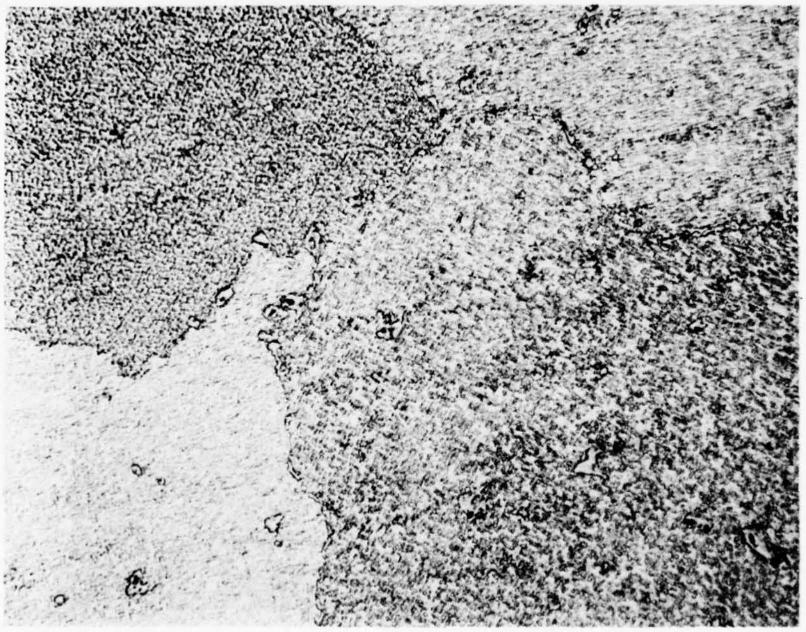


Base Material

Figure 3-5a AEP 32 coated B1900 alloy - cylindrical cast test specimens (500X)

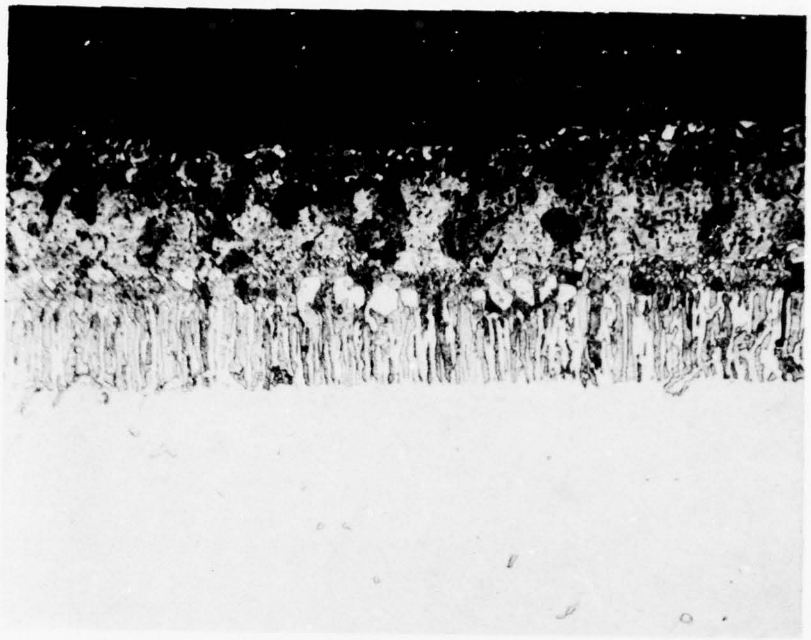


AEP 32 Coating

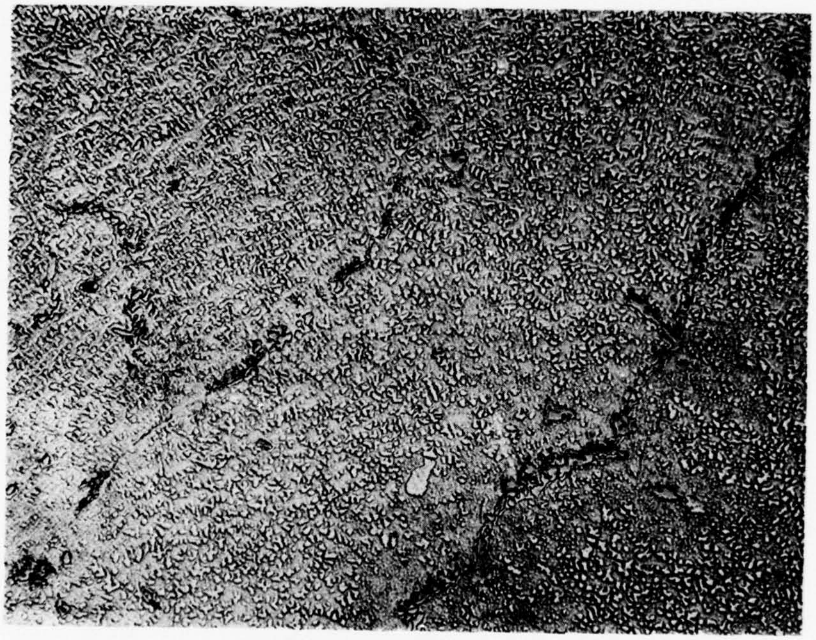


Base Material

Figure 3-6 AEP 32 coated Rene' 80 alloy - cylindrical cast test specimens (500X)



AEP 32 Coating



Base Material

Figure 3-7 AEP 32 coated alloy 713C - cylindrical cast test specimens (500X)

AEP 32 Coated

Base Material

Figure 3-8 AEP 32 coated C1023 alloy - cylindrical cast test specimens (500X)

### 3.1.4 Screening Tests

The objective of this testing effort was to determine whether AEP 32 coating, processed on the four program alloy substrates, can verify equivalence in (1) hot corrosion environment and (2) stress rupture properties when compared to the program's baseline coatings. Hot corrosion and stress rupture specimens were prepared and tested on the following alloy/coating combinations:

Alloy 713C/Alpak
Alloy 713C/AEP 32
C1023/Alpak
C1023/AEP 32

B1900/PWA 73
B1900/AEP 32
Rene' 80/Codep B-1
Rene' 80/AEP 32

- Hot Corrosion Testing Testing was conducted on a laboratory test rig, illustrated in Figure 3-9, which has been used for a number of high temperature alloy/coating evaluations. Test specimens were standard T56-A-9 solid 1st stage turbine blades. A photograph of the test fixture which accommodates sixteen specimens is shown in Figure 3-10. A test cycle consisted of heating the rotating (1800 rpm) fixtured specimens in a city gas fired furnace to an outer leading edge temperature of 1900°F followed by retraction into the cooling chamber where the rotating specimens were sprayed with an air aspirated solution of 1.4 percent sodium sulfate in deionized water. Each cycle included 1.5 minutes heating time to the testing temperature and 0.5 minute cooling time.

  Test airfoils were given a binocular examination after each 100 cycles. The coating was designated as "failed" upon observing a total coating corrosion breakdown area of 0.10 inch x 0.05 inch. A typical coating breakdown resulting from hot corrosion attack is shown in Figures 3-11 and 3-12. The analysis of hot corrosion tests show that AEP 32 coating is equivalent to Codep B-1 on alloy Rene' 80 and indicates an improved performance on alloy 713, C1023 and B1900 when compared to their base coating. Listing of individual hot corrosion test results and the log normal distribution Student t test analysis are presented in Table 3-X. A graphic summarization of test results is illustrated in Figure 13.

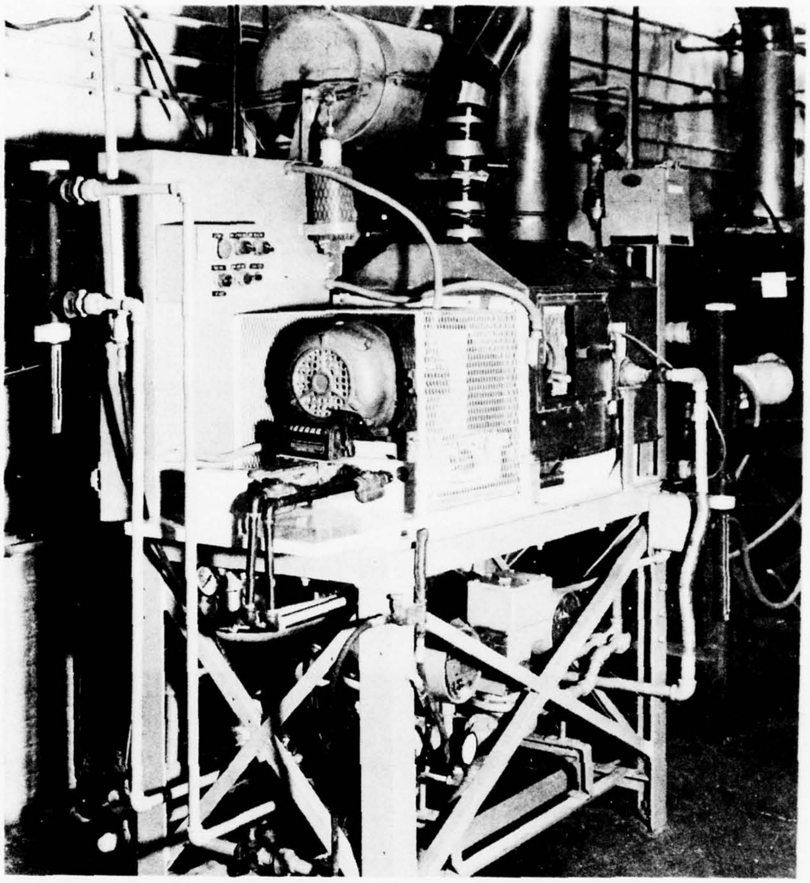
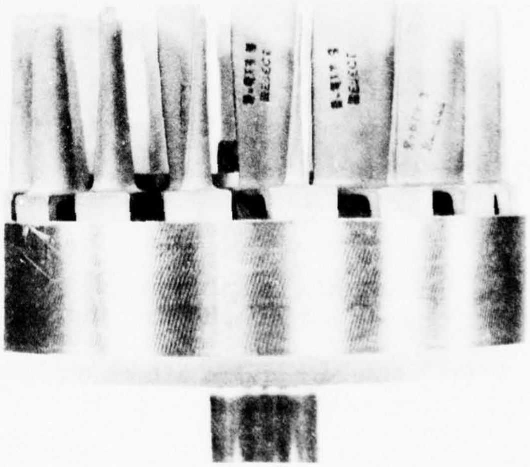


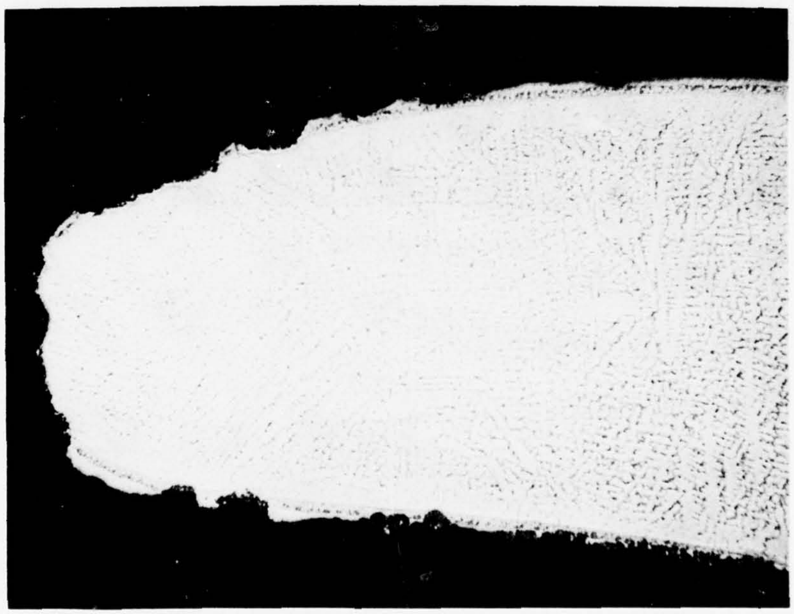
Figure 3-9 Hot corrosion test rig

Figure 3-10 Hot corrosion test blades and fixture



Magn: 5X

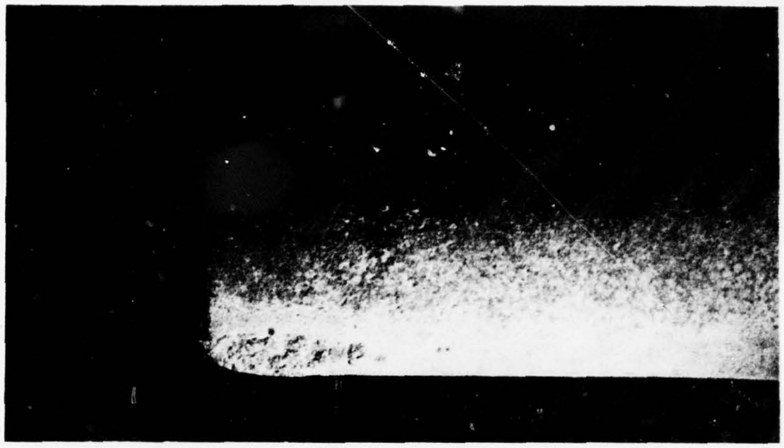
Surface condition of failed Alpak coated alloy 713C after 400 cycles of hot corrosion testing



Magn: 40X

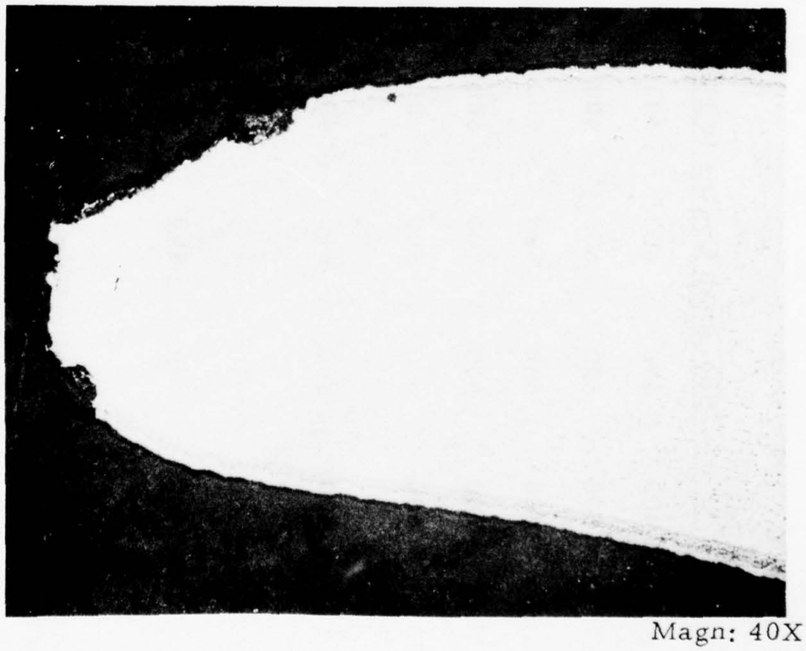
Photomicrograph of section cut through corroded areas of the upper airfoil showing the leading edge of blade

Figure 3-11 Hot corrosion attack on Alpak coated alloy 713C turbine blade test specimen



Magn: 5X

Surface condition of failed AEP 32 coated alloy 713C after 600 cycles of hot corrosion testing



Magn: 40X

Photomicrograph of section cut through corroded areas of the upper airfoil showing the leading edge of blade

**Figure 3-12** Hot corrosion attack on AEP 32 coated alloy 713C turbine blade test specimen

## Table 3-X

## Hot Corrosion Test Summary

1.5 Min. Heat Cycle at 1900$^{\circ}$F, 0.5 Min. Cool Cycle Deionized Water + 1.4% Sodium Sulfate

| Alloy/Coating | Specimen Cycles to Failure | | | | | | Log Normal Distribution Student t Test Analysis$^{(1)}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | $\overline{X}$ | $\sigma$(log) | % Prob. |
| 713C/Alpak | 400 | 400 | 400 | 300 | 500 | 300 | 377 | .086 | 93.0 |
| 713C/AEP 32 | 500 | 500 | 600 | 400 | 400 | --- | 474 | .075 | |
| C1023/Alpak | 400 | 500 | 500 | 500 | 300 | 300 | 406 | .109 | 99.7 |
| C/1023/AEP 32 | 700 | 600 | 700 | 600 | 600 | --- | 638 | .037 | |
| Rene' 80/ Codep B-1 | 500 | 600 | 500 | 400 | 400 | --- | 474 | .075 | 67.8 |
| Rene' 80/ AEP 32 | 500 | 600 | 600 | 400 | 600 | --- | 533 | .078 | |
| B1900/PWA 73 | 200 | 300 | 300 | 300 | 400 | 500 | 320 | .135 | 97.0 |
| B1900/AEP 32 | 400 | 500 | 400 | 400 | 600 | 500 | 461 | .074 | |

(1) $\overline{X}$ = mean; $\sigma$(log) = Log standard deviation; % Prob = Probability of specimens having different population means

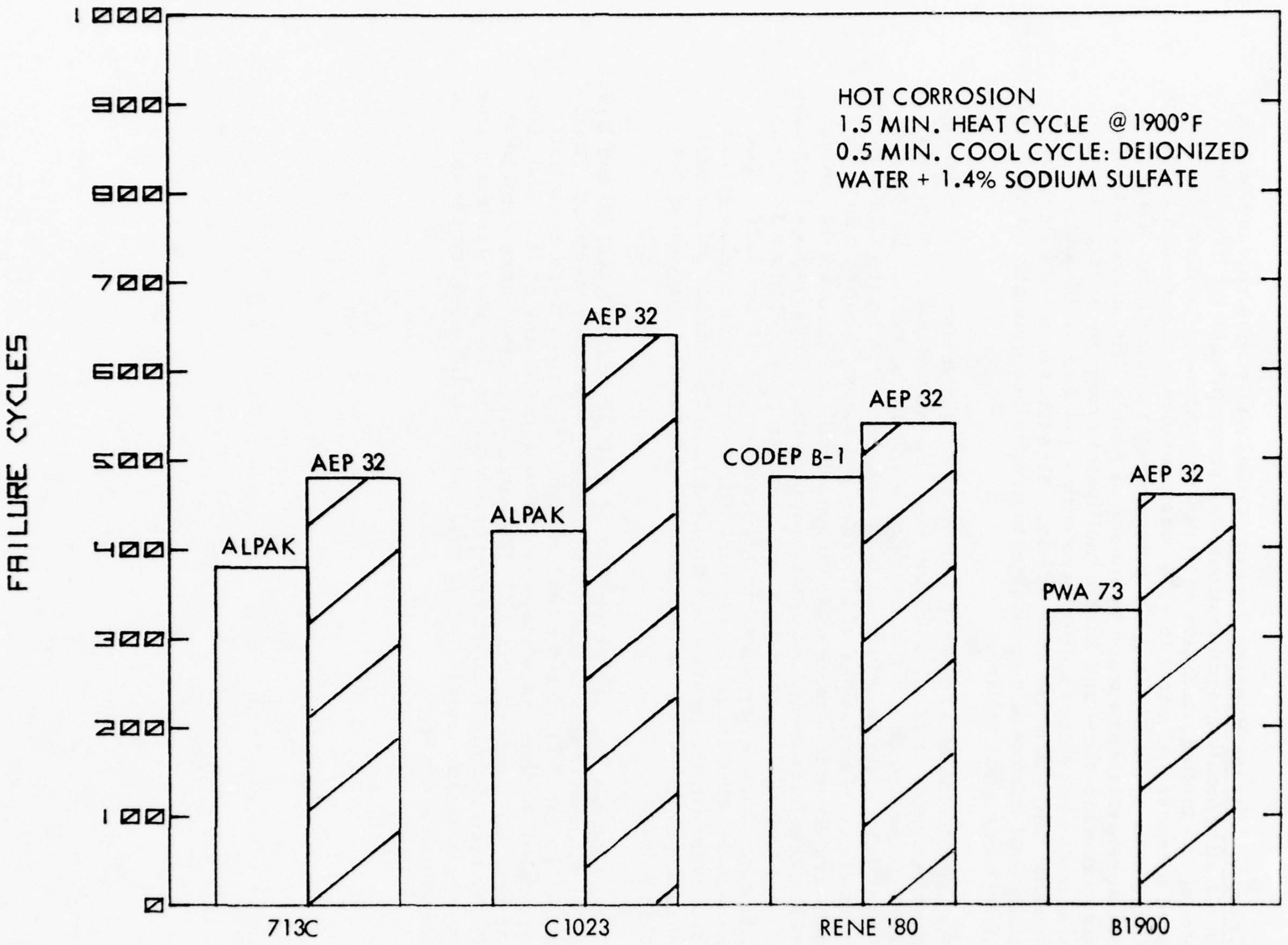


Figure 3-13 Graphic summary of hot corrosion results

- Creep and Stress Rupture Testing Creep and stress rupture testing on all alloy/coating combinations was accomplished on Arcweld Model "J" testing machines equipped with Arcweld tubular resistance wire furnaces. Control to ±5°F was provided by Leeds and Northrup Speedomax Model H, D.A.T. potentiometer controllers. Creep measurements were made by means of Riehle DHK elevated temperature extensometers and Riehle multipoint creep recorder. Test specimens were cast hollow bars with a 1/4 inch O.D. and a nominal wall thickness of 0.037-in. All stresses were calculated using wall thickness measurements determined optically on cross sections of each bar after testing.

Six specimens of each Task I alloy/coating combination were creep-rupture tested at 1400, 1600 and 1800°F. Creep and rupture data were generated on the three turbine blade alloys (713C, B1900 and Rene' 80), while only rupture data was generated on the C1023 turbine vane alloy. Tabulations of all creep and stress rupture specimen data are given in Tables 3-XI through 3-XIV. Figures 3-14 through 3-17 show Larson-Miller stress rupture life comparisons of baseline coated and AEP 32 coated alloys. Similar Larson-Miller 1% creep life comparisons are shown in Figures 3-18, 3-19 and 3-20. The curves drawn through the Larson-Miller parameter versus stress data points in the figures are the best fit second order polynomial equation derived from a least squares regression analysis of the data points.

The creep and rupture properties of AEP 32 coated Rene' 80 and B1900 were somewhat higher than their baseline coated properties. The AEP 32 coated 713C and C1023 rupture properties were essentially equivalent to their baseline Alpak coated properties at 1600 and 1800°F. At 1400°F, however, the AEP 32 coated properties were somewhat lower than the Alpak coated properties due to the finer gamma prime produced by the faster cooling rate from the diffusion temperature in the Alpak process.

## Table 3-XI

## Summary of Coated Alloy 713C Creep-Rupture Data

(Tubular test bars - nominal wall thickness of 0.037 inch)

| S/N | Coating | Test Temp, °F | Stress ksi | Rupture Time, Hrs. | Elong. % | 1.0% Creep, Hrs. | 3.0% Creep, Hrs |
|---|---|---|---|---|---|---|---|
| | AEP 32 | | | | | | |
| 1 | | 1800 | 18.5 | 23.6 | 10.5 | 16 | 23 |
| 2 | | 1800 | 16.6 | 44.3 | 4.9 | 14 | 36 |
| 3 | | 1800 | 17.4 | 50.9 | 5.6 | 26 | 46 |
| 4 | | 1800 | 15.4 | 57.5 | 11.1 | 22 | 50 |
| 5 | | 1800 | 15.6 | 82.6 | 6.9 | 37 | 75 |
| 6 | | 1800 | 15.5 | 91.5 | 7.5 | 34 | 76 |
| 7 | | 1600 | 45.8 | 7.2 | 4.0 | 4 | -- |
| 8 | | 1600 | 40.1 | 21.1 | 4.0 | 12 | -- |
| 9 | | 1600 | 38.5 | 39.0 | 7.7 | 20 | -- |
| 10 | | 1600 | 45.2 | 10.4 | 3.4 | -- | -- |
| 11 | | 1600 | 45.1 | 14.0 | 3.5 | 8 | -- |
| 12 | | 1600 | 45.9 | 27.7 | 2.6 | 18 | -- |
| 13 | | 1400 | 79.6 | 27.0 | 3.0 | 18 | -- |
| 14 | | 1400 | 93.0 | 1.7 | 1.9 | -- | -- |
| 15 | | 1400 | 90.0 | 4.2 | 3.9 | 3 | -- |
| 16 | | 1400 | 91.2 | 6.1 | 4.3 | 3 | -- |
| 17 | | 1400 | 90.6 | 10.0 | 4.6 | 6 | -- |
| | Alpak | | | | | | |
| 19 | | 1800 | 14.5 | 52.0 | 7.1 | 17 | 42 |
| 20 | | 1800 | 14.7 | 135.1 | 10.0 | 62 | 120 |
| 21 | | 1800 | 14.3 | 150.8 | 4.7 | 88 | 147 |
| 22 | | 1800 | 14.3 | 175.8 | 8.2 | 90 | 160 |
| 23 | | 1800 | 14.3 | 183.8 | 4.7 | 88 | 173 |
| 24 | | 1800 | 13.7 | 246.6 | 9.4 | 120 | 232 |
| 25 | | 1600 | 37.1 | 56.6 | 4.0 | 33 | -- |
| 26 | | 1600 | 36.4 | 71.1 | 3.5 | 52 | -- |
| 27 | | 1600 | 33.0 | 138.2 | 6.6 | 63 | 127 |
| 28 | | 1600 | 40.8 | 24.8 | 4.0 | 17 | -- |
| 29 | | 1600 | 44.1 | 25.3 | 5.2 | 16 | 25 |
| 30 | | 1600 | 43.9 | 25.3 | 4.7 | 17 | 25 |
| 31 | | 1400 | 73.1 | 51.5 | 2.0 | -- | -- |
| 32 | | 1400 | 70.0 | 110.8 | 4.2 | -- | -- |
| 33 | | 1400 | 71.4 | 133.9 | 1.8 | -- | -- |
| 34 | | 1400 | 74.1 | 67.6 | 2.5 | 56 | -- |
| 35 | | 1400 | 76.6 | 107.2 | 1.2 | -- | -- |
| 36 | | 1400 | 74.9 | 110.0 | 3.1 | -- | -- |

## Table 3-XII

## Summary of Coated B1900 Creep Rupture Data

(Tubular test bars - nominal wall thickness of 0.037 inch)

| S/N | Coating | Test Temp, °F | Stress ksi | Rupture Time | Elong % | 1.0% Creep, Hrs. | 3.0% Creep, Hrs. |
|---|---|---|---|---|---|---|---|
| | AEP 32 | | | | | | |
| 1 | | 1800 | 21.1 | 40.6 | 5.6 | 18 | 36 |
| 2 | | 1800 | 19.8 | 152.4 | 5.9 | 108 | 150 |
| 3 | | 1800 | 18.6 | 158.0 | 8.4 | 92 | 152 |
| 4 | | 1800 | 21.0 | 164.6 | 8.2 | 80 | 155 |
| 5 | | 1800 | 19.4 | 190.0 | 7.0 | 98 | 170 |
| 7 | | 1600 | 44.9 | 95.8 | 4.4 | 42 | 94 |
| 8 | | 1600 | 44.1 | 137.9 | 5.1 | 50 | 123 |
| 9 | | 1600 | 40.0 | 218.4 | 3.7 | 75 | 208 |
| 10 | | 1600 | 41.9 | 364.2 | 7.5 | 167 | 352 |
| 11 | | 1600 | 52.5 | 32.6 | 4.4 | 11 | 31 |
| 12 | | 1600 | 51.0 | 34.3 | 4.6 | 13 | 32 |
| 13 | | 1400 | 77.0 | 21.9 | 4.4 | -- | -- |
| 14 | | 1400 | 72.8 | 42.1 | 2.0 | -- | -- |
| 15 | | 1400 | 77.2 | 131.1 | 3.1 | 106 | -- |
| 16 | | 1400 | 69.9 | 281.4 | 3.4 | 208 | -- |
| 17 | | 1400 | 84.9 | 5.7 | 0.9 | -- | -- |
| 18 | | 1400 | 86.7 | 13.0 | 1.5 | 12 | -- |
| | PWA 73 | | | | | | |
| 19 | | 1800 | 19.4 | 18.0 | 9.3 | 7 | 15 |
| 20 | | 1800 | 19.8 | 45.2 | 8.8 | 23 | 42 |
| 21 | | 1800 | 20.0 | 163.2 | 12.2 | 75 | 150 |
| 22 | | 1800 | 19.8 | 193.4 | 7.9 | 127 | 192 |
| 23 | | 1800 | 19.9 | 234.9 | 8.0 | 130 | 233 |
| 25 | | 1600 | 43.3 | 64.4 | 5.7 | 26 | 63 |
| 26 | | 1600 | 40.9 | 84.0 | 5.2 | 58 | -- |
| 27 | | 1600 | 41.6 | 120.1 | 4.1 | 55 | 119 |
| 28 | | 1600 | 54.1 | 14.6 | 3.5 | 6 | -- |
| 29 | | 1600 | 50.9 | 25.6 | 3.4 | 13 | -- |
| 30 | | 1600 | 58.7 | 8.8 | 5.5 | 4 | 8 |
| 31 | | 1400 | 77.0 | 10.7 | 1.4 | -- | -- |
| 32 | | 1400 | 77.2 | 11.3 | 1.5 | -- | -- |
| 33 | | 1400 | 75.5 | 15.9 | 1.5 | -- | -- |
| 34 | | 1400 | 68.2 | 158.9 | 1.5 | -- | -- |
| 35 | | 1400 | 82.2 | 4.6 | 1.6 | -- | -- |
| 36 | | 1400 | 88.2 | 7.3 | 2.7 | -- | -- |
| 37 | | 1400 | 93.9 | 0.9 | 1.1 | -- | -- |

## Table 3-XIII

## Summary of Coated Rene' 80 Creep Rupture Data

(Tubular test bars - nominal wall thickness of 0.037 inch)

| S/N | Coating | Test Temp., °F | Stress ksi | Rupture Time, Hrs. | Elong. % | 1.0% Creep, Hrs. | 3.0% Creep, Hrs. |
|---|---|---|---|---|---|---|---|
| | AEP 32 | | | | | | |
| 1 | | 1800 | 20.0 | 70.1 | 8.4 | 30 | 66 |
| 2 | | 1800 | 22.7 | 96.2 | 10.7 | 31 | 67 |
| 3 | | 1800 | 19.7 | 105.9 | 8.6 | 40 | 82 |
| 4 | | 1800 | 20.7 | 123.2 | 6.5 | 50 | 104 |
| 5 | | 1800 | 18.8 | 132.6 | 5.0 | 70 | 127 |
| 6 | | 1800 | 19.6 | 145.7 | 10.5 | 46 | 109 |
| 7 | | 1600 | 44.3 | 81.1 | 5.2 | 33 | 76 |
| 8 | | 1600 | 43.6 | 106.8 | 11.7 | 32 | 82 |
| 9 | | 1600 | 44.5 | 155.9 | 12.0 | 67 | 120 |
| 10 | | 1600 | 46.9 | 60.2 | 7.7 | 18 | 48 |
| 11 | | 1600 | 47.1 | 105.9 | 6.9 | 36 | 83 |
| 12 | | 1600 | 46.8 | 116.5 | 8.6 | 35 | 92 |
| 13 | | 1400 | 83.7 | 184.0 | 7.6 | 40 | 140 |
| 14 | | 1400 | 83.3 | 247.0 | 10.2 | 50 | 180 |
| 15 | | 1400 | 74.9 | 491.0 | 7.6 | 100 | 385 |
| 16 | | 1400 | 106.7 | 4.9 | 7.6 | -- | -- |
| 17 | | 1400 | 92.4 | 18.8 | 7.4 | 3 | 12 |
| 18 | | 1400 | 90.8 | 33.4 | 4.4 | 13 | 33 |
| | CoDep B-1 | | | | | | |
| 19 | | 1800 | 19.6 | 52.1 | 12.2 | 18 | 43 |
| 20 | | 1800 | 19.2 | 64.3 | 12.6 | 24 | 57 |
| 21 | | 1800 | 18.4 | 66.1 | 8.9 | 20 | 58 |
| 22 | | 1800 | 19.6 | 71.7 | 7.6 | 26 | 63 |
| 23 | | 1800 | 19.2 | 84.9 | 14.0 | 26 | 67 |
| 24 | | 1800 | 19.3 | 87.4 | 10.2 | 25 | 66 |
| 25 | | 1600 | 40.8 | 75.6 | 6.2 | 14 | 66 |
| 26 | | 1600 | 42.8 | 89.8 | 6.9 | 18 | 73 |
| 27 | | 1600 | 43.5 | 96.4 | 13.1 | 16 | 59 |
| 28 | | 1600 | 49.7 | 15.6 | 6.5 | 3 | 13 |
| 29 | | 1600 | 53.2 | 21.0 | 11.2 | 4 | 13 |
| 30 | | 1600 | 48.9 | 34.6 | 6.4 | 6 | 25 |
| 31 | | 1400 | 80.0 | 16.2 | 4.7 | 3 | 32 |
| 32 | | 1400 | 81.5 | 66.0 | 12.5 | 3 | 32 |
| 33 | | 1400 | 80.0 | 90.2 | 5.2 | 23 | 73 |
| 34 | | 1400 | 94.9 | 9.3 | 6.5 | 2 | 7.5 |
| 35 | | 1400 | 90.6 | 12.2 | 8.5 | 1.5 | 7 |
| 36 | | 1400 | 92.7 | 15.6 | 7.2 | 2.5 | 10.5 |
| 37 | | 1400 | 96.4 | 7.1 | 11.4 | 1 | 4 |

## Table 3-XIV

## Summary of Coated C1023 Stress Rupture Data

(Tubular test bars - nominal wall thickness of 0.037 inch)

| S/N | Coating | Test Temp, °F | Stress ksi | Rupture Time, Hrs. | Elong. % |
|---|---|---|---|---|---|
| | AEP 32 | | | | |
| 1 | | 1800 | 20.1 | 31.3 | 12.1 |
| 2 | | 1800 | 19.7 | 40.7 | 9.8 |
| 3 | | 1800 | 18.6 | 41.4 | 5.6 |
| 4 | | 1800 | 18.5 | 51.7 | 5.8 |
| 5 | | 1800 | 17.3 | 59.2 | 7.4 |
| 6 | | 1800 | 17.9 | 61.7 | 5.5 |
| 7 | | 1600 | 41.0 | 48.7 | 4.0 |
| 8 | | 1600 | 39.2 | 50.4 | 7.5 |
| 9 | | 1600 | 40.0 | 52.3 | 4.6 |
| 10 | | 1600 | 37.5 | 76.2 | 5.7 |
| 11 | | 1600 | 44.2 | 196.6 | 7.8 |
| 12 | | 1400 | 74.8 | 50.9 | 2.7 |
| 13 | | 1400 | 73.3 | 109.9 | 2.0 |
| 14 | | 1400 | 68.9 | 117.1 | 3.7 |
| 15 | | 1400 | 74.8 | 127.4 | 3.5 |
| 16 | | 1400 | 71.8 | 205.6 | 2.7 |
| | Alpak | | | | |
| 19 | | 1800 | 16.3 | 64.2 | 5.9 |
| 20 | | 1800 | 15.7 | 74.2 | 8.0 |
| 21 | | 1800 | 14.7 | 93.7 | 8.2 |
| 22 | | 1800 | 16.3 | 100.2 | 8.1 |
| 23 | | 1800 | 15.0 | 103.9 | 5.9 |
| 24 | | 1800 | 11.5 | 887.9 | 6.4 |
| 25 | | 1600 | 40.0 | 41.7 | 5.2 |
| 26 | | 1600 | 45.1 | 44.7 | 3.7 |
| 27 | | 1600 | 42.5 | 47.7 | 3.5 |
| 28 | | 1600 | 40.8 | 69.4 | 6.4 |
| 29 | | 1600 | 42.6 | 75.3 | 3.1 |
| 30 | | 1600 | 41.5 | 78.4 | 3.7 |
| 31 | | 1400 | 79.7 | 83.6 | 2.2 |
| 32 | | 1400 | 73.4 | 100.1 | 3.7 |
| 33 | | 1400 | 81.0 | 107.4 | 1.9 |
| 34 | | 1400 | 76.4 | 153.7 | 1.6 |
| 35 | | 1400 | 75.2 | 164.8 | 3.1 |
| 36 | | 1400 | 75.4 | 198.2 | 4.0 |

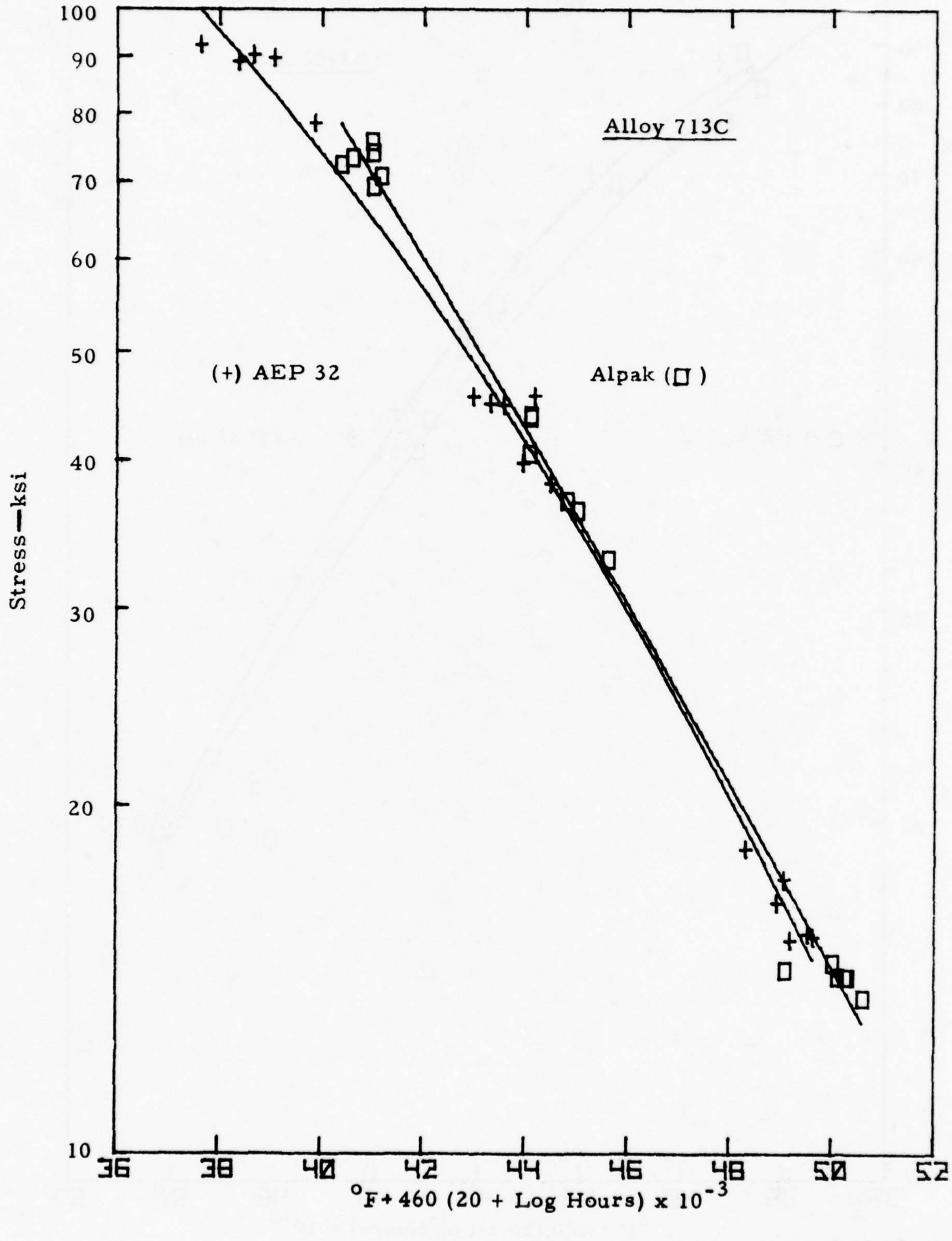


Figure 3-14 **Larson-Miller Stress Rupture Life Comparison of Alpak and AEP 32 Coated Alloy 713C**

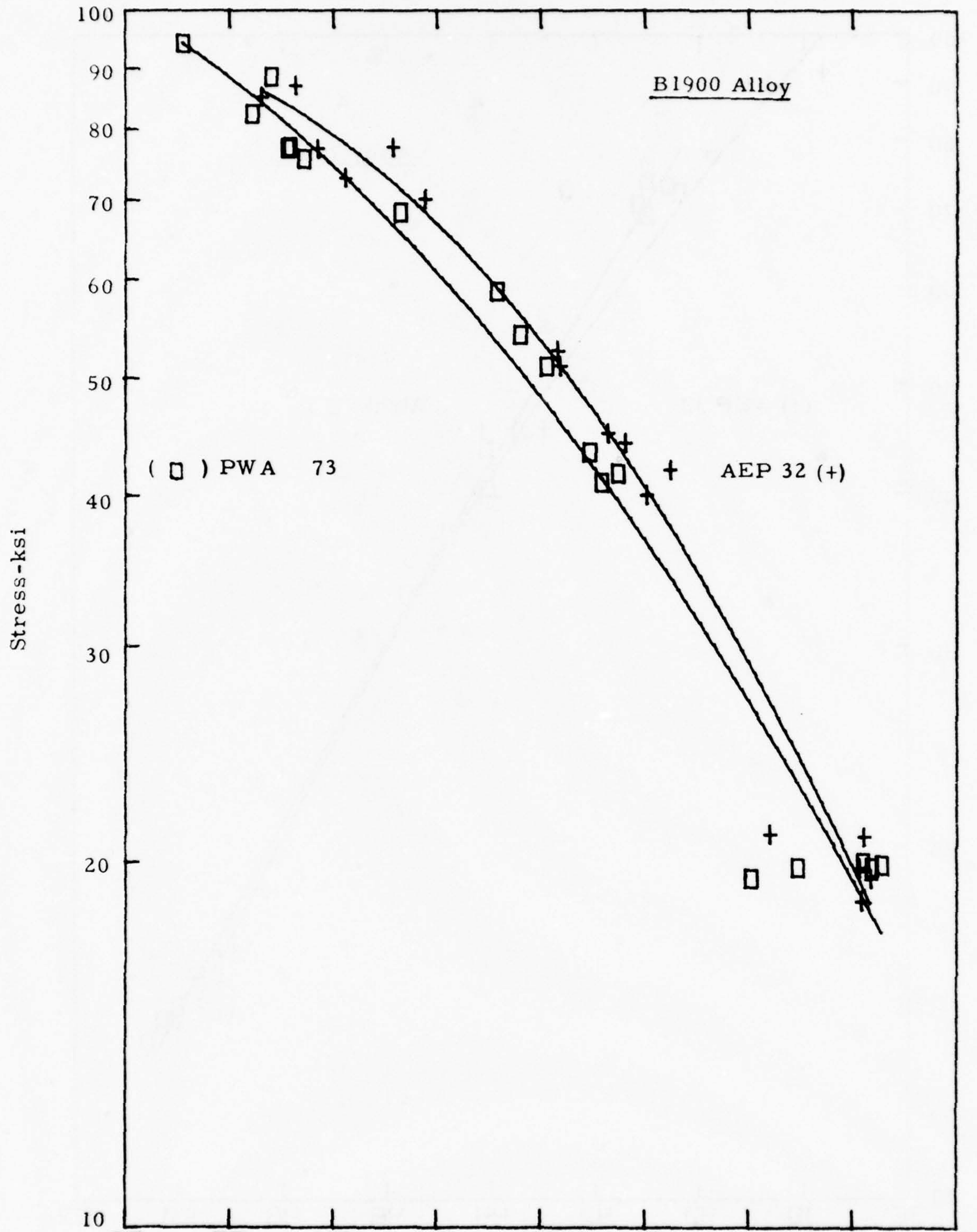


Figure 3-15 Larson-Miller Stress Rupture Life Comparison of PWA 73 and AEP 32 Coated B1900 Alloy

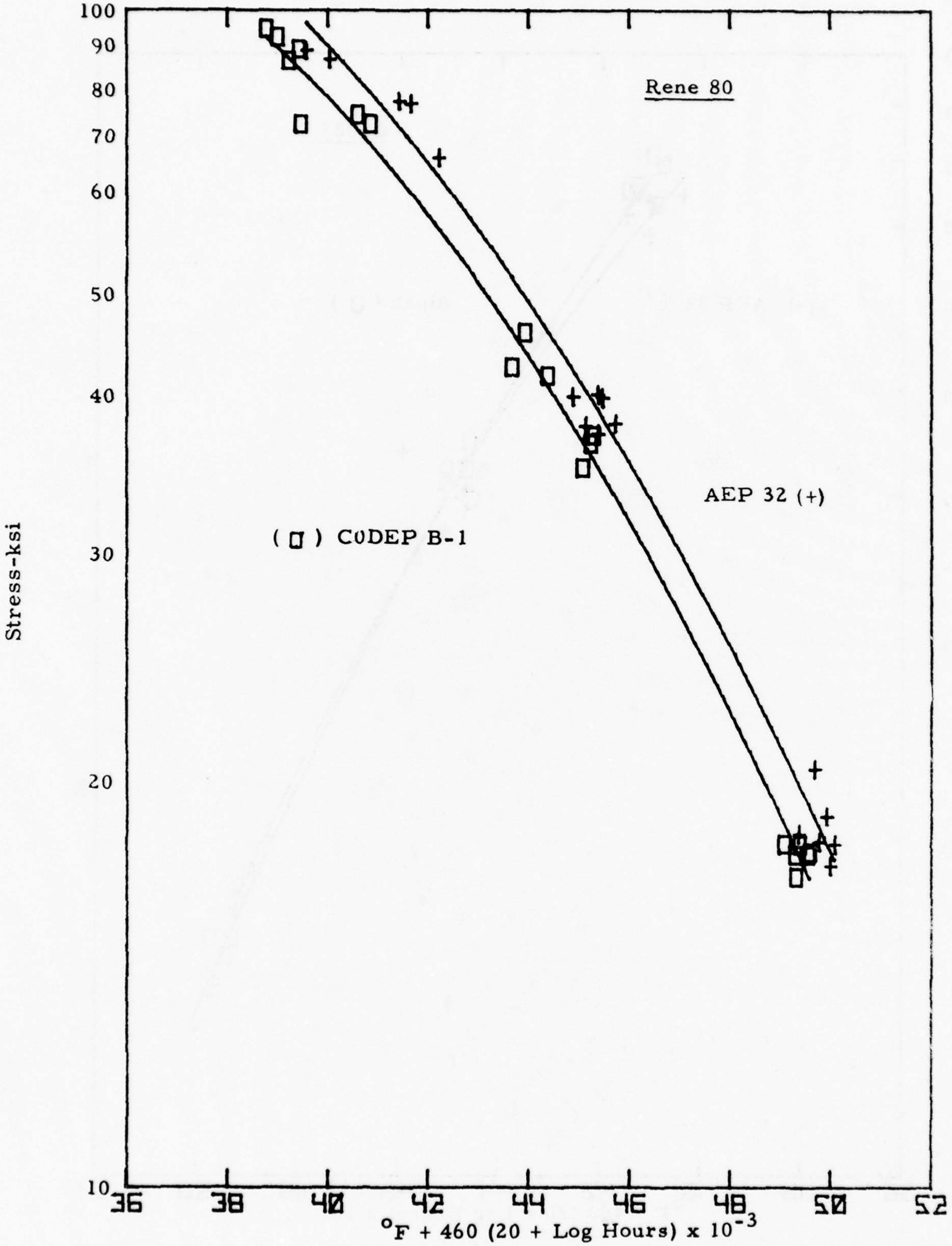


Figure 3-16 Larson-Miller Stress Rupture Life Comparison of Codep B-1 and AEP 32 Coated Rene' 80 Alloy

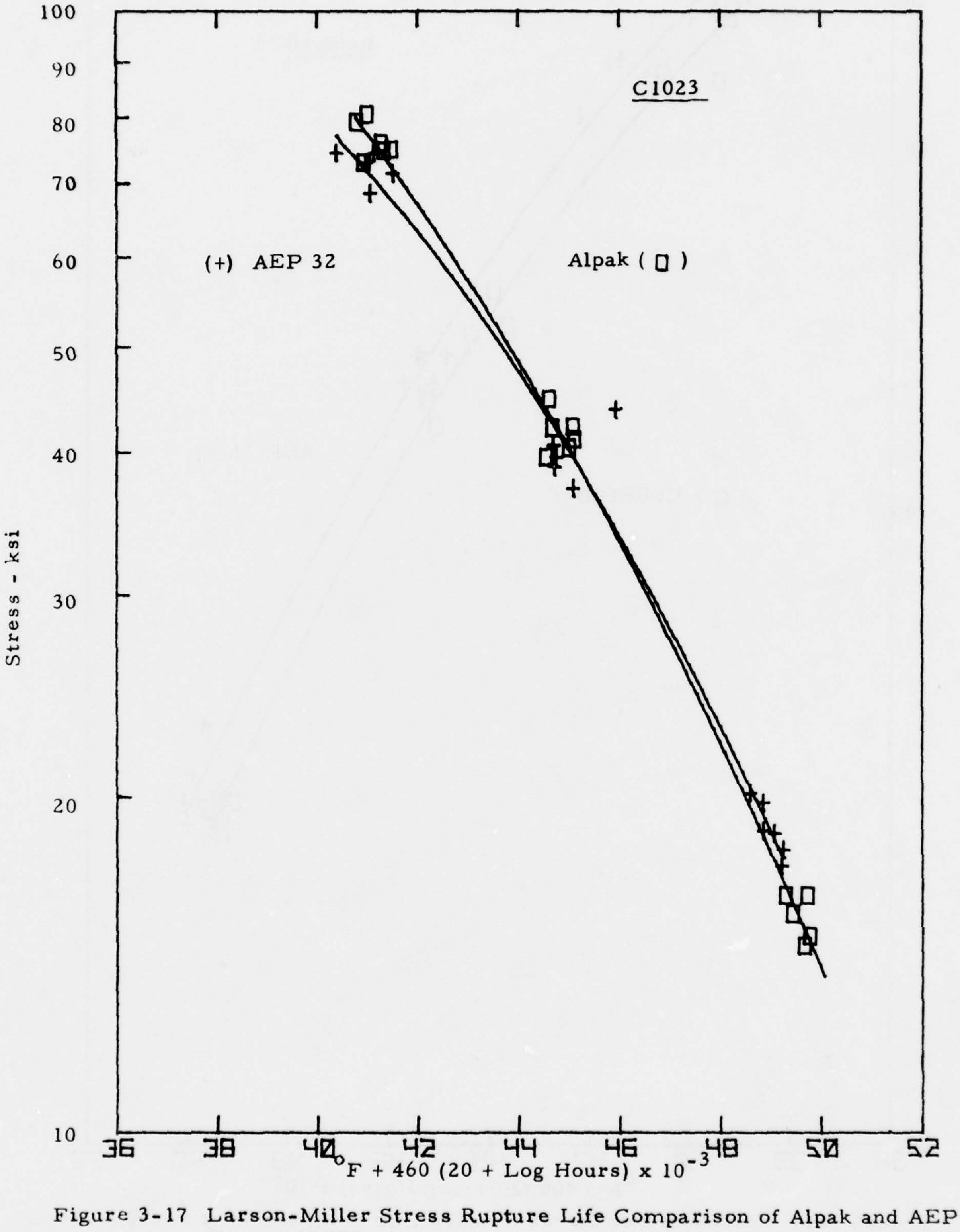


Figure 3-17 Larson-Miller Stress Rupture Life Comparison of Alpak and AEP 32 Coated C1023 Alloy

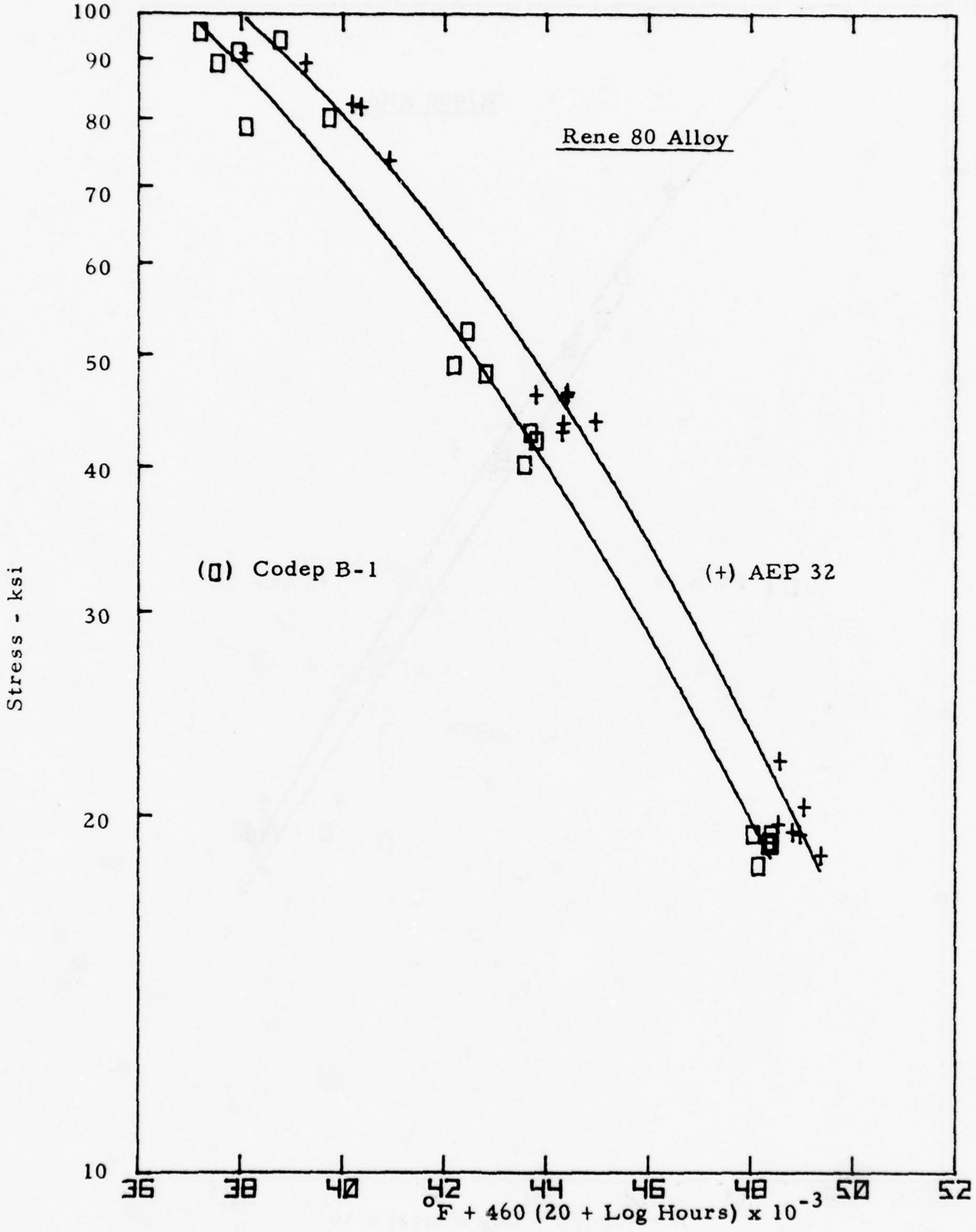


Figure 3-18 Larson-Miller 1% Creep Life Comparison of Codep B-1 and AEP 32 Coated Rene' 80 Alloy

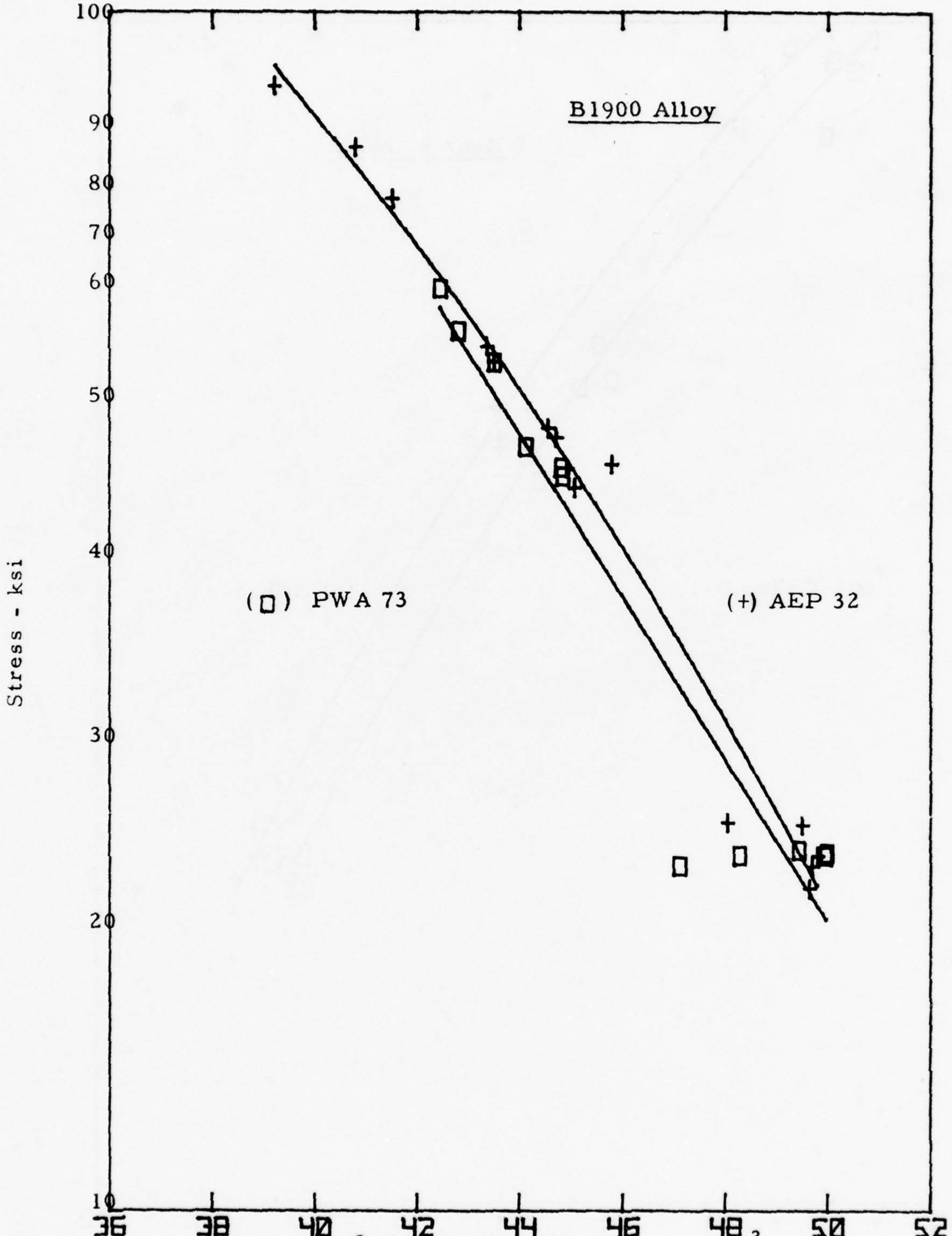


Figure 3-19 Larson Miller 1% Creep Life Comparison of PWA 73 and AEP 32 Coated B1900 Alloy

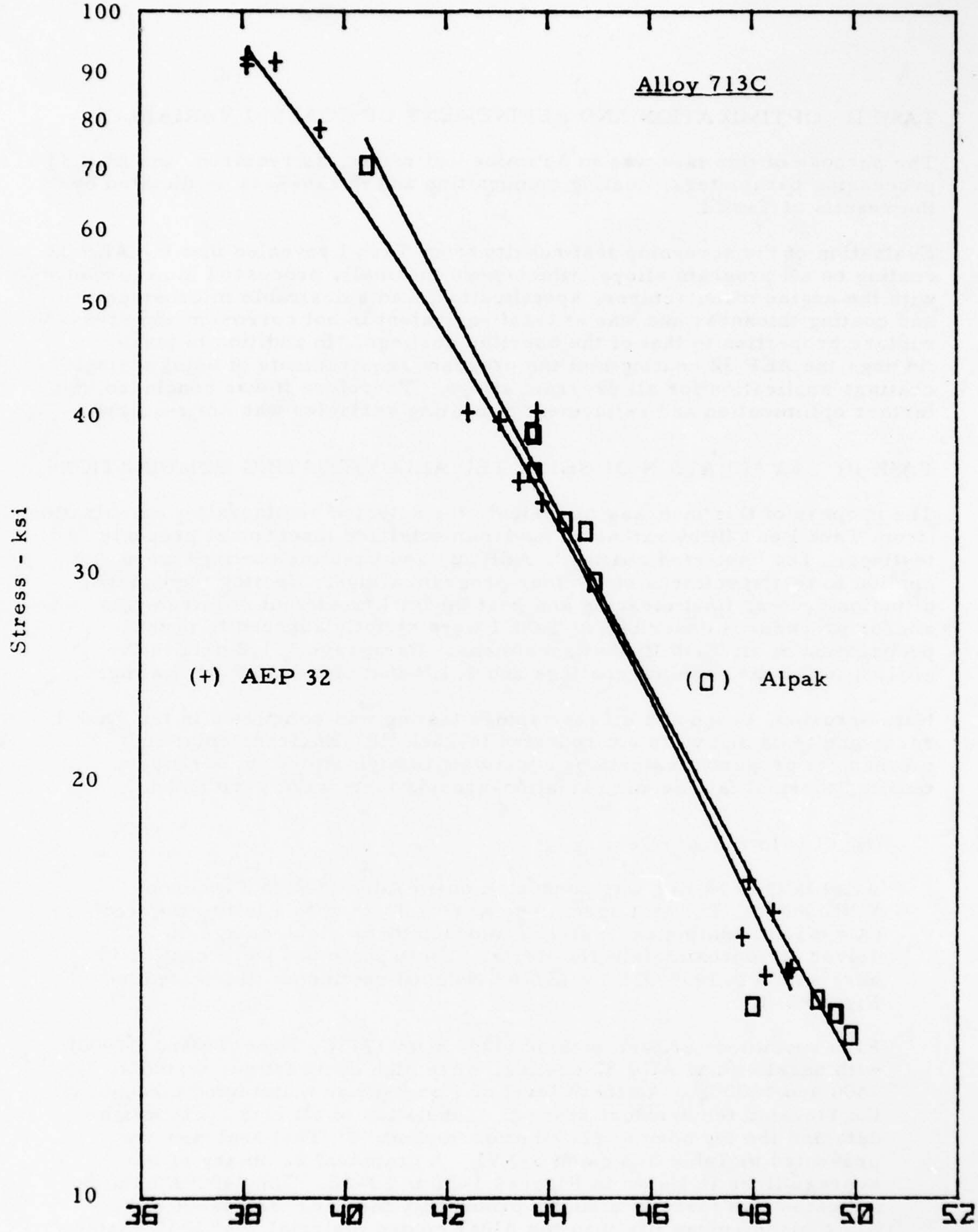


Figure 3-20 Larson-Miller 1% Creep Life Comparison of Alpak and AEP 32 Coated Alloy 713C

## 3.2 TASK II OPTIMIZATION AND REFINEMENT OF COATING VARIABLES

The purpose of this task was to optimize and refine, as required, the AEP 32 processing parameters, coating composition and thicknesses as dictated by the results of Task I.

Evaluation of the screening test results from Task I revealed that the AEP 32 coating on all program alloys, which were thermally processed in accordance with the engine manufacturers specification, had a desirable microstructure and coating thickness and was at least equivalent in hot corrosion and stress rupture properties to that of the baseline coatings. In addition to these findings the AEP 32 coating met the program requirements of being a single coatings application for all program alloys. Therefore it was concluded that further optimization and refinement of coating variables was not required.

## 3.3 TASK III EVALUATION OF SELECTED ALLOY/COATING COMBINATIONS

The purpose of this task was to evaluate the selected coating/alloy combinations (from Task I and II) by extensive environmental and mechanical property testings. The "selected coating", AEP 32, and baseline coatings were applied to test specimens of the four program alloys. Coating techniques, diffusion cycles, final cleaning and post thermal treatment requirements and/or procedures described in Task I were strictly adhered to in the preparation of all Task III test specimens. Paragraph 3.1.2 details the application of the baseline coatings and 3.1.3 that of the AEP 32 coating.

Hot corrosion, creep and stress rupture testing was completed in the Task I screening tests and were not repeated in Task III. Environmental and mechanical property evaluations consisting of high and low cycle fatigue, tensile, thermal fatigue and oxidation-erosion tests were performed.

### 3.3.1 High Cycle Fatigue Testing

Axial fatigue testing was conducted on an Amsler High Frequency Vibrophore. The test specimens were subjected to a fully reversed ($A = \infty$) alternating axial stress imposed by an electromagnetic driver at approximately 166 Hertz. Test specimens were cast solid bars with a 0.195" O.D. x 13/16" reduced section as illustrated in Figure 3-1.

Five specimens of each turbine blade alloy (713C, Rene '80 and B1900) with baseline and AEP 32 coating, were high cycle fatigue tested at 1400 and 1600°F. A stress level of ± 35 ksi was maintained throughout the elevated temperature testing. Tabulation of all high cycle fatigue data and the log normal distribution Student "T" Test analyses are presented in Table 3-XV and 3-XVI. A graphical summary of the average lives is shown in Figures 3-21 and 3-22. The 1400°F data indicates that there is a 86.4% probability that AEP 32 coated 713C has a higher mean life than the Alpak coated material. AEP 32 coated Rene' 80 shows a 62.8% probability of a higher mean life than Codep B-1 coated material. The AEP 32 coated B1900 has a 36.3% probability of having a lower mean life than PWA 73 coated material but the difference in the mean lives is only $2 \times 10^6$ cycles.

The 1600°F data show that the AEP 32 coated bars of all three alloys had slightly higher mean lives than their baseline coated bars, but the probability of the means being different was only 10-33%.

### 3.3.2 Low Cycle Fatigue Testing

Strain-controlled, axial, low cycle fatigue tests were performed by Mar-Test Inc., Cincinnati, Ohio. In these elevated temperature tests the specimens were heated inductively and temperatures were controlled using three spot welded chromel-alumel thermocouples and solid-state controllers. These tests were performed in air at a frequency of 20 cpm, $A = \infty$, and at a temperature of 1600°F. The test specimens, as illustrated in Figure 3-1, were cast solid bars with a 0.25" O.D. x 0.750" smooth reduced section.

Tables 3-XVII, 3-XVIII and 3-XIX summarize the test results provided by Mar-Test, Inc. These include on each specimen a measured modulus value, stress range, stress and strain values at the start of the test and at half-life, the value of the tensile load at failure, the number of cycles to crack initiation (Ni), cycles to failure, and the location of failure. A log normal distribution Student t test analysis is presented in Table 3-XX for the various alloy/coating combinations. Figures 3-23, 3-24 and 3-25 show the low cycle fatigue comparison of AEP 32 and baseline coated turbine blade alloys at two strain controlled levels. Evaluation of the above data indicates that AEP 32 is equivalent to PWA 73 with a slightly higher low cycle fatigue life than Alpak or Codep B-1 on their respective base alloys.

## Table 3-XV

## High Cycle Fatigue Test Summary

Test Conditions: 1400°F; ± 35 ksi; A =∞ ; 166 Hertz

| Alloy/Coating | Specimen Cycles to Failure ($10^6$) | | | | | Log Normal Distribution Student t Test Analysis (1) | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | $\overline{X}(10^6)$ | $\sigma$(log) | % Prob. |
| 713C/Alpak | 3.032 | 4.757 | 14.904 | 15.860 | --- | 7.641 | .360 | 86.4 |
| 713C/AEP 32 | 9.804 | 15.253 | 18.711(2) | 42.570 | --- | 18.578 | .267 | |
| Rene 80/ Codep B-1 | 20.697 | 24.474(2) | 34.704 | 50.106(2) | 94.336 | 38.363 | .264 | 62.8 |
| Rene 80/ AEP 32 | 28.008 | 45.564(2) | 53.600 | 62.363 | 96.161(2) | 52.796 | .196 | |
| B1900/ PWA 73 | 3.044 | 4.359 | 8.168(2) | 9.267(2) | 22.317 | 7.415 | .333 | 36.3 |
| B1900/ AEP 32 | 2.182 | 3.447 | 3.649(2) | 5.183(2) | 36.351 | 5.530 | .476 | |

(1) $\overline{X}$ = mean cycles to failure; $\sigma$(log) = log standard deviation; % prob = probability of specimens having different population means

(2) failure originated in the base metal; all others originated in the coating.

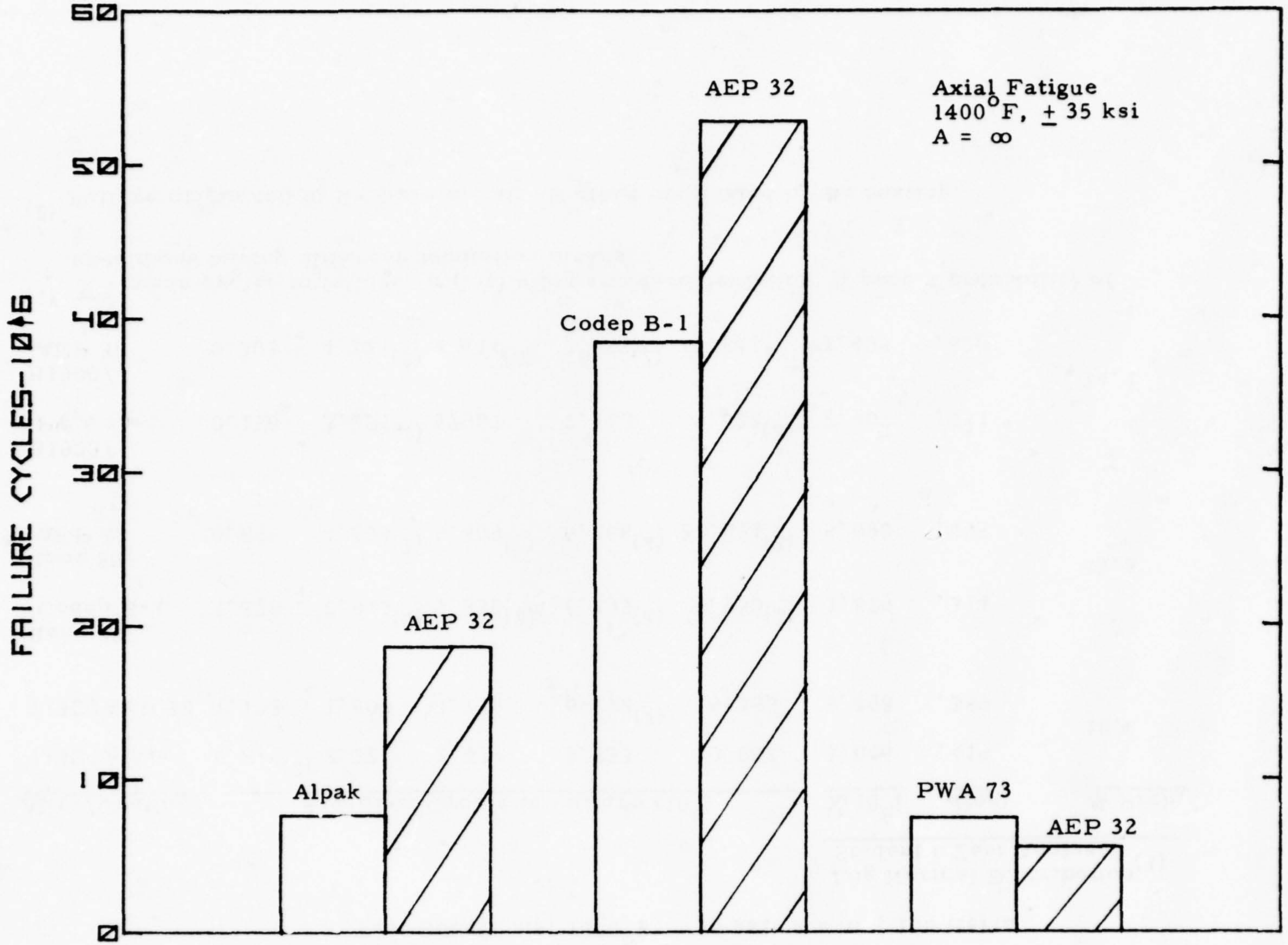


Figure 3-21 Graphic summary of average 1400°F high cycle fatigue lives

## Table 3-XVI

## High Cycle Fatigue Test Summary

Test Conditions: 1600$^\circ$F; $\pm$ 35 ksi; A = $\infty$ ; 166 Hertz

| Alloy/Coating | Specimen Cycles to Failure ($10^6$) | | | | | Log Normal Distribution Student t Test Analysis $^{(1)}$ | | |
|---|---|---|---|---|---|---|---|---|
| | | | | | | $\overline{X}(10^6)$ | $\sigma$(log) | % Prob. |
| 713C/Alpak | 0.814$^{(2)}$ | 2.226 | 2.471 | 5.833 | 10.052 | 3.046 | .419 | 10.4 |
| 713C/AEP 32 | 1.178 | 1.500 | 3.749 | 6.272$^{(2)}$ | 9.388 | 3.298 | .389 | |
| Rene 80/ Codep B-1 | 1.378 | 2.913$^{(2)}$ | 3.830$^{(2)}$ | 6.393$^{(2)}$ | 8.930$^{(2)}$ | 3.879 | .314 | 33.5 |
| Rene 80/ AEP 32 | 0.896 | 4.803$^{(2)}$ | 5.809$^{(2)}$ | 6.268$^{(2)}$ | 21.804$^{(2)}$ | 5.090 | .495 | |
| B1900/ PWA 73 | 0.156 | 3.255$^{(2)}$ | 5.967 | 7.118 | 9.622$^{(2)}$ | 2.907 | .731 | 14.1 |
| B1900/ AEP 32 | 0.303 | 4.271$^{(2)}$ | 4.414$^{(2)}$ | 7.583$^{(2)}$ | 11.841 | 3.483 | .620 | |

(1) $\overline{X}$ = mean cycles to failure; $\sigma$ (log) = log standard deviation; % prob = probability of specimens having different population means

(2) Failure originated in the base metal; all other originated in the coating.

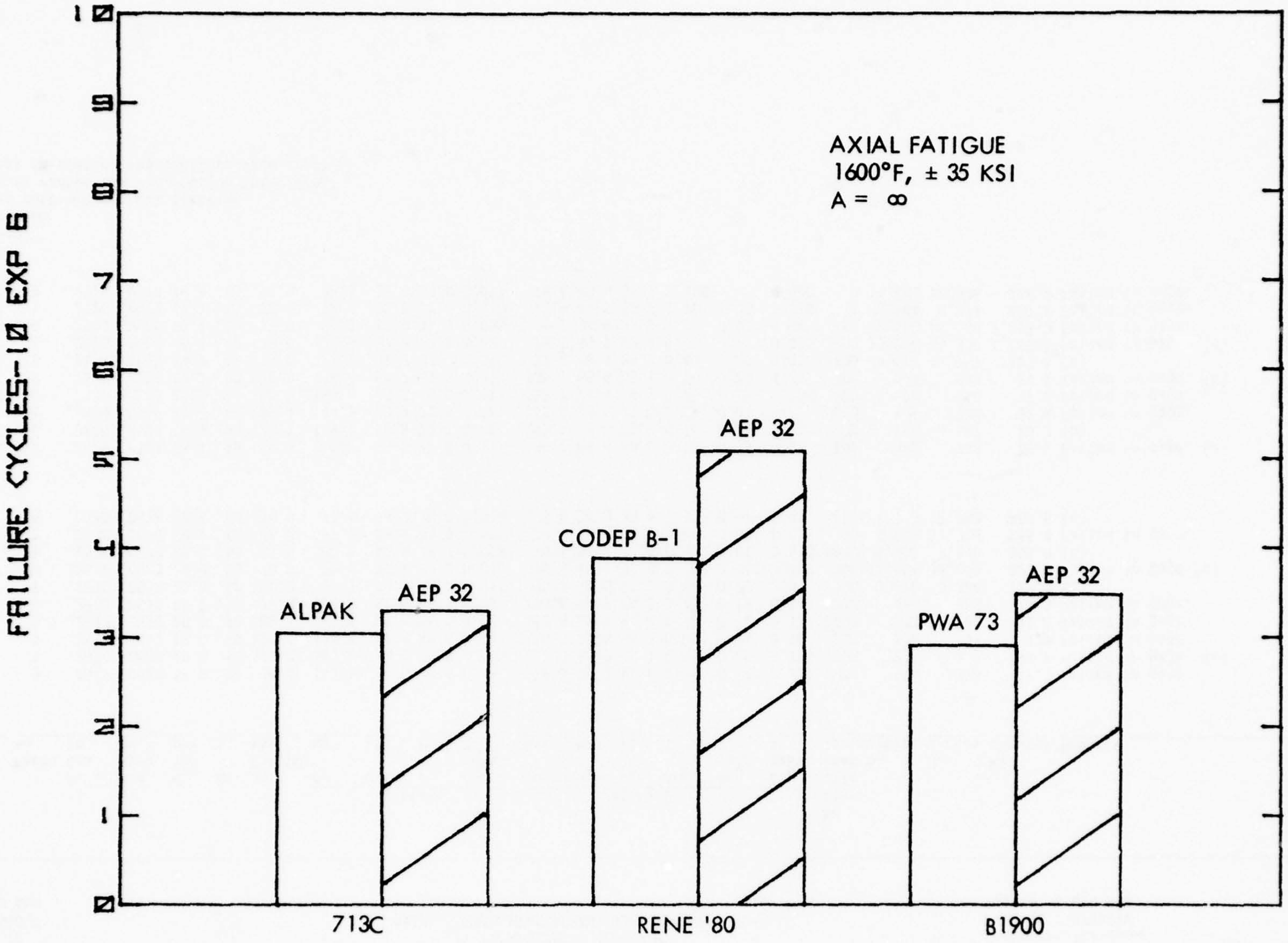


Figure 3-22 Graphic summary of average 1600°F high cycle fatigue lives

## Table 3-XVII

$\alpha = 8.0 \times 10^{-6}$
Temp. = 1600°F
Freq. = 20 cpm
A = ∞

LCF DATA SUMMARY FOR 713C
AXIAL STRAIN MEASUREMENT AND CONTROL

Engineer: Thevenow
P.O. No.: H763976
Job No. : 019-048

| | | | | | | | at start | | | | at $N_f/2$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spec. No. | Mach. No. | R.T. Dia. in. | Hot Area in.$^2$ | E, $10^6$ psi | $\Delta\varepsilon$ % | $\Delta\sigma$ PSEUDO ksi | $\Delta\sigma$ ksi | $\sigma_t$ ksi | $\sigma_c$ ksi | $\Delta\varepsilon_p$ meas. % | $\Delta\sigma$ ksi | $\sigma_t$ ksi | $\sigma_c$ ksi | $\Delta\varepsilon_e$ % | $\Delta\varepsilon_p$ calc. % | $\Delta\varepsilon_p$ meas. % | $N_f$ tensile load lbs. | $N_i$ cycles | $N_f$ cycles | $N_f$ minutes | Remarks |
| ALPAK | | | | | | | | | | | | | | | | | | | | | |
| ALPAK-1 | 9 | .2542 | .0520 | 18.5 | .90 | 166.5 | 145.6 | 74.0 | 71.6 | 0.18 | 139.8 | 70.2 | 69.6 | 0.76 | 0.14 | 0.205 | 3200 | 146 | 226 | 11.3 | Failed in gage. |
| ALPAK-2 | 9 | .2520 | .0503 | 19.0 | .90 | 171.0 | 167.0 | 83.1 | 83.9 | 0.095 | 161.0 | 81.9 | 79.1 | 0.85 | 0.05 | 0.125 | 1250 | 232 | 392 | 19.6 | Failed in gage. (a) |
| ALPAK-3 | 9 | .2540 | .0519 | 18.9 | .90 | 170.1 | 154.1 | 75.1 | 79.0 | 0.14 | 149.3 | 72.6 | 76.7 | 0.79 | 0.11 | 0.16 | 200 | 123 | 143 | 7.1 | Failed in gage. |
| ALPAK-4 | 9 | .2543 | .0520 | 20.9 | .90 | 188.1 | 170.0 | 85.0 | 85.0 | 0.16 | 163.5 | 82.1 | 81.4 | 0.78 | 0.12 | 0.18 | 3400 | 235 | 263 | 13.2 | Failed in gage. |
| ALPAK-5 | 9 | .2530 | .0515 | 19.7 | .90 | 177.3 | 157.3 | 81.6 | 75.7 | 0.15 | 153.4 | 79.2 | 74.2 | 0.78 | 0.12 | 0.19 | 1300 | 266 | 356 | 17.8 | Failed in gage. |
| ALPAK-6 | 15 | .2530 | .0515 | 20.0 | .50 | 100.0 | 97.5 | 48.5 | 49.0 | 0.012 | 95.7 | 50.5 | 45.2 | 0.48 | 0.02 | 0.02 | 2300 | 3,266 | 3,386 | 169.3 | (b) |
| ALPAK-7 | 9 | .2522 | .0503 | 19.8 | .40 | 79.2 | 78.4 | 39.2 | 39.2 | 0.012 | 78.9 | 43.1 | 35.8 | 0.398 | 0.002 | 0.012 | 2300* | 16,364 | 16,578 | 823.9 | Failed in gage.(c) |
| ALPAK-8 | 15 | .2520 | .0503 | 20.4 | .40 | 81.6 | 80.5 | 40.8 | 39.7 | 0.008 | 79.5 | 51.7 | 27.8 | 0.39 | 0.01 | 0.015 | 2900 | 6,800 | 7,110 | 355.0 | (b) |
| ALPAK-9 | 9 | .2530 | .0515 | 19.2 | .40 | 76.8 | 77.8 | 38.9 | 38.9 | 0.006 | 77.8 | 38.9 | 38.9 | 0.40 | 0.00 | 0.015 | 50 | 9,948 | 11,308 | 565.4 | Failed in gage. |
| ALPAK-10 | 15 | .2533 | .0516 | 19.5 | .40 | 78.0 | 77.4 | 38.7 | 38.7 | 0.010 | 75.6 | 36.8 | 38.8 | 0.39 | 0.01 | 0.01 | ($^1$) | ($^1$) | 17,753 | 887.6 | (b) |
| AEP-32 | | | | | | | | | | | | | | | | | | | | | |
| AEP-32-13C | 15 | .2520 | .0503 | 18.4 | .90 | 165.6 | 140.2 | 68.6 | 71.6 | 0.21 | 138.2 | 68.6 | 69.6 | 0.75 | 0.15 | 0.20 | 700 | 382 | 702 | 35.1 | Failed in gage. (a) |
| AEP-32-14C | 15 | .2520 | .0503 | 19.9 | .90 | 179.1 | 149.7 | 72.6 | 77.1 | 0.22 | 149.1 | 73.6 | 75.5 | 0.75 | 0.15 | 0.21 | 3800 | 438 | 467 | 23.3 | (b) |
| AEP-32-15C | 9 | .2530 | .0515 | 20.6 | .90 | 185.4 | 144.3 | 72.4 | 71.9 | 0.26 | 142.3 | 70.5 | 71.8 | 0.69 | 0.21 | - | 600 | 436 | 756 | 37.8 | Failed in gage. |
| AEP-32-16C | 15 | .2530 | .0515 | 20.2 | .90 | 181.8 | 150.8 | 72.8 | 78.0 | 0.21 | 150.7 | 74.4 | 76.3 | 0.75 | 0.15 | 0.205 | 900 | 170 | 340 | 17.0 | Failed in gage. |
| AEP-32-17C | 15 | .2530 | .0515 | 19.2 | .90 | 172.8 | 134.6 | 64.7 | 69.9 | 0.26 | 135.1 | 65.6 | 69.5 | 0.70 | 0.20 | 0.26 | 700 | 374 | 594 | 29.7 | Failed in gage. (a) |
| AEP-32-18C | 15 | .2535 | .0517 | 19.2 | .40 | 76.8 | 77.0 | 39.3 | 37.7 | 0.018 | 77.6 | 48.4 | 29.2 | 0.40 | 0.00 | 0.015 | 2700 | 9,692 | 10,153 | 507.6 | (b) |
| AEP-32-19C | 1 | .2520 | .0503 | 18.4 | .40 | 73.6 | 75.5 | 37.8 | 37.7 | 0.02 | 75.1 | 45.7 | 29.4 | 0.41 | - | 0.025 | 80 | 13,200 | 25,332 | 1,266.6 | Failed in gage. (a) |
| AEP-32-20C | 9 | .2515 | .0509 | 19.4 | .40 | 77.6 | 80.2 | 38.9 | 41.3 | 0.035 | 76.2 | 38.9 | 37.3 | 0.39 | 0.01 | 0.04 | 150 | 10,653 | 21,306 | 1,065.3 | Failed in gage. |
| AEP-32-12C | 1 | .2525 | .0513 | 18.1 | .40 | 72.4 | 72.5 | 35.5 | 37.0 | 0.030 | 72.9 | 44.8 | 28.1 | 0.40 | 0.00 | 0.025 | 0 | 6,884 | 8,024 | 401.2 | Failed in gage. |
| AEP-32-11C | 9 | .2525 | .0513 | 18.6 | .40 | 74.4 | 75.4 | 36.4 | 39.0 | 0.017 | 75.6 | 40.9 | 34.7 | 0.405 | - | 0.020 | 0 | 12,636 | 16,336 | 816.8 | Failed in gage. |

* Near end.
($^1$) Ink problem.
(a) Stopped test after gross cracking.
(b) Failed at radius-uniform section interface.
(c) Internal initiation and small surface crack.

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## Table 3-XVIII

$\alpha = 9.4 \times 10^{-6}$
Temp. = 1600°F
Freq. = 20 cpm
A = ∞

LCF DATA SUMMARY FOR RENE 80 AEP-32 AND Codep B-1
AXIAL STRAIN MEASUREMENT AND CONTROL

Engineer: Thevenow
P.O. No.: H763976
Job No. : 019-048

| Spec. No. | Mach. No. | R.T. Dia. in. | Hot Area in.$^2$ | E, $10^6$ psi | $\Delta\varepsilon$ % | $\Delta\sigma$ PSEUDO ksi | at start $\Delta\sigma$ ksi | at start $\sigma_t$ ksi | at start $\sigma_c$ ksi | at start $\Delta\varepsilon_p$ meas. % | at $N_f/2$ $\Delta\sigma$ ksi | at $N_f/2$ $\sigma_t$ ksi | at $N_f/2$ $\sigma_c$ ksi | at $N_f/2$ $\Delta\varepsilon_e$ % | at $N_f/2$ $\Delta\varepsilon_p$ calc. % | at $N_f/2$ $\Delta\varepsilon_p$ meas. % | $N_f$ tensile load, lbs. | $N_i$ cycles | $N_f$ cycles | $N_f$ minutes | Remarks |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Codep B-1 | | | | | | | | | | | | | | | | | | | | | |
| B1-1 | 9 | .2522 | .0514 | 22.6 | .70 | 158.2 | 126.5 | 66.1 | 60.4 | 0.18 | 127.4 | 65.8 | 61.6 | 0.56 | 0.14 | 0.17 | 3350 | 416 | 468 | 23.4 | Failed out of gage. |
| B1-2 | 9 | .2522 | .0514 | 21.1 | .70 | 147.7 | 119.4 | 58.9 | 60.5 | 0.21 | 114.8 | 58.9 | 55.9 | 0.54 | 0.16 | 0.22 | 600 | 456 | 676 | 33.8 | Failed out of gage. |
| B1-3 | 9 | .2520 | .0513 | 20.0 | .70 | 140.0 | 131.4 | 65.1 | 66.3 | 0.10 | 128.1 | 67.8 | 60.3 | 0.64 | 0.06 | 0.12 | 3300 | 373 | 693 | 34.6 | Failed in gage. |
| B1-4 | 9 | .2516 | .0512 | 23.5 | .70 | 164.5 | 141.3 | 69.8 | 71.5 | 0.14 | 136.4 | 70.2 | 66.2 | 0.58 | 0.12 | 0.13 | 700 | 305 | 610 | 30.5 | (d) |
| B1-5 | 9 | .2510 | .0509 | 20.9 | .70 | 146.3 | 127.7 | 63.3 | 64.4 | 0.14 | 123.8 | 62.9 | 60.9 | 0.59 | 0.11 | 0.16 | 50 | 733 | 1,053 | 52.6 | Failed in gage. |
| B1-6 | 9 | .2522 | .0514 | 21.3 | .52 | 110.8 | 107.4 | 51.0 | 56.4 | 0.04 | 105.1 | 54.7 | 50.4 | 0.49 | 0.03 | 0.065 | 200 | 1,360 | 1,560 | 78.0 | Failed in gage. |
| B1-7 | 9 | .2515 | .0511 | 23.2 | .35 | 81.2 | 79.2 | 41.5 | 37.7 | 0.014 | 80.2 | 43.0 | 37.2 | 0.345 | 0.005 | 0.015 | (a) | (b) | 9,380 | 469.0 | Failed in gage. |
| B1-8 | 9 | .2520 | .0513 | 21.8 | .30 | 65.4 | 61.0 | 31.2 | 29.8 | 0.012 | 62.2 | 38.8 | 23.4 | 0.285 | 0.015 | 0.01 | 750 | 54,089 | 55,689 | 2,784.4 | (d) |
| B1-9 | 9 | .2513 | .0510 | 21.2 | .35 | 74.2 | 76.5 | 37.2 | 39.3 | 0.018 | 76.1 | 44.1 | 32.0 | 0.36 | - | 0.016 | 750 | 20,127 | 26,754 | 1,337.7 | (d) |
| B1-10 | 9 | .2520 | .0513 | 21.1 | .35 | 73.8 | 72.5 | 36.6 | 35.9 | 0.020 | 73.1 | 44.4 | 28.7 | 0.345 | 0.005 | 0.02 | 400 | 14,098 | 19,298 | 964.9 | (d) |
| B1-11 | 9 | .2510 | .0509 | 21.4 | .35 | 74.9 | 73.7 | 36.7 | 37.0 | 0.020 | 72.3 | 44.8 | 27.5 | 0.34 | 0.01 | 0.025 | 400 | 9,451 | 18,903 | 945.6 | (d) |
| AEP-32 | | | | | | | | | | | | | | | | | | | | | |
| AEP-32-1 | 5 | .2517 | .0512 | 19.9 | .70 | 139.3 | 132.8 | 64.4 | 68.4 | 0.09 | 127.5 | 66.6 | 60.9 | 0.64 | 0.06 | 0.11 | 500 | 1,377 | 2,217 | 110.8 | (d) |
| AEP-32-2 | 5 | .2512 | .0510 | 20.6 | .70 | 144.2 | 132.4 | 63.7 | 68.7 | 0.11 | 126.9 | 64.7 | 62.2 | 0.62 | 0.08 | 0.13 | 400 | 578 | 758 | 37.9 | Failed in gage. |
| AEP-32-3 | 9 | .2507 | .0508 | 21.4 | .70 | 149.8 | 144.7 | 71.9 | 72.8 | 0.10 | 139.4 | 72.8 | 66.6 | 0.65 | 0.05 | 0.12 | 3600 | 336 | 459 | 22.9 | Failed out of gage. |
| AEP-32-4 | 5 | .2522 | .0514 | 20.5 | .70 | 143.5 | 122.6 | 60.3 | 62.3 | 0.14 | 117.7 | 59.9 | 57.8 | 0.57 | 0.13 | 0.16 | 700 | 556 | 996 | 49.8 | Failed in gage. |
| AEP-32-5 | 9 | .2490 | .0501 | 21.2 | .70 | 148.4 | 144.5 | 72.8 | 71.7 | 0.07 | 141.7 | 72.2 | 69.5 | 0.67 | 0.03 | 0.08* | 750 | 330 | 866 | 43.3 | (d) |
| AEP-32-6 | 9 | .2522 | .0514 | 21.5 | .35 | 75.2 | 73.0 | 36.6 | 36.4 | 0.012 | 72.0 | 38.9 | 33.1 | 0.335 | 0.015 | 0.12$^+$ | - | - | 20,568 | 1,028.4 | Failed in gage. |
| AEP-32-7 | 5 | .2520 | .0513 | 21.0 | .35 | 73.5 | 72.1 | 36.6 | 35.5 | 0.01 | 71.1 | 43.3 | 27.8 | 0.34 | 0.01 | 0.015 | 550 | (c) | 25,607 | 1,280.3 | (d) |
| AEP-32-8 | 5 | .2520 | .0513 | 21.3 | .35 | 74.6 | 74.5 | 36.6 | 37.9 | 0.01 | 73.5 | 42.9 | 30.6 | 0.345 | 0.005 | 0.014* | 0 | 8,100 | 27,286 | 1,364.3 | Failed in gage. |
| AEP-32-9 | 15 | .2520 | .0513 | 22.7 | .35 | 79.4 | 78.6 | 39.4 | 39.2 | 0.01 | 79.9 | 52.6 | 27.3 | 0.35 | 0.00 | 0.005 | 100 | 18,754 | 20,054 | 1,002.7 | Failed in gage. |
| AEP-32-10 | 15 | .2525 | .0515 | 21.6 | .35 | 75.6 | 75.7 | 37.3 | 38.4 | 0.008 | 76.1 | 44.7 | 31.4 | 0.35 | 0.00 | 0.008$^1$ | 900 | 35,310 | 36,530 | 1,826.5 | Failed out of gage. |

* "$N_f/2$" value actually taken at $N_i$.
$^+$ "$N_f/2$" value actually taken at 3,050 cycles. Test ran 3,050 cycles @ 1600°F - then Lepel shut off. Ran 17,518 more cycles at R.T.
($^1$) "$N_f/2$" value actually taken at 20,640 cycles.
(a) Not recorded.
(b) Not observable - ink problem.
(c) Ink problem - $N_i$ between 13,000 and 24,000 cycles.
(d) Stopped test after gross cracking.

Mar-Test Inc. 11/77.

# Table 3-XIX

$\alpha$ = 9.4 x $10^{-6}$ (assumed)
A = ∞
Freq. = 20 cpm
Temp. = 1600°F

LCF DATA SUMMARY FOR B1900 AEP-32 AND PWA-73
AXIAL STRAIN MEASUREMENT AND CONTROL

Engineer: Thevenow
P.O. No.: H763976
Job No. : 019-048

| | | | | | | | at start | | | | at $N_f/2$ | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Spec. No. | Mach. No. | R.T. Dia. in. | Hot Area in.$^2$ | E, $10^6$ psi | $\Delta\varepsilon$ % | $\Delta\sigma$ PSEUDO ksi | $\Delta\sigma$ ksi | $\sigma_t$ ksi | $\sigma_c$ ksi | $\Delta\varepsilon_p$ meas. % | $\Delta\sigma$ ksi | $\sigma_t$ ksi | $\sigma_c$ ksi | $\Delta\varepsilon_e$ % | $\Delta\varepsilon_p$ calc. % | $\Delta\varepsilon_p$ meas. % | $N_f$ tensile load lbs | $N_i$ cycles | $N_f$ cycles | $N_f$ minutes | Remarks |
| AEP-32 | | | | | | | | | | | | | | | | | | | | | |
| AEP-32-21B | 9 | .2515 | .0511 | 22.0 | .70 | 154.0 | 126.6 | 61.0 | 65.6 | 0.175 | 124.5* | 62.4* | 62.1* | 0.57* | 0.13* | 0.175* | 700 | 380 | 892 | 44.6 | Failed in gage. (a) |
| AEP-32-22B | 9 | .2520 | .0513 | 21.3 | .70 | 149.1 | 129.0 | 64.3 | 64.7 | 0.16 | 124.4 | 64.3 | 60.1 | 0.58 | 0.12 | 0.17 | 700 | 460 | 862 | 43.1 | Failed in gage. |
| AEP-32-23B | 9 | .2515 | .0511 | 20.5 | .70 | 143.5 | 129.7 | 64.6 | 65.1 | 0.12 | 127.8 | 65.8 | 62.0 | 0.62 | 0.08 | 0.12 | 2400 | 746 | 1,266 | 63.3 | Failed in gage. |
| AEP-32-24B | 9 | .2512 | .0510 | 20.1 | .70 | 140.7 | 128.8 | 64.1 | 64.7 | 0.11 | 126.1 | 65.1 | 61.0 | 0.63 | 0.07 | 0.115 | 3100 | 876 | 1,116 | 55.8 | Failed in gage. |
| AEP-32-25B | 15 | .2517 | .0512 | 21.8 | .70 | 152.6 | 130.8 | 66.4 | 64.4 | 0.15 | 127.3 | 63.1 | 64.2 | 0.58 | 0.12 | 0.16 | 800 | 430 | 919 | 46.0 | Failed in gage. (a) |
| AEP-32-26B | 15 | .2508 | .0508 | 23.6 | .35 | 82.6 | 83.5 | 42.7 | 40.8 | 0.16 | 82.7 | 47.8 | 34.9 | 0.35 | 0.00 | 0.015 | 2300 | 12,812 | 12,952 | 647.6 | Failed in gage. |
| AEP-32-27B | 3 | .2538 | .0520 | 21.7 | .35 | 76.0 | 72.5 | 37.1 | 35.4 | 0.01 | 72.5 | 39.8 | 32.7 | 0.33 | 0.02 | 0.016 | 200 | 11,890 | 23,781 | 1,189.0 | Failed in gage. (a) |
| AEP-32-28B | 9 | .2518 | .0512 | 20.1 | .35 | 70.4 | 68.4 | 33.8 | 34.6 | 0.007 | 67.0* | 44.5* | 22.5* | 0.33* | 0.02* | 0.02* | 0 | 10,800 | 34,223 | 1,711.1 | Failed in gage. (b) |
| AEP-32-29B | 3 | .2515 | .0511 | 21.0 | .35 | 73.5 | 71.8 | 36.6 | 35.2 | 0.01 | 72.2 | 39.1 | 33.1 | 0.34 | 0.01 | 0.01 | 50 | 15,100 | 22,660 | 1,133.0 | Failed in gage. (b) |
| AEP-32-30B | 3 | .2512 | .0510 | 21.5 | .35 | 75.2 | 73.3 | 37.8 | 35.5 | 0.01 | 72.7 | 39.4 | 33.3 | 0.34 | 0.01 | 0.013 | 0 | 38,305 | 39,445 | 1,972.3 | Failed in gage. |
| PWA-73 | | | | | | | | | | | | | | | | | | | | | |
| PWA-73-1 | 9 | .2517 | .0512 | 19.4 | .70 | 135.8 | 123.0 | 63.5 | 59.5 | 0.11 | 119.5 | 63.5 | 56.0 | 0.62 | 0.08 | 0.13 | 0 | 779 | 1,459 | 72.9 | Failed in gage. |
| PWA-73-2 | 9 | .2523 | .0514 | 21.4 | .70 | 149.8 | 130.4 | 64.2 | 66.2 | 0.13 | 126.4 | 63.2 | 63.2 | 0.59 | 0.11 | 0.15 | 0 | 536 | 1,073 | 53.7 | Failed in gage. |
| PWA-73-3 | 9 | .2515 | .0511 | 20.0 | .70 | 140.0 | 125.6 | 62.6 | 63.0 | 0.12 | 121.3 | 62.6 | 58.7 | 0.61 | 0.09 | 0.135 | 3150 | 874 | 974 | 48.7 | Failed in gage. |
| PWA-73-4 | 9 | .2518 | .0512 | 20.3 | .35 | 71.0 | 73.2 | 36.1 | 37.1 | 0.018 | 71.1 | 39.1 | 32.0 | 0.35 | 0.00 | 0.02 | 0 | 19,468 | 21,668 | 1,083.4 | Failed in gage. |
| PWA-73-5 | 9 | .2524 | .0514 | 21.9 | .70 | 153.3 | 135.9 | 66.1 | 69.8 | 0.13 | 130.7 | 65.0 | 65.4 | 0.62 | 0.08 | 0.15* | 0 | 460 | 1,097 | 54.8 | Failed in gage. (a) |
| PWA-73-6 | 9 | .2515 | .0511 | 22.2 | .70 | 155.4 | 131.1 | 62.6 | 68.5 | 0.16 | 128.2 | 61.6 | 66.6 | 0.58 | 0.12 | 0.165 | 0 | 568 | 808 | 40.4 | Failed in gage. |
| PWA-73-7 | 15 | .2514 | .0511 | 21.3 | .35 | 74.6 | 73.4 | 36.2 | 37.2 | 0.01 | 72.4 | 36.8 | 35.6 | 0.34 | 0.01 | 0.01 | 1800 | 12,474 | 15,275 | 763.7 | (c) |
| PWA-73-8 | 9 | .2517 | .0512 | 19.9 | .70 | 139.3 | 127.0 | 62.7 | 64.3 | 0.11 | 121.5 | 59.0 | 62.5 | 0.61 | 0.09 | 0.125 | 500 | 984 | 1,848 | 92.4 | Failed in gage. (a) |
| PWA-73-9 | 15 | .2518 | .0512 | 21.6 | .35 | 75.6 | 75.2 | 38.1 | 37.1 | 0.018 | 72.8 | 37.5 | 35.3 | 0.34 | 0.01 | 0.025 | 0 | 35,486 | 36,886 | 1,844.3 | Failed in gage. |
| PWA-73-10 | 9 | .2530 | .0517 | 21.1 | .35 | 73.8 | 72.0 | 36.8 | 35.2 | 0.01 | 73.5 | 38.7 | 34.8 | 0.35 | 0.00 | 0.01 | 0 | 12,493 | 13,393 | 669.6 | Failed in gage. (b) |
| PWA-73-11 | 9 | .2514 | .0511 | 21.5 | .35 | 75.2 | 73.4 | 37.2 | 36.2 | 0.01 | 72.4 | 39.1 | 33.3 | 0.34 | 0.01 | 0.016 | 0 | 43,950 | 46,950 | 2,347.5 | Failed in gage. (b) |

* "$N_f/2$" values actually taken at $N_i$.
(a) Stopped test after gross cracking.
(b) System did not shut down upon specimen separation.
(c) Failed at radius-uniform section interface.
(d)

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## Table 3-XX

## Low Cycle Fatigue Test Summary

Test Conditions: 1600°F/20 cpm/A = ∞ /Strain Control

| | | | | | | | Log Normal Distribution Student t Test Analysis$^{(1)}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| Alloy/Coating | $\Delta\epsilon$ % | Specimen Cycles to Failure | | | | | $\overline{X}$ | $\sigma$(log) | % Prob. |
| 713C/Alpak | .40 | 7,110 | 11,308 | 16,578 | 17,753 | --- | 12,403 | .183 | 43 |
| 713C/AEP 32 | .40 | 8,024 | 10,153 | 16,336$^{(2)}$ | 21,306 | 25,332 | 14,834 | .211 | |
| 713C/Alpak | .90 | 143 | 226 | 263 | 356$^{(2)}$ | 392 | 260 | .174 | 99 |
| 713C/AEP 32 | .90 | 340 | 467 | 594 | 702 | 756 | 549 | .142 | |
| Rene 80/Codep B-1 | .35 | 9,380$^{(2)}$ | 18,903 | 19,298 | 26,754$^{(2)}$ | --- | 17,394 | .192 | 86 |
| Rene 80/AEP 32 | .35 | 20,054 | 25,607 | 27,286 | 36,530 | --- | 26,748 | .107 | |
| Rene 80/Codep B-1 | .70 | 468 | 610 | 676 | 693 | 1,053 | 676 | .127 | 69 |
| Rene/ 80/AEP 32 | .70 | 459 | 758$^{(2)}$ | 866 | 996 | 2,217 | 922 | .248 | |
| B1900/PWA 73 | .35 | 13,393 | 15,275 | 21,668 | 36,886 | 46,950 | 23,825 | .237 | 10 |
| B1900/AEP 32 | .35 | 12,952$^{(2)}$ | 22,660 | 23,781 | 34,223 | 39,445 | 24,821 | .188 | |
| B1900/PWA 73 | .70 | 808 | 974 | 1073 | 1097$^{(2)}$ | 1848 | 1114 | .134 | 49 |
| B1900/AEP 32 | .70 | 862$^{(2)}$ | 892 | 919 | 1116 | 1266$^{(2)}$ | 1000 | .072 | |

(1) $\overline{X}$ = mean cycles to failure; $\sigma$(log) = log standard deviation; % prob. = probability of specimens having different population means

(2) Failure originated in the base metal; all others originated in the coating.

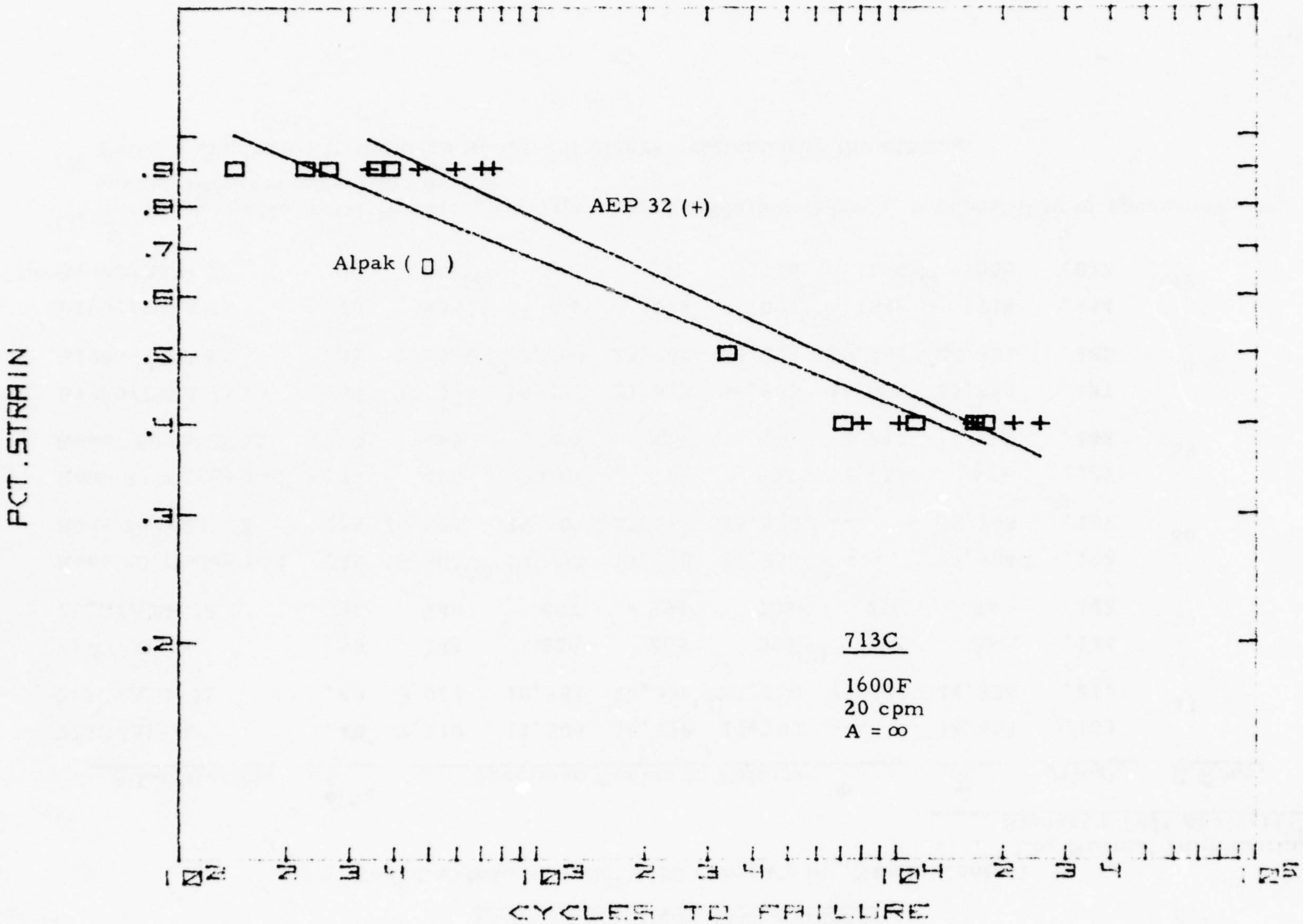


Figure 3-23 Low cycle fatigue comparison of Alpak and AEP 32 coated 713C alloy

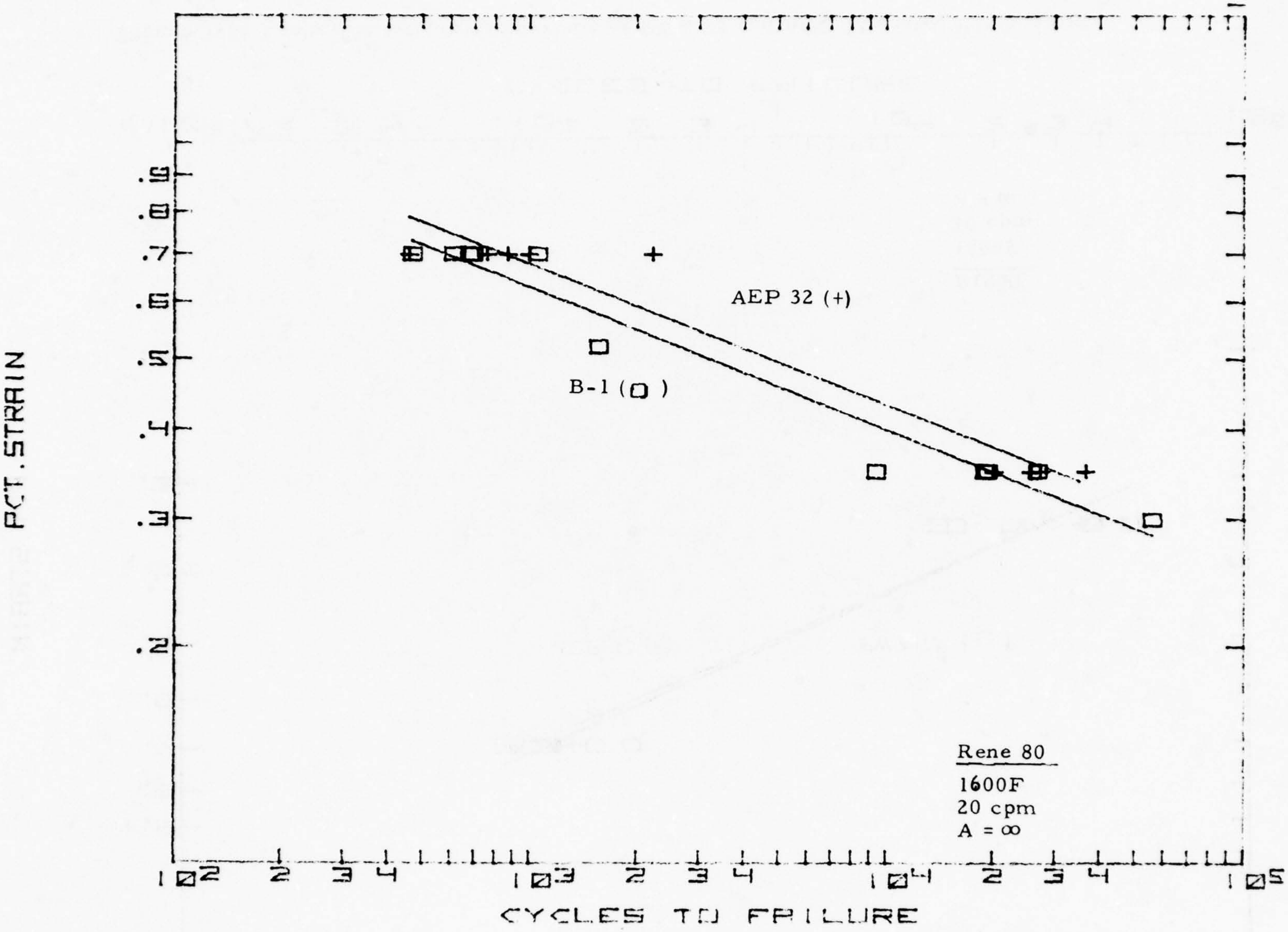


Figure 3-24 Low cycle fatigue comparison of Codep B-1 and AEP 32 coated Rene'80 alloy

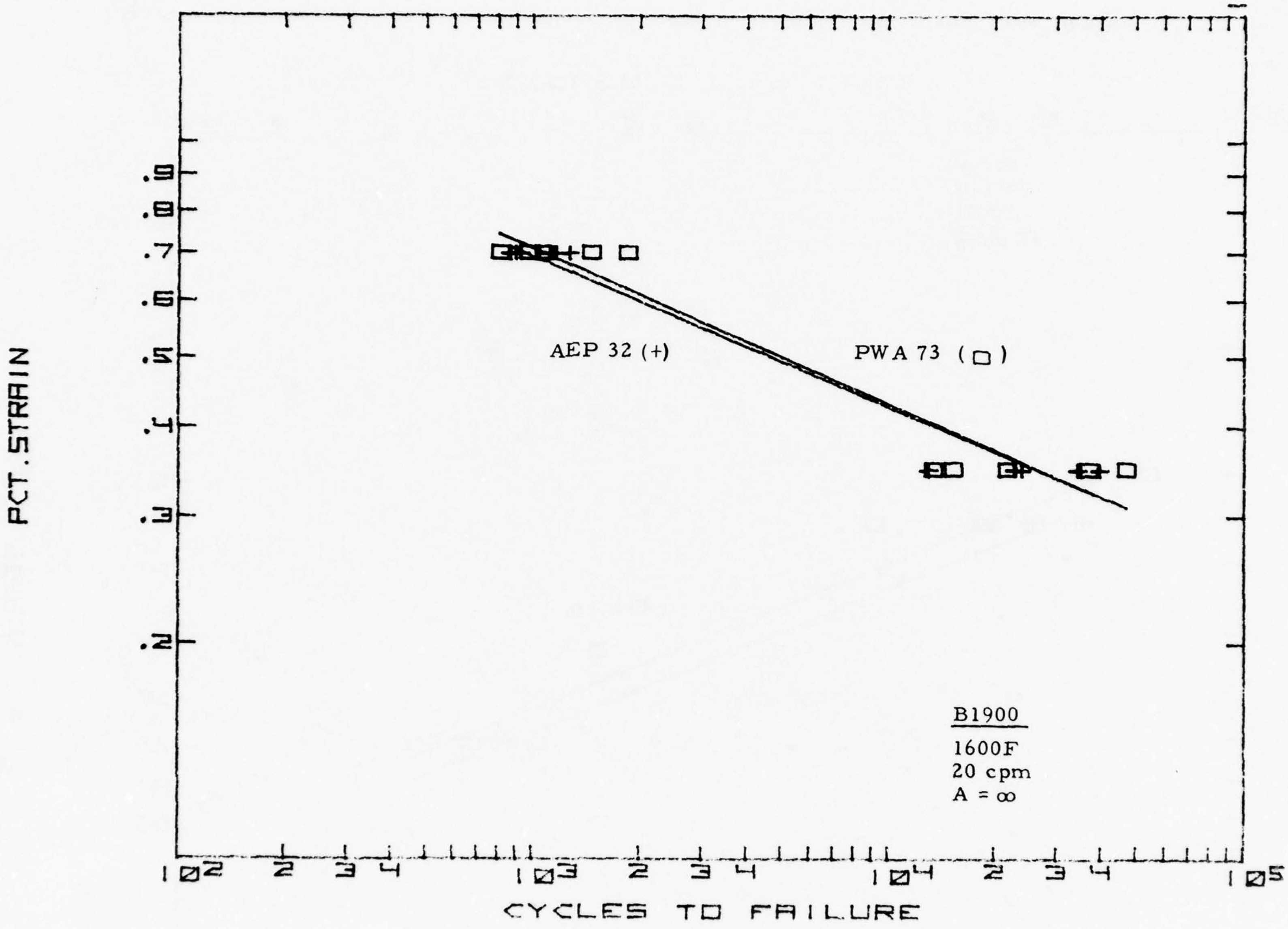


Figure 3-25 Low cycle fatigue comparison of PWA 73 and AEP 32 coated B1900 alloy

### 3.3.3 Tensile Testing

Tensile tests were performed on four specimens of each alloy/coating combination at temperatures of 1400, 1600 and 1800°F using a Riehle tensile machine equipped with a Marshall split furnace. The tests were conducted in air at a controlled strain rate of 0.005 in/in/min. Test specimens were cast solid bars with a 1/4" O.D. x 1 1/4" long test section.

Tabulations of all tensile property data are given in Tables 3-XXII through 3-XXV. Summary plots of average 0.2% yield, ultimate tensile strength and percent elongation for comparing baseline coated and AEP 32 coated alloys are shown in Figures 3-26 through 3-29.

The 1600°F yield strength of AEP 32 coated alloy 713C was appreciably lower than that of the Alpak coated bars as shown in Figure 3-26. This is a consequence of the faster cooling rate from the diffusion temperature, used in the Alpak process, which produces a finer gamma prime particle size than the slower retort cool in the AEP process. The difference in matrix gamma prime particle size between Alpak and AEP 32 coated alloy 713C was previously shown in Figures 3-4 and 3-7, respectively.

A similar effect of cooling rates from the coating diffusion temperature on the tensile yield and ultimate strength values of Alpak and AEP 32 coated C1023 is shown in Figure 3-27. The finer gamma prime in Alpak coated C1023 was previously shown in Figure 3-5 compared to the coarser gamma prime of AEP 32 coated C1023 in Figure 3-8.

Average tensile properties plots of coated Rene' 80 as illustrated in Figure 3-28 show higher ultimate and yield strength for AEP 32 at 1400 and 1600°F and equivalent at 1800°F when compared to Codep B-1. The reason for these differences are not explainable at this time. The average tensile properties for AEP 32 and PWA 73 coated B1900 alloy were evaluated as equivalent.

## Table 3-XXII

## Summary of Tensile Properties of Coated Alloy 713C

| Test Temp °F | Coating | Tensile Strength ksi | 0.2% Yield Strength ksi | Elong. % in 1" | Reduction of Area % |
|---|---|---|---|---|---|
| 1400 | Alpak | 143.4 | 123.6 | 4.1 | 4.1 |
| | | 145.0 | 126.6 | 2.9 | 6.2 |
| | | 140.2 | 122.7 | 3.0 | 5.6 |
| | | 143.7 | 122.0 | 4.5 | 6.3 |
| | Average | 143.0 | 123.7 | 3.6 | 5.6 |
| 1400 | AEP 32 | 141.5 | 117.4 | 5.0 | 7.0 |
| | | 145.0 | 117.4 | 5.5 | 5.6 |
| | | 142.5 | 120.3 | 5.0 | 4.1 |
| | | 142.4 | 120.8 | 3.2 | 4.7 |
| | Average | 142.8 | 119.0 | 4.7 | 5.4 |
| 1600 | Alpak | 118.0 | 102.0 | 8.0 | 14.5 |
| | | 117.6 | 101.8 | 7.2 | 11.7 |
| | | 121.0 | 105.2 | 6.5 | 11.0 |
| | | 120.4 | 108.4 | 6.8 | 8.7 |
| | Average | 119.2 | 104.4 | 7.1 | 11.5 |
| 1600 | AEP 32 | 111.1 | 79.6 | 11.1 | 13.1 |
| | | 111.5 | 82.2 | 11.5 | 13.9 |
| | | 114.8 | 87.0 | 9.7 | 14.6 |
| | | 114.3 | 87.7 | 4.4 | 8.7 |
| | Average | 112.9 | 84.7 | 9.1 | 12.6 |
| 1800 | Alpak | 68.3 | 53.1 | 13.0 | 19.8 |
| | | 65.1 | 49.7 | 17.6 | 25.2 |
| | | 67.1 | 56.7 | 12.8 | 19.0 |
| | | 70.1 | 54.2 | 12.4 | 22.6 |
| | Average | 67.8 | 53.4 | 14.0 | 21.6 |
| 1800 | AEP 32 | 66.0 | 50.3 | 18.1 | 20.4 |
| | | 67.7 | 51.0 | 16.0 | 18.2 |
| | | 66.0 | 48.8 | 15.2 | 16.1 |
| | | 66.4 | 48.3 | 18.8 | 25.2 |
| | Average | 66.5 | 49.6 | 17.0 | 20.0 |

## Table 3-XXIII

### Summary of Tensile Properties of Coated Rene' 80 Alloy

| Test Temp °F | Coating | Tensile Strength ksi | 0.2% Yield Strength ksi | Elong. % in 1" | Reduction of Area % |
|---|---|---|---|---|---|
| 1400 | Codep B-1 | 141.3 | 91.7 | 6.1 | 6.3 |
| | | 141.3 | 94.4 | 6.2 | 6.3 |
| | | 141.0 | 90.3 | 4.9 | 4.8 |
| | | 142.5 | 90.2 | 5.9 | 4.9 |
| | Average | 141.4 | 91.7 | 5.8 | 5.6 |
| 1400 | AEP 32 | 148.7 | 111.6 | 3.3 | 6.2 |
| | | 152.3 | 111.5 | 4.8 | 4.9 |
| | | 133.9 | 111.2 | 2.1 | 6.3 |
| | | 151.5 | 112.3 | 6.2 | 4.7 |
| | Average | 146.6 | 111.6 | 4.1 | 5.5 |
| 1600 | Codep B-1 | 107.6 | 76.5 | 10.4 | 16.8 |
| | | 97.9 | 72.2 | 2.6 | 1.6 |
| | | 107.4 | 76.0 | 10.0 | 9.4 |
| | | 107.1 | 72.6 | 10.7 | 13.8 |
| | Average | 105.0 | 74.3 | 8.4 | 10.4 |
| 1600 | AEP 32 | 115.9 | 88.1 | 9.1 | 12.4 |
| | | 112.0 | 85.6 | 2.5 | 4.9 |
| | | 111.2 | 86.7 | 12.8 | 20.6 |
| | | 115.3 | 85.7 | 20.0 | 26.0 |
| | Average | 113.6 | 86.5 | 11.1 | 16.0 |
| 1800 | Codep B-1 | 68.4 | 46.2 | 13.6 | 19.9 |
| | | 68.2 | 42.3 | 23.9 | 33.7 |
| | | 69.4 | 44.9 | 15.7 | 24.0 |
| | | 69.4 | 42.2 | 21.0 | 35.4 |
| | Average | 68.8 | 43.9 | 18.6 | 22.2 |
| 1800 | AEP 32 | 66.6 | 44.1 | 23.1 | 34.8 |
| | | 67.2 | 42.4 | 16.3 | 26.9 |
| | | 67.5 | 43.1 | 25.4 | 38.4 |
| | | 67.1 | 41.9 | 17.6 | 26.9 |
| | Average | 67.1 | 42.9 | 20.6 | 31.8 |

# Table 3-XXIV

## Summary of Tensile Properties of Coated B1900 Alloy

| Test Temp °F | Coating | Ultimate Strength ksi | 0.2% Yield Strength ksi | Elong. % in 1" | Reduction of Area % |
|---|---|---|---|---|---|
| 1400 | PWA 73 | 134.6 | 111.6 | 5.9 | 7.8 |
| | | 130.2 | 111.7 | 5.8 | 7.0 |
| | | 134.9 | 111.4 | 5.0 | 7.1 |
| | | 133.4 | 108.7 | 7.1 | 11.6 |
| | Average | 133.3 | 110.8 | 6.0 | 8.4 |
| 1400 | AEP 32 | 132.8 | 111.0 | 5.5 | 6.3 |
| | | 129.9 | 107.4 | 5.7 | 7.1 |
| | | 128.5 | 107.9 | 5.8 | 7.9 |
| | | 128.9 | 104.6 | 5.9 | 7.1 |
| | Average | 130.0 | 107.7 | 5.7 | 7.1 |
| 1600 | PWA 73 | 113.1 | 88.4 | 8.6 | 9.5 |
| | | 112.6 | 87.6 | 8.6 | 10.2 |
| | | 109.1 | 94.3 | 15.0 | 23.2 |
| | | 111.7 | 93.8 | 8.2 | 9.3 |
| | Average | 111.6 | 91.0 | 10.1 | 13.1 |
| 1600 | AEP 32 | 110.9 | 84.7 | 10.0 | 9.4 |
| | | 111.9 | 88.9 | 8.2 | 7.9 |
| | | 111.5 | 85.3 | 11.2 | 11.7 |
| | Average | 111.4 | 86.3 | 9.8 | 7.2 |
| 1800 | PWA 73 | 76.5 | 53.9 | 11.9 | 13.1 |
| | | 74.7 | 52.5 | 16.1 | 18.9 |
| | | 74.7 | 62.7 | 14.1 | 13.8 |
| | | 78.7 | 56.5 | 14.4 | 17.4 |
| | Average | 76.2 | 56.4 | 14.1 | 15.8 |
| 1800 | AEP 32 | 76.9 | 56.3 | 15.4 | 20.4 |
| | | 75.9 | 50.7 | 15.1 | 17.5 |
| | | 74.7 | 51.3 | 9.2 | 10.9 |
| | | 75.9 | 55.3 | 13.0 | 20.4 |
| | Average | 75.8 | 53.4 | 13.2 | 17.3 |

## Table 3-XXV

## Summary of Tensile Properties for Coated C1023 Alloy

| Test Temp °F | Coating | Tensile Strength ksi | 0.2% Yield Strength ksi | Elong. % in 1" | Reduction for Area % |
|---|---|---|---|---|---|
| 1400 | Alpak | 143.0 | 136.9 | 2.2 | 5.2 |
| | | 143.0 | 136.2 | 2.2 | 5.2 |
| | | 142.6 | 138.2 | 2.1 | 5.2 |
| | | 142.5 | 127.9 | 2.2 | 4.9 |
| | Average | 142.8 | 134.8 | 2.2 | 5.1 |
| 1400 | AEP 32 | 134.7 | 115.0 | 6.4 | 6.3 |
| | | 135.3 | 115.7 | 3.8 | 4.0 |
| | | 145.4 | 122.9 | 1.8 | 4.1 |
| | | 139.7 | 122.3 | 1.9 | 3.2 |
| | Average | 138.8 | 119.0 | 3.5 | 4.4 |
| 1600 | Alpak | 127.3 | 118.8 | 4.2 | 3.2 |
| | | 129.3 | 118.4 | 6.9 | 4.8 |
| | | 128.1 | 115.2 | 4.5 | 4.0 |
| | | 127.3 | 117.6 | 5.0 | 4.0 |
| | Average | 128.0 | 117.5 | 5.2 | 4.0 |
| 1600 | AEP 32 | 109.9 | 84.1 | 7.8 | 7.1 |
| | | 112.6 | 87.4 | 9.3 | 6.4 |
| | | 117.3 | 102.8 | 10.0 | 12.4 |
| | Average | 113.2 | 91.4 | 9.0 | 8.6 |
| 1800 | Alpak | 77.8 | 66.7 | 12.6 | 22.0 |
| | | 74.3 | 61.9 | 16.8 | 25.2 |
| | | 73.7 | 60.7 | 16.9 | 24.0 |
| | | 74.5 | 63.0 | 15.5 | 29.5 |
| | Average | 75.1 | 63.1 | 15.4 | 25.2 |
| 1800 | AEP 32 | 69.3 | 48.5 | 17.6 | 25.2 |
| | | 72.5 | 50.7 | 17.5 | 30.1 |
| | | 69.5 | 47.7 | 18.0 | 24.0 |
| | | 70.1 | 48.6 | 21.0 | 30.7 |
| | Average | 70.4 | 48.9 | 18.5 | 27.5 |

Figure 3-26 Average tensile properties of coated alloy 713C

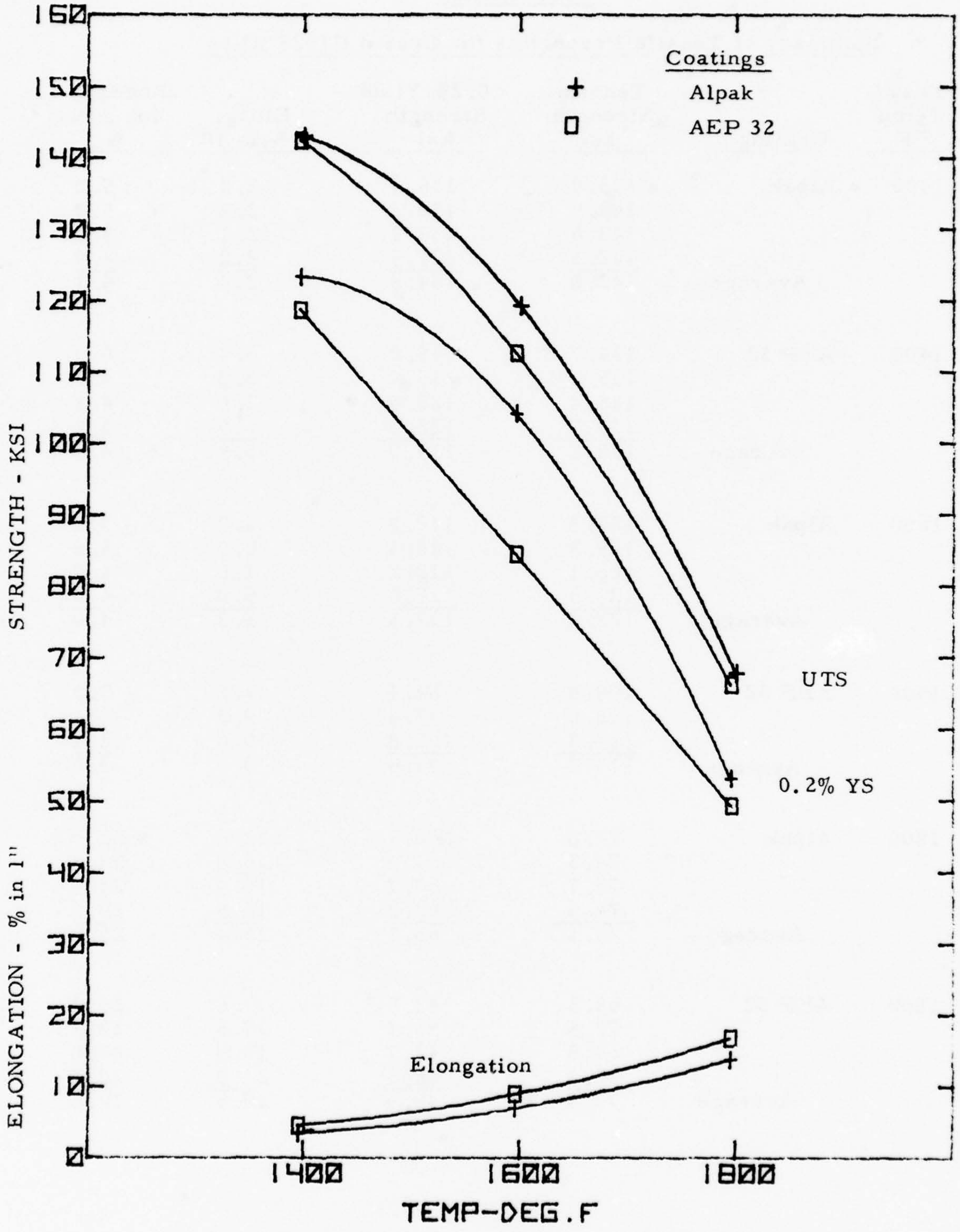


Figure 3-27 Average tensile properties of Coated C1023 alloy

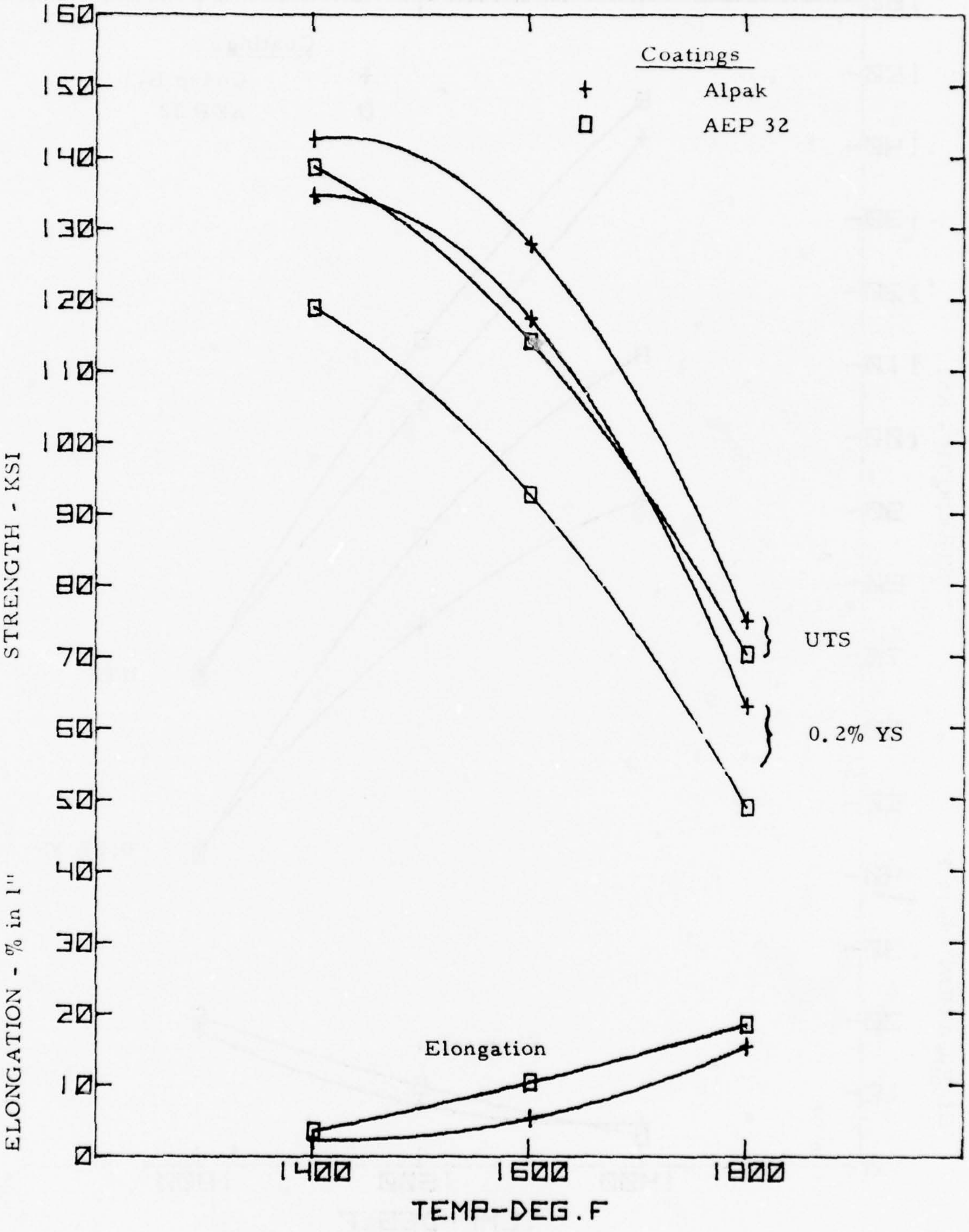


Figure 3-28 Average tensile properties of coated Rene' 80 alloy

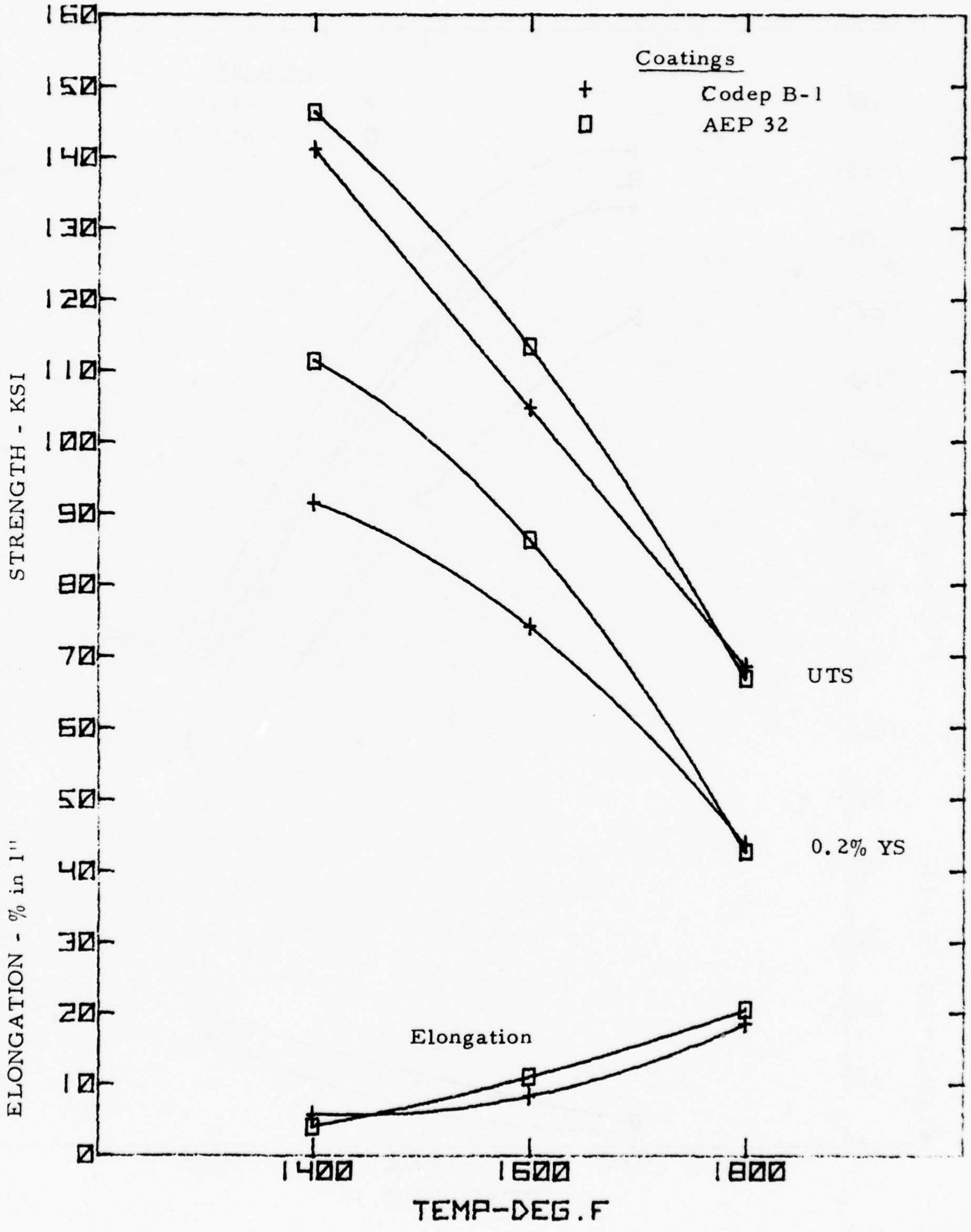
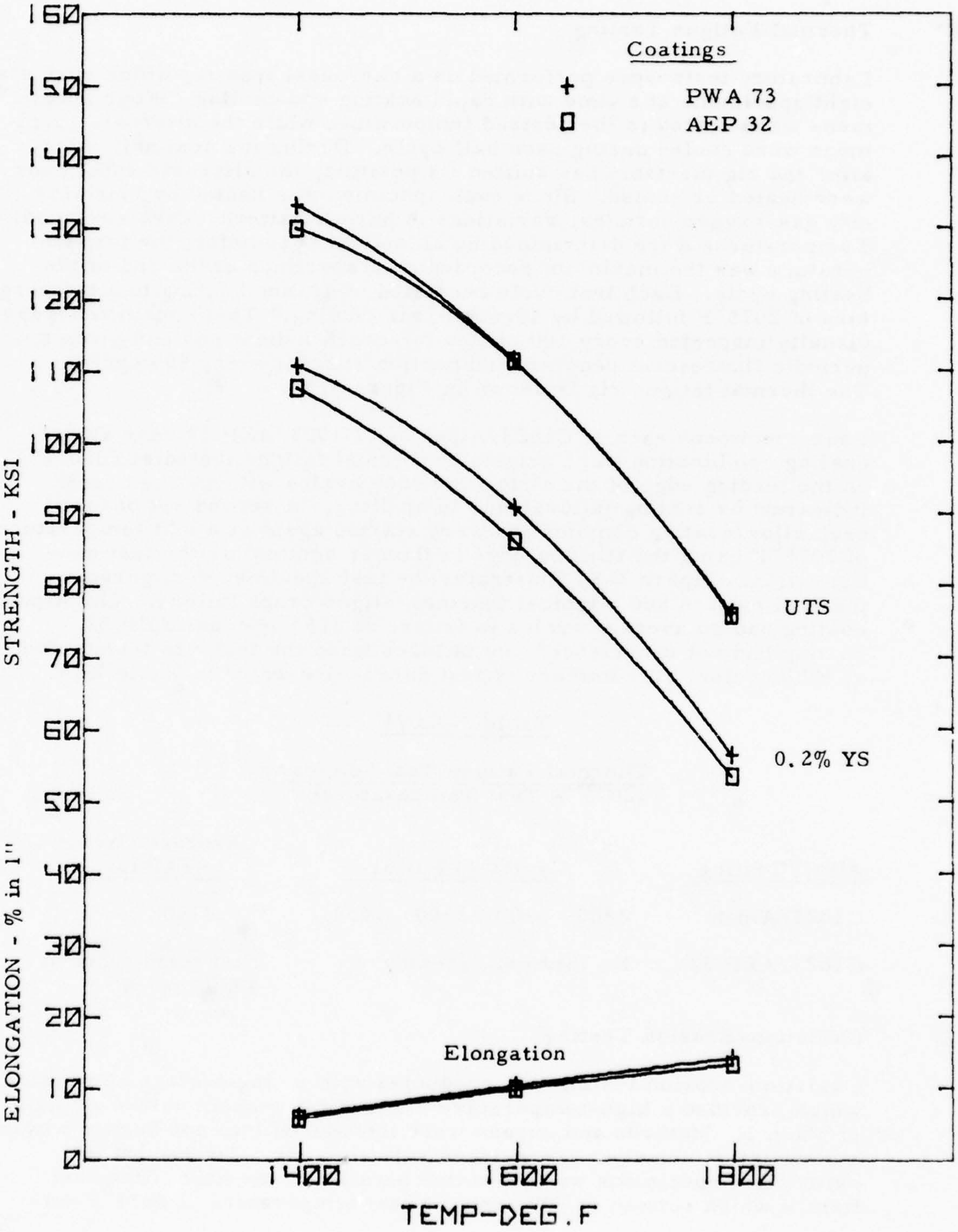


Figure 3-29 Average tensile properties of coated B1900 alloy



### 3.3.4 Thermal Fatigue Testing

Laboratory tests were performed on a carrousel type rig which evaluates eight specimens at a time with rapid heating and cooling. Four specimens were heated to the desired temperature while the alternate specimens were cooled during each half cycle. During the next half cycle, after the rig turntable has shifted its position, the alternate specimens were heated or cooled. Since each specimen was heated by four air-city gas-oxygen burners, variations in burner patterns were averaged. Temperatures were determined by an optical pyrometer; the test temperature was the maximum recorded on a specimen at the end of the heating cycle. Each test cycle consisted of 40-sec heating to a temperature of 2075°F followed by 40-sec of air cooling. Test specimens were visually inspected every 100 cycles for crack indications and given a periodic fluorescent penetrant inspection at least every 500 cycles. The thermal fatigue rig is shown in Figure 3-30.

Four specimens each of C1023/Alpak and C1023/AEP 32 vane alloy/coating combination were originally thermal fatigue tested at 2050°F on the leading edge of the airfoil for 5000 cycles without any crack indication or coating failures due to spalling. A second set of four each alloy/coating combination were started again at a test temperature of 2075°F using the trailing edge (a thinner section) as the test configuration. Figure 3-31 illustrates the test specimen configuration, thermal pattern and a typical thermal fatigue crack failure. The Alpak coating had an average cycles to failure of 3150 whereas AEP 32 coating had not experienced any failures when the test was terminated at 4850 cycles. A summary of test data is presented in Table XXVI.

Table 3-XXVI

Thermal Fatigue Test Summary
(2075°F Test Temperature)

| Alloy/Coating | Cycles to Failure | | | | Average Cycles to Failure |
|---|---|---|---|---|---|
| C1023/Alpak | 2800 | 3200 | 3200 | 3400 | 3150 |
| C1023/AEP 32 | No thermal cracking | | | | Test terminated at 4950 cycles |

### 3.3.5 Oxidation-Erosion Testing

Oxidation-erosion testing was conducted with a single-stage combustor which provided a high-temperature erosive gas stream with a velocity of Mach 1. Methane and oxygen were introduced into and burned within a combustion chamber pressurized with shop air. Twelve hollow, cylindrical specimens were mounted parallel to the axis of the test fixture which rotated at 300 rpm. A test temperature of 2075°F was continuously maintained for the test time of 100 hr with the exception of shutdowns to change the gas supply. Three samples were tested for each coating/alloy combination. The specimens were evaluated by sectioning at the point of maximum erosion and by measuring the amount of coating removed. Each specimen was also sectioned at a location remote from the erosion area to determine the original coating thickness. The oxidation-erosion test rig is shown in Figure 3-32. The results of the oxidation-erosion test, summarized in Table XXVII, reveal that AEP 32 coating is slightly better than Alpak on both alloy 713C and C1023. As compared to Codep B-1 and PWA 73, it appears to be at least equivalent. It is suggested from these results that a shorter test time or a lower temperature possibly 2000°F for 100 hours may have been more selective for the coated alloys, Rene' 80 and B1900.

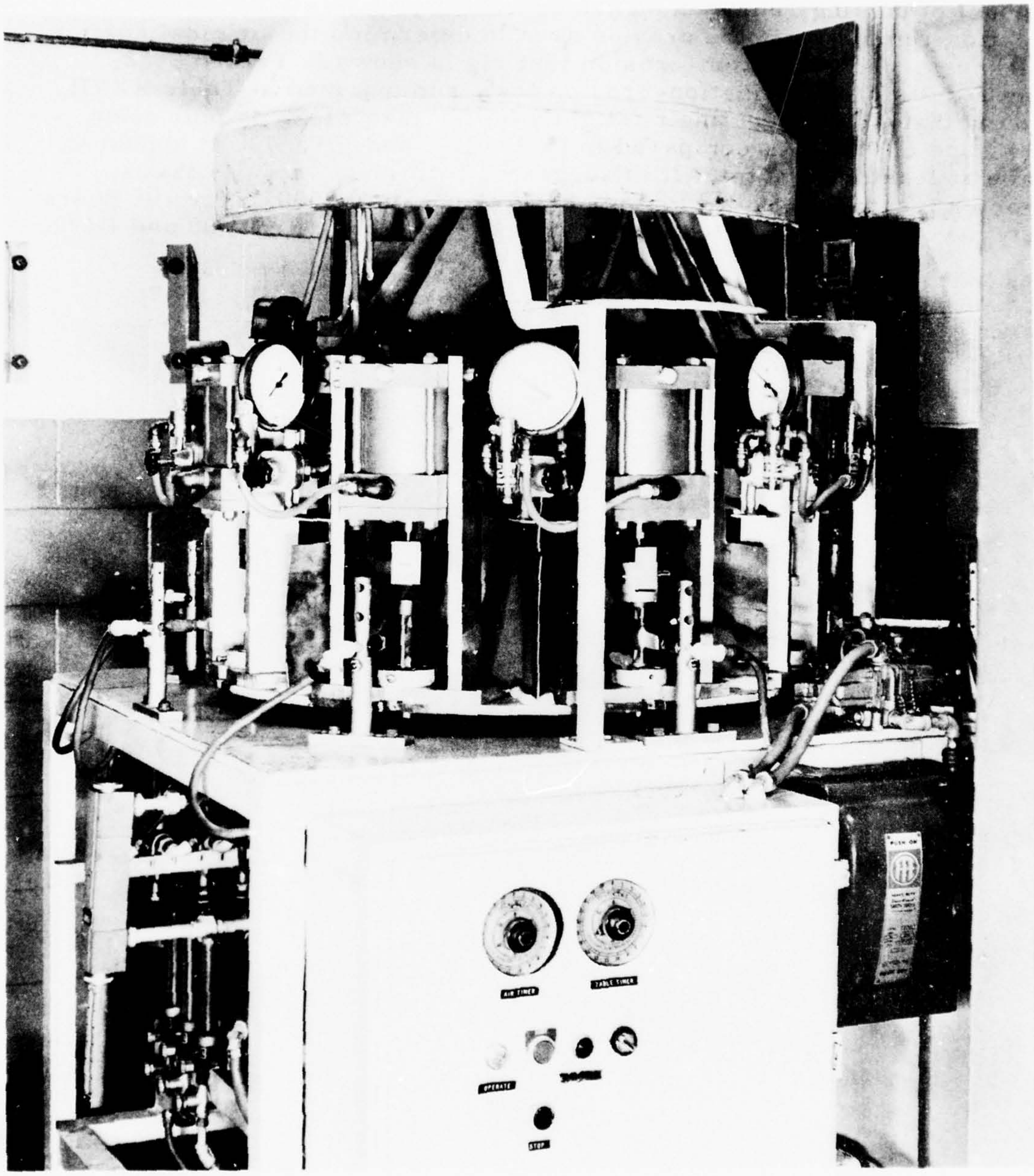
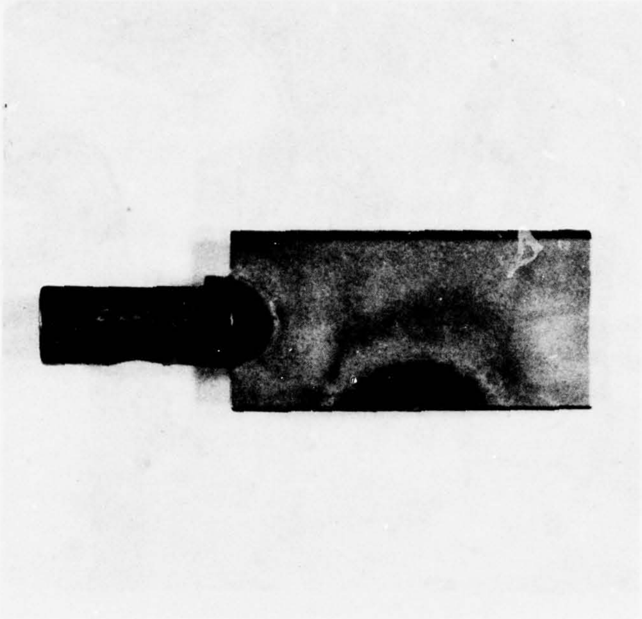
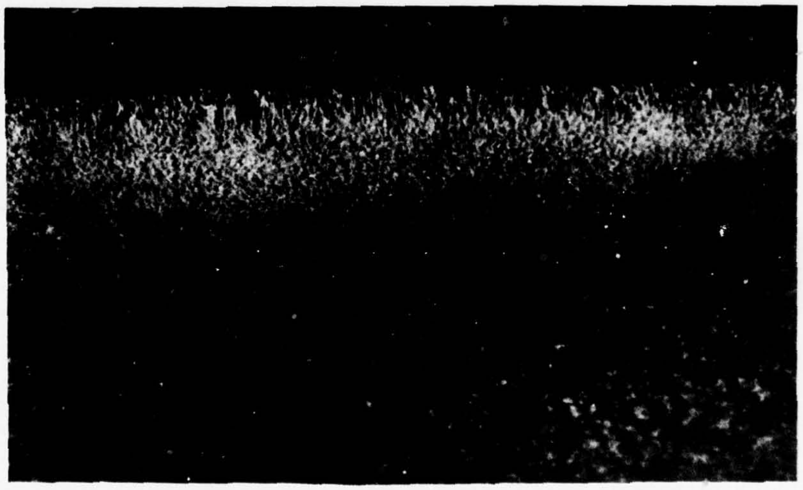


Figure 3-30 Thermal fatigue test rig



Magn: 1X

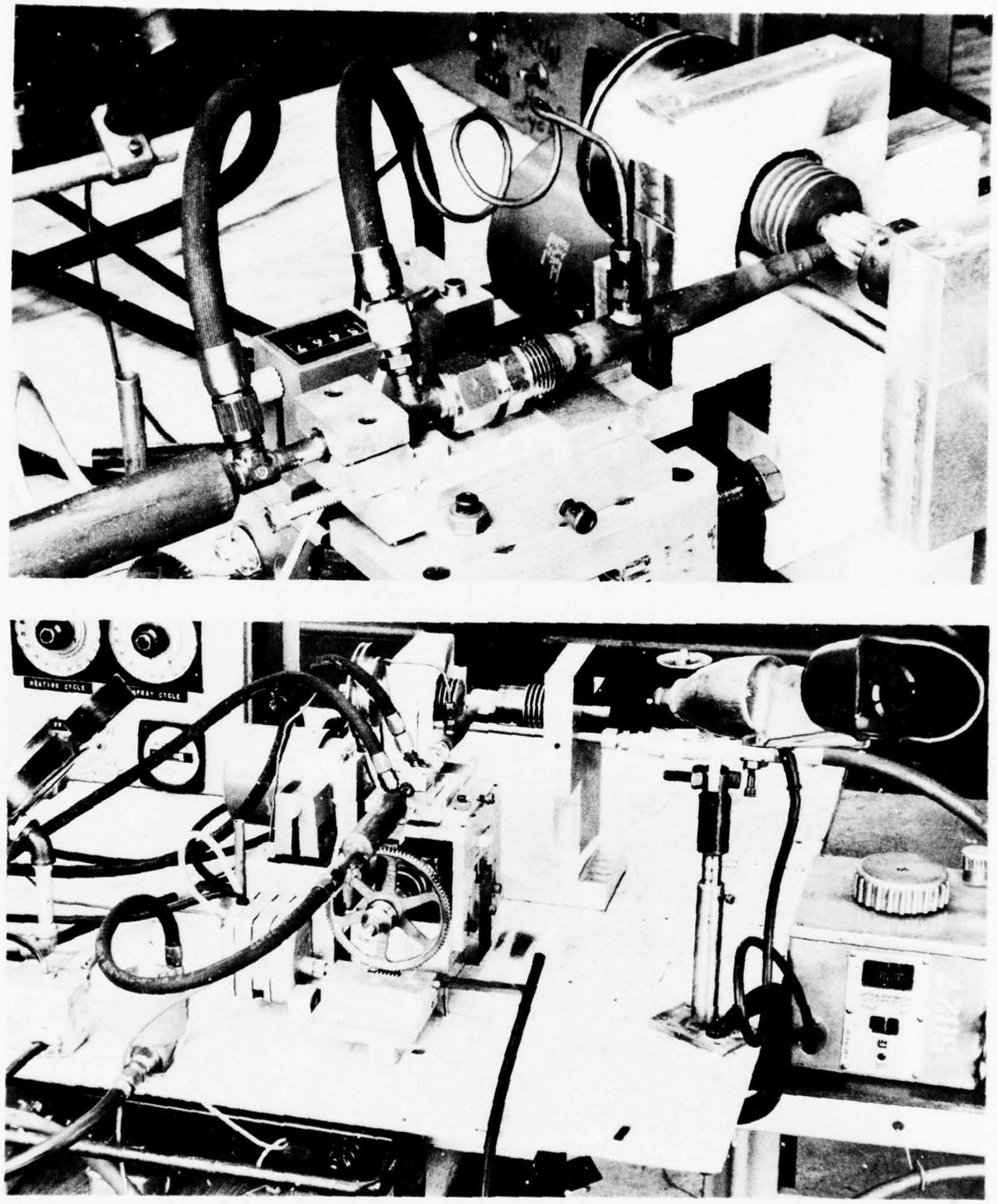
(a) C1023/Alpak thermal fatigue specimen



Magn: 10X

(b) Thermal fatigue crack after 2800 cycles on C1023/Alpak

Figure 3-31 Thermal fatigue test specimens showing (a) thermal pattern and (b) a typical crack failure on C1023/Alpak



The upper photo shows the position of the air-oxygen-methane burner relative to the test specimens. The lower photo shows the rig in operation with the hot gases impinging on the rotating test specimen.

Figure 3-32 Oxidation-erosion test rig

## Table 3-XXVII

## Oxidation-Erosion Test Results

| Alloy/Coating | Specimens | Initial Coating, Mils | Coating Removed After 100 Hrs, Mils |
|---|---|---|---|
| 713C/Alpak | 1 | 3.4 | 1.9 |
| | 2 | 3.0 | 1.0 |
| | 3 | 3.8 | 2.1 |
| 713C/AEP 32 | 1 | 3.0 | 1.9 |
| | 2 | 2.9 | 0.6 |
| | 3 | 2.9 | 0.4 |
| C1023/Alpak | 1 | 3.1 | 1.9 |
| | 2 | 2.7 | 1.5 |
| C1023/AEP 32 | 1 | 2.5 | 0.8 |
| | 2 | 2.8 | 1.8 |
| Rene' 80/Codep B-1 | 1 | 2.4 | -* |
| | 2 | 2.7 | -* |
| | 3 | 2.5 | -* |
| Rene' 80/AEP 32 | 1 | 1.9 | -* |
| | 2 | 1.7 | -* |
| | 3 | 1.7 | -* |
| B1900/PWA 73 | 1 | 3.1 | -* |
| | 2 | 3.4 | 2.2 |
| B1900/AEP 32 | 1 | 3.1 | -* |
| | 2 | 2.9 | 1.7 |

-* Coating removed

## 3.4 TASK IV RECOATING OF ENGINE RUN TURBINE COMPONENT HARDWARE

### 3.4.1 Discussion

Aluminide coatings in aircraft gas turbine engines function in high temperature oxidizing environments. Degradation of the coatings is caused principally by depletion of aluminum on the surface of the nickel aluminide from formation of aluminum oxides. Even though the aluminum oxides are protective, they are removed by gas path erosion and spalling followed by formation of additional aluminum oxides. The continuous loss of aluminum from the coating nickel aluminides continues until the surface coating is incapable of further protection from the operating environments. During engine service the extent of the nickel aluminide degradation is quite variable. Some turbine components have remnants of protective coating while others from the same engine have completely exposed substrate with varying degrees of hot corrosion attack. Further, this broad spectrum of surface conditions often exists on individual turbine components. The highly variable surface condition of the turbine components must be considered in surface preparation for overhaul recoating. Residual coating material can be removed by chemical stripping while areas of hot corrosion may require abrasive treatment to effect their removal.

The turbine hardware supplied for this task of the program exhibited a broad spectrum of the surface conditions described above. All components were re-inspected due to their marginal condition and only the five best of each alloy/configuration were given the complete AEP 32 recoating operation. The remaining parts were used for stripping, recoating and processing experiments.

### 3.4.2 Chemical Stripping Procedure

The chemical stripping of all turbine hardware was accomplished by using a DDA approved stripping solution and procedure. To establish the immersion time for completely stripping the coating from the various alloy/coating combinations, a 55 minute cycle was established and repeated as required. The procedure is summarized in Table 3-XXVIII.

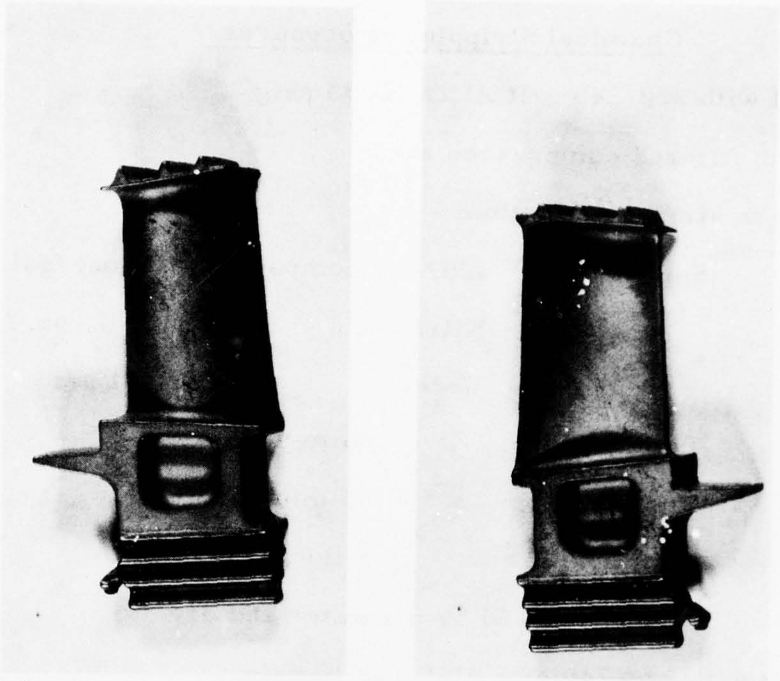
The various engine-run components used for the stripping experiments were representative of the program alloys and their base coatings. Chemical stripping of these representative components required two (2) 55 minute cycles for Rene' 80/Codep B-1 coating and three (3) 55 minute cycles for alloy 713/Alpak, C1023/Alpak and B1900/PWA 73 coatings. After each cycle a heat tint inspection was followed by a microexamination to determine and/or verify when complete coating removal was accomplished. Figure 3-33 through 3-36 illustrates the component configuration in the as-received condition; their respective coating; and their surface condition after chemical stripping.

## Table 3-XXVIII

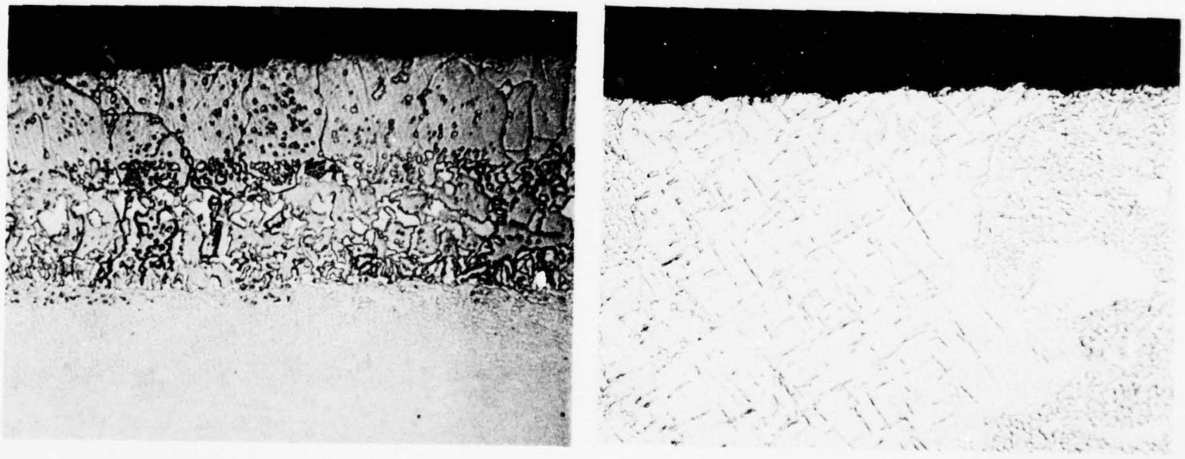
## Chemical Stripping Procedures

- Dry blast with 220-240 grit $Al_2O_3$ at 30 psig
- Clean with filtered compressed air
- Immerse in stripping solution
  - Solution: ASC-2N compound* - 20 oz./gal.
    Nitric acid - 10 fl. oz./gal.
    Water - to make 1 gal.
  - Temperature: 85 to $90^{\circ}$F
  - Time: 55 minutes
  - Agitation: Mild
- Rinse in cold water followed by hot water and dry
- Dry blast with 220-240 grit $Al_2O_3$ at 30 psig
- Heat tint at $1300 \pm 25^{\circ}$F/air/15-20 min.
- Visual inspection
- Repeat cycle above as required

* ASC-2N compound is an off-the-shelf product purchased from Alloy Surfaces Company, Inc.

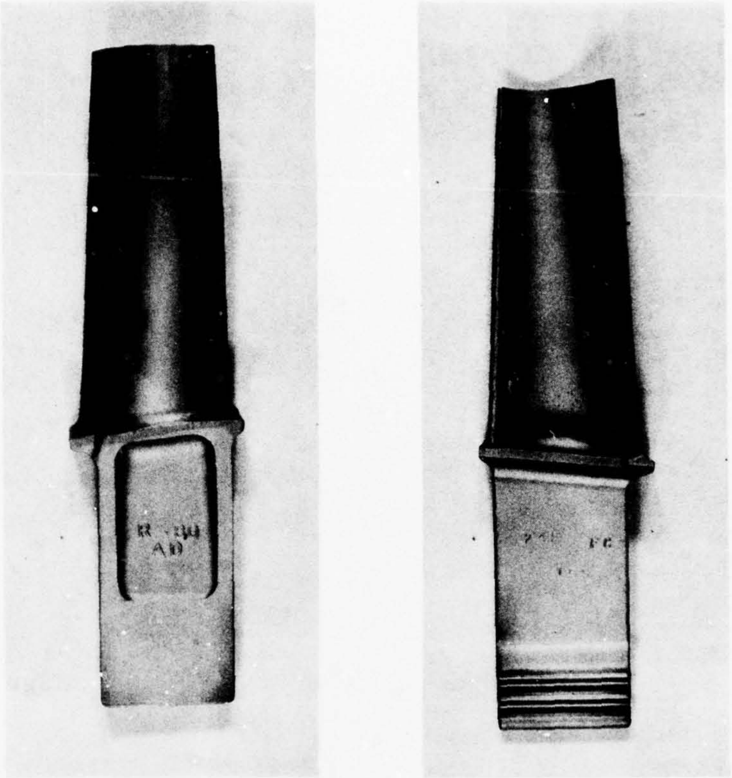


(a) Blades as-received 1X

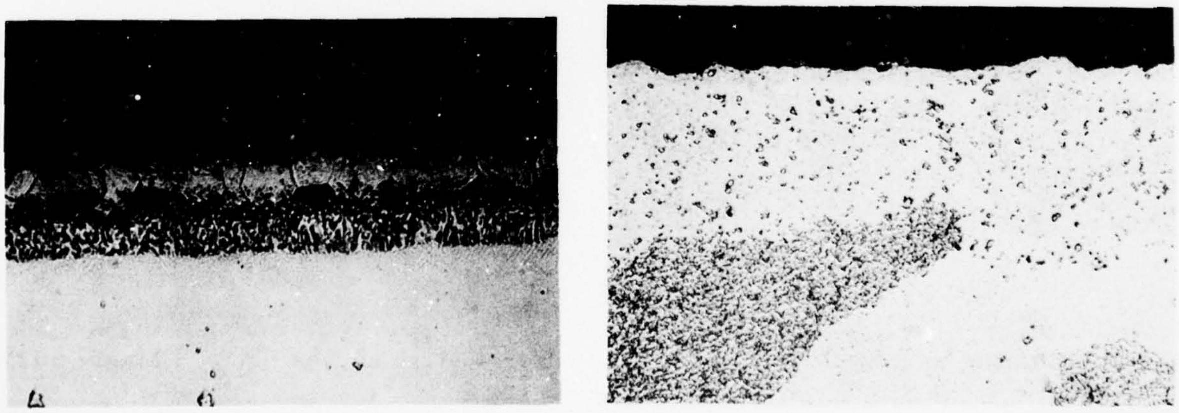


(b) Coating as received After 3 strip cycles Magn: 500X

Figure 3-33 Alloy 713C/Alpak coated T56 1st Stage Turbine Blade, P/N 6876564, as received for recoating. (b) Photomicrographs illustrate typical airfoil surface condition before and after chemical stripping.

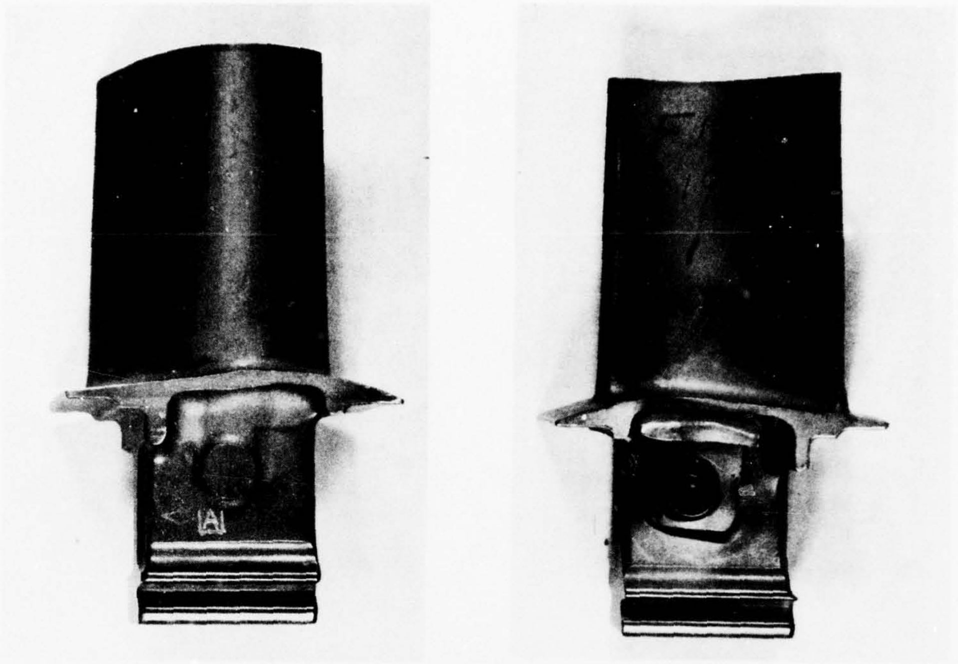


(a) Blade as received Magn: 3/4X

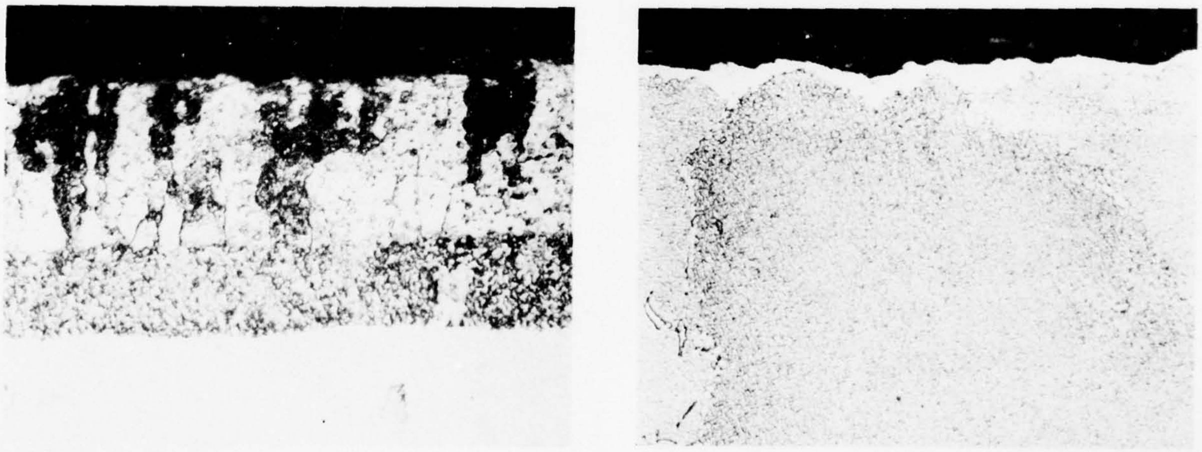


(b) Coating as received After 2 strip cycles Magn: 500X

Figure 3-34 (a) Rene' 80/Codep B-1 coated J79 1st Stage Turbine Blade, P/N 110R342P03, as received. (b) Photomicrographs are typical of blades mid-airfoil surfaces before and after chemical stripping.

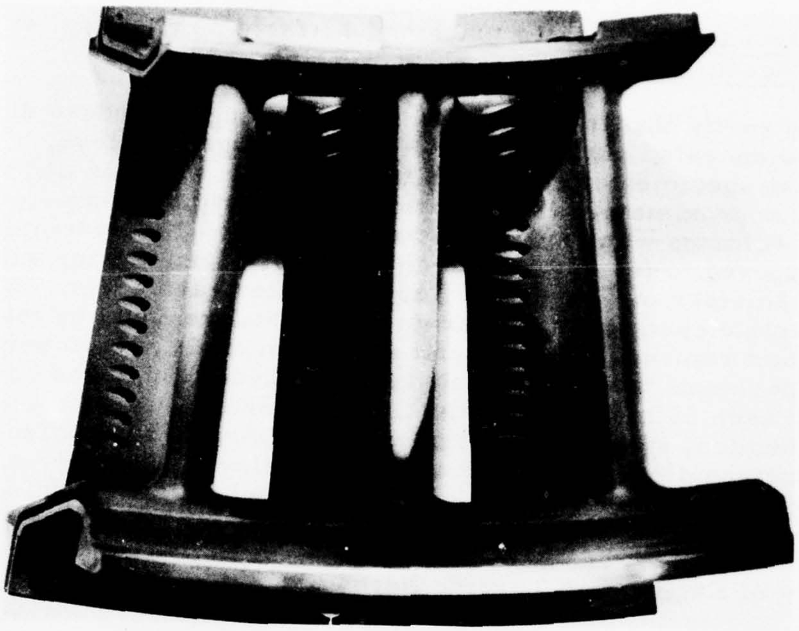


(a) Blades as received Magn: 1X

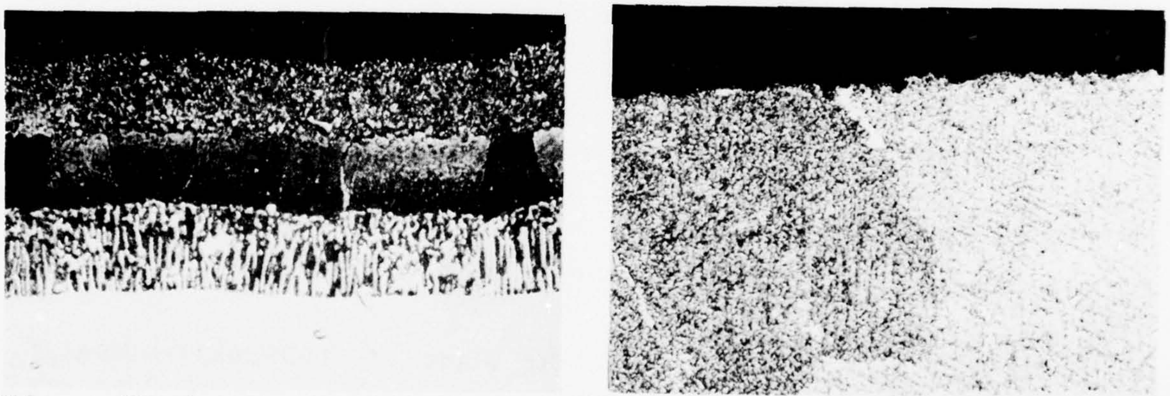


(b) Coating as received After 3 strip cycles Magn: 500X

Figure 3-35 (a) B1900/PWA 73 coated F100 1st Stage Turbine Blade, P/N 4039571, as received for recoating. (b) Photomicrograph illustrates typical airfoil surface condition before and after chemical stripping.



(a) Vane as received Magn: 1X



(b) Coating as received After 3 strip cycles Magn: 500X

Figure 3-36 (a) C1023/Alpak coated TF 41 2nd Stage Vane Assy., P/N 6866849, as received for recoating.
(b) Photomicrographs illustrate typical airfoil surface condition before and after chemical stripping.

O **Exposure of uncoated machined surfaces to chemical stripping procedure**

To verify that the DDA chemical stripping procedure did not attack the uncoated surfaces of the various program alloys, a cylindrical test specimen of each alloy was centerless ground and index marked at approximately 120° locations. The original diameters of the specimens were measured and recorded. The specimens were exposed to four 55 minute chemical stripping cycles with the diameters measured and recorded after each cycle. In order to isolate chemical attack from base metal removal by the abrasive smut removal (220-240 grit aluminum oxide, 25-30 psig), the specimens were water rinsed and wiped clean at the completion of each 55 minute treatment. Test results revealed that the chemical stripping treatment did not significantly affect the bare surface dimensions of the program alloys. The only measurable difference was a reduction of 0.0005 inch on the B1900 alloy cylinder.

### 3.4.3 Recoating of Engine-Run Turbine Hardware

Hardware used for this evaluation represents the various program alloy/coating combinations and was supplied by Air Force Logistics Centers (ALC) located at San Antonio, Texas (SAALC) and Oklahoma City, Oklahoma (OCALC). Table 3-XXIX summarizes the alloy/coating and respective hardware configuration in addition to the responsible ALC overhaul facility. Five (5) components of each configuration were processed for evaluation.

Table 3-XXIX

Summary of Engine Run Turbine Hardware for Recoating

| Alloy/Coating | Engine | Component | P/N | ALC |
|---|---|---|---|---|
| 713C/Alpak | T56 | 1st Stg Blade | 6876564 | SAALC |
| Rene' 80/Codep B-1 | J79 | 1st Stg Blade | 11OR342PO3 | OCALC |
| B1900/PWA 73 | TF 30 | 1st Stg Vane | 556652 | OCALC |
| B1900/PWA 73 | F100 | 1st Stg Blade | P4039571 | SAALC |
| C1023/Alpak | TF 41 | 2nd Stg Vane | 6866849 | OCALC |

- Surface Preparation

  All hardware was prepared for recoating as outlined in Table 3-XXVIII. Two 55 minute stripping cycles were used on the Rene' 80/Codep B-1 components and three 55 minute cycles on all other alloy/coating hardware. Representative samples were used as control specimens to verify complete coating removal.

- Recoating with AEP 32

  After heat tint verification that the part was properly prepared for recoating, all hardware was given a final cleaning by degreasing and dry blasting with 240 grit $Al_2O_3$ at 30 psig. Masking and recoating of hardware was performed in accordance with the AEP 32 coating procedures discussed in Task I and again detailed in the Documentation Section, Task V. Special anoding was required and developed for the TF41 2nd Stage Vane Assembly as illustrated in Figure 3-37. All other anoding was a simple 4 sided basket configuration.

- Thermal Treatments

  The coating diffusion temperatures and time used for the various components were as noted in Table 3-VII. Post-Diffusion Heat Treatments were conducted as indicated in Table 3-IX for the AEP 32 coatings on program alloys.

- Heat Tint Inspection

  The various coated and diffused components were cleaned by dry blasting to a uniform surface condition with 240 grit $Al_2O_3$ at 25-30 psig followed by removing the residual abrasive with filtered air blast. The parts were then given a heat tint treatment at 1300 ± 25°F for 15 to 20 minutes and inspected for coating coverage. The variation in colors noted were slightly different for each coating/alloy combination. In general there were two colors that indicated coating coverage, which was verified by metallographic examination, in addition to the typical blue color which was representative of the non-coated base alloy. A bronze-tan color is representative of the coating; however, a black-grey color was also detected on various parts and identified as a chrome rich outer layer of the AEP 32 coating. This black-grey color is extremely thin and may be removed by dry blasting; however, this is not recommended or necessary. This condition, as indicated by the black-grey color, was on most of the AEP 32 coated program test samples and was not found to be detrimental on the various alloys environmental or mechanical properties.

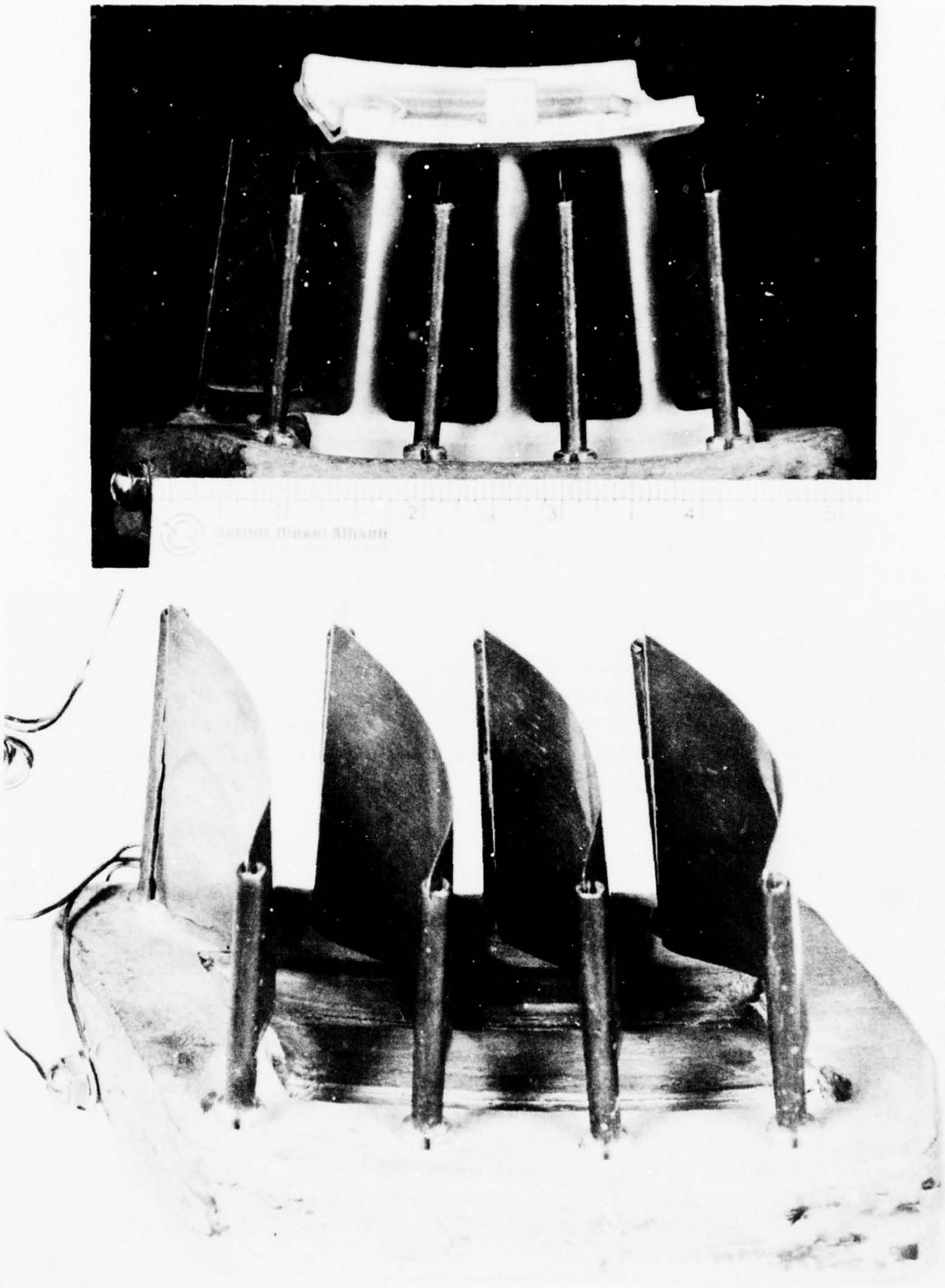


Figure 3-37 Multiple anode fixture required for TF 41 2nd Stage Vane (C1023/AEP 32)

Preliminary investigation of the applicability of thermoelectric probe inspection (TEP) of AEP 32 overhaul coating strongly suggests that with proper calibration for each alloy/coating combination the TEP technique could be implemented.

### 3.4.4 Evaluation of Recoated Engine-Run Turbine Hardware

Representative overhaul blades and vanes, fully processed as described in Paragraph 3.4.3 were sectioned for metallographic evaluation. Results of this evaluation are discussed in the following sub-sections.

- T56-A7 First Stage Turbine Blade (713C Alloy) Recoated with AEP 32

  Appearance of a typical Model T56-A7 1st Stage Turbine Blade reprocessed with AEP 32 coating is shown in Figure 3-38. Coating thickness on the airfoil sections was recorded for the cross-sections indicated by white lines and is reported in Table 3-XXX. Coating thickness was slightly heavier on the leading and trailing edges, but the coating thickness requirements of the specification for the base coating were met in all areas.

  Typical microstructure of AEP 32 on the 713C T56-A7 1st Stage Blade is shown in Figure 3-39. A slightly different structure was observed at leading and trailing edges, as shown in Figure 3-40.

- J79 1st Stage Turbine Blade (Rene' 80 Alloy) Recoated with AEP 32

  Appearance of a typical Model J79 1st Stage Turbine Blade reprocessed with AEP 32 coating is shown in Figure 3-41. Coating thickness measurements conducted on the airfoil sections indicated in Figure 3-41 are reported in Table 3-XXI. The AEP 32 coating was uniform in thickness and conformed to the specification limits for the baseline coating on this component. The various light and dark appearing surface areas observed in Figure 3-41 were not reflected in coating thickness or obvious microstructural variations.

  Typical microstructure of AEP 32 coating on the Rene' 80 TF 30 Blade is shown in Figure 3-42.

- F100 1st Stage Turbine Blade (B1900 Alloy) Recoated with AEP 32

  Appearance of a typical Model F100 1st Stage Blade reprocessed with AEP 32 coating is shown in Figure 3-43. Coating thickness measurements conducted on the airfoil sections indicated in Figure 3-43 are shown in Table 3-XXXII. Coating thickness and structure was very uniform and conformed to the specification limits for the baseline coating on this component except for occasional thin spots on the concave side of the airfoil near the blade base.

Typical microstructure of AEP 32 on the B1900 F100 Blade is shown in Figure 3-44.

- TF 30 1st Stage Turbine Vane (B1900 Alloy) Recoated with AEP 32

Appearance of a typical Model TF 30 1st Stage Turbine Vane reprocessed with AEP 32 coating is shown in Figure 3-45. Coating thickness measurements conducted on the airfoil cross-sections indicated in Figure 3-45 are shown in Table 3-XXXIII. In general, the coating was slightly thicker at the leading and trailing edges, but was still within the specification limits for the base coating. The coating was thin on the concave surfaces of the airfoil, particularly near the outer shroud. This coincides with a difference in surface texture observed visually in the airfoil/shroud radius as shown in Figure 3-45. Metallographic evaluation of the shroud sections indicated in Figure 3-45 suggests that this vane configuration will require contour fixturing similar to that used for multi-airfoil vane assemblies in order to ensure adequate coating thickness and structure on the concave airfoil surfaces and in the radius just described.

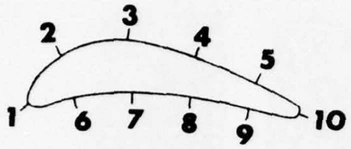
Typical microstructure of AEP 32 on the B1900 TF 30 1st Stage Vane is shown in Figure 3-46. The series of photomicrographs in Figure 3-47 reflect the microstructures in the area of the bare spot at the airfoil/shroud radius described above. These photographs also show considerable residual oxidation products which had penetrated the base coating during engine service and were not completely removed prior to recoating.

- TF 41 2nd Stage Turbine Vane Assy (C1023 Alloy) Recoated with AEP 32

Appearance of a typical Model TF 41 2nd Stage Turbine Vane Assembly reprocessed with AEP 32 coating is shown in Figure 3-48. Coating thickness measurements conducted on the airfoil sections indicated in Figure 3-48 are shown in Table 3-XXXIV. Coating thickness was uniform in structure and thickness and met the specification limits for the baseline coating on this component, except for thin spots on the leading and trailing edges caused by overblasting. Typical microstructure of AEP 32 on the C1023 TF 41 Vane Assembly is shown in Figure 3-49.

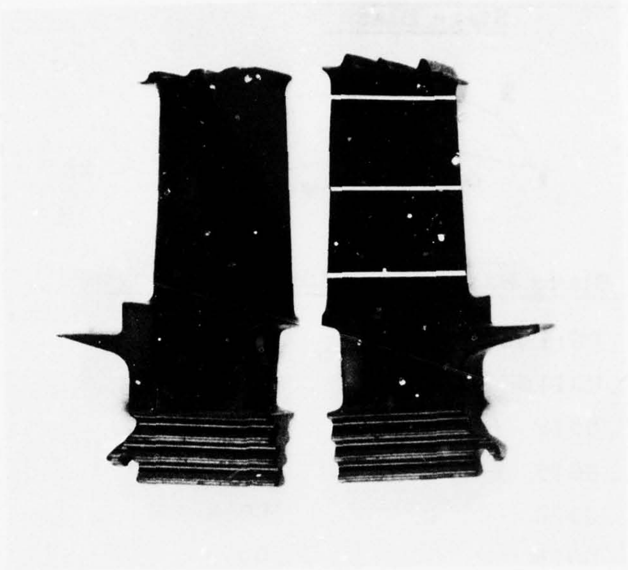
## Table 3-XXX

## Coating Thickness Measurements on 713C T56 A7 1st Stage Blade



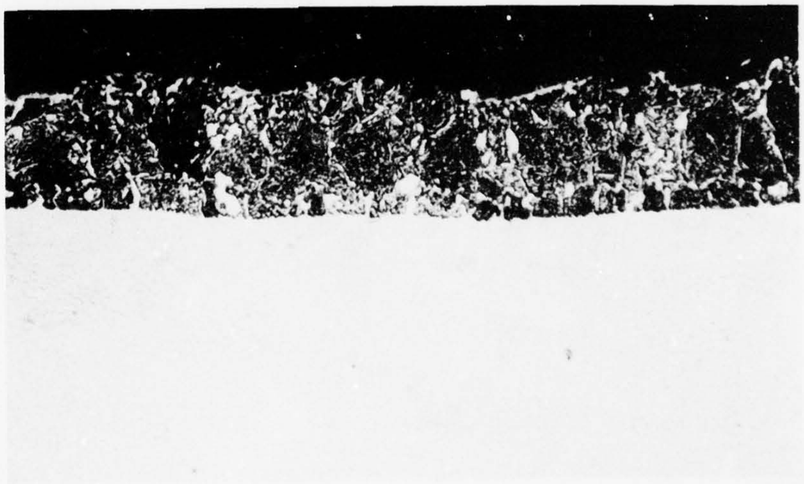
| Station No. | Near Blade Base | Mid Blade Length | Near Blade Tip |
|---|---|---|---|
| 1 | .0011 inch | .0018 | .0022 |
| 2 | .0014 | .0021 | .0015 |
| 3 | .0016 | .0019 | .0014 |
| 4 | .0015 | .0015 | .0014 |
| 5 | .0012 | .0018 | .0015 |
| 6 | .0015 | .0018 | .0015 |
| 7 | .0014 | .0012 | .0012 |
| 8 | .0014 | .0014 | .0012 |
| 9 | .0011 | .0012 | .0012 |
| 10 | .0018 | .0015 | .0020 |
|  | Avg. .0014 | Avg. .0016 | Avg. .0015 |

The specification for the baseline coating (Alpak) on 713C requires a coating thickness of .0010-.0030 inch.



Magn: 1X

Figure 3-38 Appearance of a typical overhaul T56 1st Stage Turbine Blade reprocessed with AEP 32



Magn: 500X

Figure 3-39 Typical microstructure of AEP 32 coating on reprocessed alloy 713C, T56 1st Stage Turbine Blades

Magn: 100X

Magn: 500X

Figure 3-40 Microstructure typical of leading and trailing edges on AEP 32-recoated 713C alloy T56 1st Stage Turbine Blade