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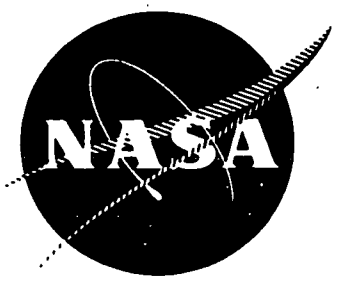

EXAMINATION OF THE INFLUENCE OF COATINGS ON THIN SUPERALLOY SECTIONS

by

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GENERAL ELECTRIC COMPANY

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16. Abstract

The effects of two coatings, Codep B-1 and CoCrAlY, with and without simulated engine exposures at 982C (1800F) and 1093C (2000F), were evaluated on cast sections of Rene 80. Section thicknesses were from 0.075 cm (0.030 inch) to 0.15 cm (0.060 inch). Tensile and stress rupture properties, mechanical fatigue, thermal fatigue, ballistic impact and hot corrosion at R.T. and elevated temperatures were investigated. Thin sections generally had poorer tensile strengths and lower stress rupture lives than standard 1/4" round gage bars. The coatings, as-applied, had little effect on tensile strengths, rupture lives and mechanical fatigue and they increased thermal fatigue, ballistic impact and hot corrosion resistance. By providing considerable exposure protection to the Rene 80, the coatings improved all properties compared to exposed bare specimens.

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UNIT CONVERSION TABLE

S. I. units are used throughout the report. Tables and Figures (where possible) have S. I. units with standard American units in parentheses. In the text, only S. I. units are shown. The conversions for commonly encountered values are listed below. The principal measurements were taken with instruments calibrated in American units, except for weight, which was measured directly in milligrams.

	S. I.	American
Linear measure	0.00254 cm	0.001 inch
	0.075 cm	0.030 inch
	0.11 cm	0.045 inch
	0.15 cm	0.060 inch
	0.635 cm	0.250 inch
Temperature	760°C	1400°F
	871°C	1600°F
	927°C	1700°F
	982°C	1800°F
	1093°C	2000°F
Stress	689 MN/m^2	100.0 ksi
	345 MN/m^2	50.0 ksi
	138 MN/m^2	20.0 ksi
Impact energy	1.36 N-m	1.0 ft-lbs

SUMMARY

The present program investigated the effects of two coatings, an aluminide type, Codep B-1, and a vapor deposited CoCrAlY coating, applied to a high strength nickel-base alloy, Rene 80. Cast flat sections ranging from 0.075 cm to 0.15 cm in thickness were studied. Exposures to simulate long time engine operation were carried out at 982C for up to 1000 hours and at 1093C for up to 500 hours in jet fuel combustion products with cyclic air cooling. The properties investigated were tensile, stress rupture, mechanical fatigue, ballistic impact and hot corrosion resistance. All specimens were given the Rene 80 thermal treatment at the same time.

Tensile testing was conducted at room temperature, 760C, 982C, and 1093C before and after burner rig exposure (at 982C and 1093C) on bare and coated flat specimens. The change in 0.2% yield strength compared to standard 0.635 cm (1/4 inch) diameter bar reveals there is a loss in yield strength due to decreased cross section size at 982C and with increased test temperature for bare and coated specimens. The percent change varied from around -6% at room temperature to -20% at 1093C. There was no discernible difference between bare and coated yield strength losses, the data being limited and falling within the scatter band for each specimen condition and test temperature. After even longer exposures at 982C and 1093C, as shown in Table A, the Codep B-1 specimens show less strength degradation due to exposure than the bare specimens at each size.

As shown in Table B, the general response of the ultimate strength is similar to the yield strength results with the exception that thinner sections at room temperature, unexposed, were stronger. The tensile elongation of the thin sections before and after exposure are comparable to the standard bar elongations as shown in Table C.

The effect of stress during 982C exposure was to produce an additional 5-20% loss in strengths compared to unstressed material for bare and CoCrAlY coated Rene 80, with no change in elongation. Codep B-1 coated material did not show significant differences between the two conditions.

A. Average Percent Change in 0.2% Yield Strength Compared to Standard 0.635 cm (1/4 inch) Bar

Test Temp. °C	Spec. Thick. cm	Bare	Codep B-1 Coated	Bare 754 hrs at 982C	Codep B-1 989 hrs at 982C	Bare 168 hrs at 1093C	Codep B-1 487 hrs at 1093C
R.T.	0.075	-7	-6	-28	-17	-20	+5
	0.11	-5	-3	-26	-17	-8	+4
	0.15	-6	-7	-19	-17	-6	+2
760	0.075	-9	-8	-19	+1	-11	+28
	0.15	-9	-9	-5	-2	-	+14
982	0.075	-24	-17	-20	-19	-10	+43
	0.11	-12	-11	-19	0	+5	+12
	0.15	-9	-12	-12	-2	+9	+41
1093	0.075	-17	-20	-9	+4	-30	-17
	0.15	-22	-30	+29	+25	-51	-3

B. Average Percent Change in Ultimate Tensile Strength

R.T.	0.075	+10	+9	-31	-20	-7	+5
	0.11	+7	+14	-30	-18	+5	+10
	0.15	-4	-5	-20	-14	+4	-2
760	0.075	-17	-15	-46	-23	-47	-9
	0.15	-13	-15	-42	-24	-41	-19
982	0.075	-23	-7	-24	-21	-33	+10
	0.11	-11	-11	-21	-13	-17	-2
	0.15	-10	-6	-16	-9	-16	+14
1093	0.075	-17	-8	-17	-12	-28	-9
	0.15	-9	-7	+3	+3	-23	-13

C. Tensile Elongation, Percent

R.T.	0.075	8.5*	8.0	1.3*	8.4	9.9*	4.2*
	0.11	7.3*	8.9*	2.0	3.8	11.7	5.0
	0.15	3.9*	4.2*	1.8	6.5	9.6	4.9
	Std bar	3.5*					
760	0.075	11.4	3.9	0.3*	1.8	0.9	3.0*
	0.15	4.9	5.2	1.8	3.8*	1.1	3.5*
	Std bar	8.0*					
982	0.075	20.5	13.9	4.6	4.3*	2.5*	8.9
	0.11	16.4	16.5	8.2	5.5	3.3*	8.8
	0.15	20.0	14.0	7.3	16.5	5.0*	8.5
	Std bar	16.3					
1093	0.075	10.2	15.0	9.4	14.0*	12.4	15.0*
	0.15	12.5	9.1	17.0	19.8	13.0	22.5
	Std bar	16.2					

* specimen(s) failed at or outside gage length mark.

Strengths for coated specimens based on original metal thicknesses (before coating).

Stress rupture testing was conducted at 760C, 982C and 1093C before and after burner rig exposure (at 982C and 1093C) on bare and coated specimens. Loads applied were equivalent to stresses to cause failure in approximately 100 to 300 hours on standard 0.635 cm (1/4 inch) diameter bars. Tests on the thin cast sections resulted in unusually short rupture lives. While due in part to testing technique problems, even when resolved, thin specimens had shorter lives. This is reflected in Table D under the bare and Codep B-1 coated headings. It will be noted in Table D, in which some of the more significant test result trends are assembled, that at all three temperatures, the thicker the cast specimen, either bare or coated, unexposed or exposed, the longer the rupture lives. For example, at 982C, coated Rene 80 0.15 cm (0.060 inch) thick had a rupture life double that of the 0.075 cm (0.030 inch) thick specimens. While the coating affected unexposed stress-rupture lives slightly (possibly lower at 760C and higher at 1093C), it affords considerable protection to the 1093C exposure. For example, after a 487 hour exposure at 1093C, the Codep B-1 coated 0.11 cm (0.045 inch) specimens tested at 982C averaged 33.3% of standard bar life compared to 4.7% for the bare specimens which had only 168 hours exposure.

D. Comparative Stress Rupture $_{\tau}$ Life. % of 0.635 cm (1/4 inch) Diameter Standard Bar Life

Test Temp. °C	Spec. Thick. cm	Bare	Codep B-1 Coated	Bare 754 hrs at 982C	Codep B-1 988 hrs at 982C	Bare 168 hrs at 1093C	Codep B-1 487 hrs at 1093C
760	0.075	7.4*	2.4*	6.6	0.5	**	1.6
	0.15	13.3*	2.9*	1.2	36.8	**	0.5
982	0.075	17.3*	8.9*	21.0	1.7	1.0	6.7
	0.11	14.7*	16.3*	18.4	5.2	4.7	33.3
	0.15	45.3*	16.7*	25.3	22.0	7.3	32.0
1093	0.075	33.7	44.8	28.5	27.9	6.0	44.8
	0.15	45.6*	46.5	62.8	79.7	31.7	70.9

* Indicates specimen(s) poorly gripped during test

** Specimens failed on loading

$_{\tau}$ Stresses for coated specimens based on original metal thicknesses (before coating).

Considering the losses in life due to testing techniques on the results in Table D, the following Table E is presented as an estimate of the actual life levels to be expected from the thin section bare or coated specimens.

E. Proposed Stress Rupture Life, Percent of Standard Bar

Test Temp. °C	Specimen Thickness, cm.	Bare	Coated
760	0.075 0.15	20 40	15 35
982	0.075 0.15	40 60	40 60
1093	0.075 0.15	50 60	60 60

Stress for coated material based on original metal thickness

Room temperature mechanical fatigue performance in bending as listed in Table F, was lowered slightly by the Codep B-1 coating even though the surface layer is hard and rather brittle at room temperature. Both coatings were only slightly affected by the exposures, while the bare material was weakened considerably by the 1093C exposure. The bare material after 982C exposure gave unusually high fatigue results. These will be rechecked in a subsequent program.

F. Bending Fatigue Strength at 10^7 Cycles, Room Temperature

	Bare	Codep B-1 Coated	Bare 754 hrs at 982C	Codep B-1 988 hrs at 982C	Bare 168 hrs at 1093C	Codep B-1 487 hrs at 1093C
Strength, MN/m^2 (ksi)	372 (54)	359 (52)	551 ? (80)?	331 (48)	221 (32)	283 (41)

Thermal fatigue tests, with a temperature range of 1093C to under 204C, showed that Codep B-1 improved the crack resistance of Rene 80 by at least 2 to 3 times depending on exposure as shown in Table G. The CoCrAlY coating provided a somewhat smaller improvement.

G. Average Thermal Fatigue Test Results

	Bare	Codep B-1 Coated	Bare 761 hrs at 982C	Codep B-1 975 hrs at 982C	Bare 180 hrs at 1093C	Codep B-1 483 hrs at 1093C
Cycles to First Crack	2218	no cracks up to 4000	1300	no cracks up to 4000	1300	no cracks up to 4000
Cycles to Cracks 0.5 - 1.0 cm	2450	"	1450	"	1550	"
Cycles to Cracks over 1.0	2900	"	1850	"	1850	"

Ballistic impact strength (Table H), as measured by the energy necessary to crack the Rene 80, was improved by the coatings, although some of the coatings were craze cracked. The CoCrAlY coating was slightly superior in this test.

H. Average Ballistic Impact Strength

Test Temp.	Bare	Codep B-1 Coated	Bare 761 hrs at 982C	Codep B-1 975 hrs at 982C	Bare 180 hrs at 1093C	Codep B-1 483 hrs at 1093C
R.T.	1.45 (1.07)	2.64 (1.95)	< 0.16 (< 0.12)	0.16 (0.12)	< 0.16 (< 0.12)	2.03 (1.50)
982C	0.34 (0.25)	> 0.68 (> 0.50)	< 0.33 (< 0.24)	0.50 (0.37)	0.35 (0.26)	0.68 (0.50)

Impact strength in N-M, (ft-lbs).

Both coatings present great resistance to oxidation during the exposures and to hot corrosion. Typical corrosion attack values are included in Table I.

I. Hot Corrosion at 927C, 5 ppm Sea Salt Test Results

	Bare	Codep B-1 Coated	Bare 758 hrs at 982C	Codep B-1 962 hrs at 982C	Bare 229 hrs at 1093C	Codep B-1 532 hrs at 1093C
Test Time hrs	473.5	435	346	328	61	61
External Metal Loss, cm	0.0079	0.0054*	0.0223	0.0012	0.0190	0.0053
Max. Additional Penetration, cm	0.0040	0.0055*	0.0152	0	0.0127	0

* Coating lost in these areas. Where coating was intact, attack was nil.

The elevated temperature exposures prior to the hot corrosion test degraded the performance of the coatings, particularly the 1093C exposure on Codep B-1 as follows:

Coating	Exposure	Time Period In Which First Failure Occurred, hrs
Codep B-1	Unexposed	202-271
"	982C, 962 hrs	146-165
"	" 1000 hrs, stressed	61-127
"	1093C, 532 hrs	42-61
CoCrAlY	Unexposed	> 473.5
"	982C, 962 hrs	146-165
"	" 1000 hrs, stressed	61-127
"	1093C, 532 hrs	146-165

The exposures changed the composition and hardness of the coatings. The 982C and 1093C exposures lowered the aluminum content of the Codep B-1 coating from ~ 31% to ~ 18% and ~ 6% respectively. The same exposures for the CoCrAlY coating lowered aluminum from ~ 12% to an average of ~ 10% and ~ 3% respectively. Microhardnesses of the coatings' diffusion zones and additive layers were lowered by exposure as indicated:

Effect of Exposures on Average Microhardness of Coatings

Coating	Exposure	Vickers Hardness		
		Rene 80 Substrate	Diffusion Zone at coating/substrate interface	External Coating Layer
Codep B-1	Unexposed	473	918	571
	982C, 989 hrs	409	736	496
	1093C, 487 hrs	449	591	422
CoCrAlY	Unexposed	439	535	693
	982C, 990 hrs	374	-	417
	1093C, 375 hrs	444	-	333

INTRODUCTION

The purpose of the present program is to examine the influence of both coatings and high temperature exposures, singly and in combination, on several important properties of cast thin superalloy sections, as well as to investigate the strengths of the thin sections compared to standard size bars. Such information will provide a guide towards proper long-life turbine blade design involving thin superalloy castings by indicating the changes in properties that may be expected due to thin sections, coatings and exposures. The program is not intended to obtain enough data for quantitative design, but to discover those areas of greatest concern, and towards which further work should be devoted. Fortunately, the behavior of most of the high strength cast nickel-base superalloys is similar, as is the behavior of most of the aluminide-type protective coatings used on them, making the results obtained here on the particular alloy and coatings chosen applicable as a guide to a wide range of other alloy/coating combinations. The alloy and coatings selected are Rene 80 and Codep B-1 and CoCrAlY respectively. Their selection is discussed subsequently.

The specimen thicknesses selected are 0.15 cm, 0.11 cm and 0.075 cm. All were made within present casting technology. The casting design, casting parameters and specimen treatments were chosen to be as close as possible to those used for turbine blades. The 0.075 cm specimen, while not down to the thinnest section actually used, is representative of many present applications. The range of thicknesses (plus standard size bars) did permit some correlation of properties to section size.

Exposures to simulate maximum possible engine conditions were chosen: 1000 hours at 982C and 500 hours at 1093C in a fuel combustion products atmosphere with frequent rapid cooling cycles to near room temperature. The effects of stress during static air exposure at 982C were also investigated.

The properties examined were:

1. Yield strength, ultimate tensile strength and elongation at room temperature, 760C, 982C and 1093C.
2. Stress rupture life and elongation at 760C, 982C and 1093C.
3. Mechanical fatigue (bending) at room temperature.
4. Thermal fatigue, maximum temperature 1093C, minimum temperature <204C.
5. Ballistic impact at room temperature and 982C.
6. Hot corrosion resistance at 927C, 5 ppm sea salt using a burner rig with JP-5 fuel.

Not all thickness specimens were tested at every condition listed above. Oxidation behavior was obtained during the high temperature cyclic exposures.

Mechanical property data for use in the design of cast aircraft gas turbine blades generally have been obtained from tests using cast standard size bars, usually about 0.64 cm diameter, or from similar bars machined from sections of large engine blades. However, small engine blades and hollow and air-cooled sections of large engine blades have thicknesses and shapes quite different from the common test bars. For example, solid small turbine blades have been made with a maximum airfoil thickness of ~0.15 cm, tapering to under 0.05 cm. Hollow airfoils, with wall thicknesses of under 0.075 cm have been cast, and wall thicknesses near cooling passages have been cast as low as 0.04 cm. The solid and hollow blades have essentially sheet-like load carrying shapes rather than the round shape of the normal cast test bar.

It has been recognized for many years (ref. 1, for example) that section size and shape affect properties of metallurgically identical specimens. Many material specifications account for this by setting different strength requirements for different sizes of product. AMS specification 5545, for the nickel-base superalloy Rene 41 sheet permits 69 MN/m^2 (10,000 psi) lower ultimate tensile strength at 760C for sheet thinner than 0.046 cm compared to sheet over 0.061 cm. Unfortunately, the complexity of the mechanism relating geometrical variables to tensile, fatigue, creep-rupture strength, etc., has prevented development of acceptable prediction methods, and empirical tests must be used to provide the required data. An illustration from General Electric Co. work of the effect of section thickness on stress rupture life of the wrought nickel-base superalloy U700 is shown in Figure 1. Stress-rupture life in air at 982C, 138 MN/m^2 (20,000 psi) is plotted as a function of the thickness of sheet-type specimens or of the diameter of round specimens machined from wrought bar stock, and compared to the life of standard size 0.64 cm bars machined from the same bar stock. Little difference is shown between round and flat specimens of similar size, but a pronounced loss in stress rupture life occurs for thin specimens. It is expected that section size effects would apply to cast superalloys as well as wrought alloys.

In addition to the purely geometrical effects, cast superalloy properties depend on many metallurgical structural factors controlled by casting variables, composition, thermal treatments, etc. Such features as grain size, grain shape, and orientation, number of grains across a section and chemical segregation all have bearing on the resultant properties. In thin castings, the relatively large ratio of surface area to volume causes rapid cooling and presents difficulty from the standpoint of the metal filling the mold while pouring and of the feeding of metal during solidification contraction (to avoid shrinkage porosity). Consequently, higher metal superheat may be used in pouring thin castings than heavy ones. The thermal conditions may result in thin castings containing predominantly columnar grains, whereas heavier castings may exhibit a larger percentage of equiaxed grains.

Besides the more obvious grain size, shape and orientation patterns, the solidification of superalloys occurs dendritically, which results in chemical segregation. Thus, while the average composition may be a desirable one, the local composition may be sufficiently different so as to cause undesirable phase formation. The finer dendritic structure in thin castings is another factor affecting mechanical behavior.

The effects of two of the individual factors mentioned above on mechanical properties of cast superalloys have been investigated, and the results listed below:

1. Grain orientation. Thermal fatigue, stress rupture strength and ductility is higher in the <100> direction than in the <110> direction or in random orientations, (ref. 2).

2. Grain size. The effect of grain size on properties is related to the equicohesive temperature. In the conventional view, coarse grains provide higher strengths above, and finer grains below this temperature. The equicohesive temperature for many superalloys is in the region of 760C to 982C depending on alloy and strain rate.

The combined effects of the various factors are integrated in tests performed on actual thin castings. Many laboratories have initiated programs to investigate the relationship between various structures and properties. Hessler and Ewing (ref. 3) have reported reductions in stress rupture life in thin castings at 927C on their superalloy M3608F. In a preliminary program at General Electric Co., the effect of cast section size was determined on the stress rupture, tensile and fatigue properties of Rene 80. Reductions in stress-rupture life at 982C greater than indicated in Figure 1 were found, with reductions in tensile strengths at 871C and in low cycle fatigue strengths at 649C and 871C. Machining of the surface of the cast specimens generally resulted in improved properties. Similar results were obtained in a program specifically designed to obtain an improved cast thin section alloy (ref. 4).

The prior work alone indicates that thin cast sections require special design data However, the retention of mechanical properties during engine operation is of prime importance. First stage turbine blades are exposed for long times to temperatures that may cause metallurgical and structural changes which affect properties. This area has stimulated much work, and the papers of an International Symposium (ref. 5) provide much information on the metallurgical and some mechanical property aspects of stability of superalloys. Many studies on nickel-base superalloys indicate three major areas of metallurgical instabilities:

1. Precipitation of complex intermetallic phases such as σ, μ, Laves, etc. These compounds tend to be embrittling at low to moderate testing temperatures and usually weakening at higher temperatures.

2. Precipitation of carbides such as $M_{23}C_6$ and M_6C. The former carbide frequently is formed at grain boundaries and may reduce ductility, while the latter usually has little effect on mechanical properties, although both carbides may act as creep inhibitors if properly distributed.

3. Agglomeration and solution of Ni_3(Al, Ti, Cb), γ'. Since the γ' is the major strengthening phase, any change in its size and distribution will affect properties.

Efforts have been made in the course of superalloy development to avoid or minimize the detrimental effects of each of the above problems. The PhaComp technique developed from the studies of Boesch and Slaney (ref. 6) and Woodyatt, Sims and Beattie (ref. 7) does present a method of preventing formation of σ type phases in a given superalloy base. The carbide problem is attacked in most modern superalloys by inclusion of elements such as Ta, Cb, W and Hf, which tend to stabilize the initially formed MC carbide, and in amounts which favor M_6C formation rather than $M_{23}C_6$, if possible, (for example: B-1900 has 4% Ta; Mar-M 246 has 1-1/2% Ta and 10% W; NASA-TRW VIA has 5-1/2% W, 8-1/2% Ta + Cb and 1/2% Hf). Fortunately, these same elements, plus proper balancing of Al, Ti, Cr, Co, etc., help to stabilize the γ'.

In spite of the advances in alloy design, changes in properties do occur in nickel-base superalloys with exposure to temperatures in the range of operation of turbine blades.

Not only are metallurgical changes important, but the oxidation and/or corrosion attack at the surface act to decrease the metal cross sectional area, to cause stress concentration problems, and to permit contamination by oxygen and nitrogen. Many of the effects can be minimized by machining off the affected surfaces. Since a turbine blade must operate for long time without the advantage of such cleaning, the data should be taken on specimens whose surface is undisturbed from exposure to test. Of course, one of the purposes of protective coatings is to decrease or eliminate the surface attack. The effects on stress-rupture life, while interesting and important, are usually incorporated in design data by inclusion of long time rupture tests throughout the whole range of operating temperatures. However, properties such as tensile strength (to resist sudden overspeed conditions), impact strength (to resist foreign object damage), fatigue, thermal shock resistance, etc. can be determined only by running the appropriate tests on specimens having the necessary long time/temperature exposure. Superalloy users and developers have been performing such tests for many years on every one of the alloys recently used for turbine blades. Using standard size test bars, the trends for the alloys tested show loss of low temperature tensile strength and ductility due to exposure, with a loss of tensile strength and increase in ductility at high test temperatures (the crossover temperature varies with alloy). No significant effects of exposure on stress rupture life seem evident, although a slight loss occurs for several alloys. (A drop in life of 50% represents a loss in strength of only 5 to 10%). The room temperature impact strength for most superalloys is reduced by exposure.

While the data indicate some cause for concern over the effects of exposure on properties, it should be remembered that on thin sections, the effects due to surface attack will be magnified and greater losses in properties may result. No tests have been reported to date on exposed thin superalloy sections.

The increased temperatures and longer lives required for turbine blades in more recent engines have necessitated greater resistance to property degradation and environmental attack - both hot corrosion (sulfidation) at temperatures up to about 1000C and to oxidation up to 1100C. The newer high strength nickel-base superalloys, containing lower chromium than older alloys, have proven particularly susceptible to severe hot corrosion attack even though their oxidation resistance is fair. Reference 8 contains many papers on the problem. Protective coatings have been developed and have been shown to be satisfactory in engine service. The bulk of the experience has been on aluminide-type coatings. The newer metal CrAlY coatings appear to be even better in hot corrosion resistance, but are usually thicker coatings. Both types of coatings require heating the parts (which can alter the properties) and both produce a surface layer of a material having different properties than the base alloy. Thicknesses of from 0.005 to 0.013 cm are common, and obviously represent a greater fraction of the cross-section on thin parts. It becomes correspondingly more important therefore to determine the effects of coatings on the mechanical properties of thin sections to permit proper design.

Work has shown that coatings on standard size bars, if the stress is based on the parent metal thickness, affect neither stress rupture life nor tensile strengths of many different superalloys (including SEL, Rene 77, Rene 100, etc.). Low temperature impact strength and fatigue strength can be lowered, while thermal fatigue is usually improved. Stress rupture tests on aluminide coated thin sections of wrought U700 (the same material represented in Figure 1) have indicated no detrimental effects compared to uncoated sections of the same thickness. A large range of superalloy-coating combinations were evaluated on thin castings (ref. 9). Only a single thickness was tested: an ~0.08 cm (0.032 inch) wall hollow specimen with a rounded edge rectangular cross section. The inner surface

was not coated, and failures generally initiated at this bare surface. Problems occurred due to occasional unequal wall thickness on each side of the specimen and to casting defects. Uncoated specimens and standard size bars of the same heats of material used for the thin wall castings were not included for comparison. However, within these limitations, the relative stress-rupture life of the thin wall castings appeared to be considerably lower than expected from standard size bars. Tensile, fatigue (mechanical and thermal), ballistic impact and corrosion/oxidation properties were determined also. This work clearly indicated the need for further investigations on the effect of coatings and section size on properties of superalloys.

The effects, separately, of coatings and of exposures on the properties of nickel-base superalloys have been discussed. It should be expected that the effect of exposure on coated superalloys would be less than on uncoated because of the surface protection. However, there is one additional metallurgical factor to consider. During high temperature exposure, further diffusion between the base alloy and the coating occurs. The total thickness of a typical coating increases during exposures due to diffusion. The increase in the affected cross-section can cause larger regions that are embrittled by intermetallic phase formation or reduced in strength by γ' changes. Properties of the coating itself vary as its composition shifts during exposure.

The effects of high temperature exposures on various aluminide coated, cast superalloys using standard size bars have shown that the coated alloys react to exposure in a similar fashion to the uncoated alloys. While the trends are the same (lowered tensile and impact strengths; slighter effects on rupture and fatigue), the coated alloys tend to change less with exposure than do the uncoated alloys. Diffusion effects do not cover a large enough percentage of the cross-sectional area to make their presence felt in the standard size bars. Data on the effects of exposure on the mechanical properties of MCrAlY type coated superalloys have not been published. Studies on the combined effects of coatings and exposures on cast thin superalloy sections have not been performed.

MATERIALS AND TEST SPECIMENS

Alloy and Coatings Selection

There are several high strength cast nickel-base superalloys in use in present engines or considered for use in advanced engines, such as B-1900, IN 100, Mar-M 246, Rene 80, Rene 100, NASA/TRW VIA, etc. On a rupture-strength-to-weight basis, there is little to choose from. However, when other factors including ductility, corrosion resistance, coatability (with aluminide coating, and with strip and recoat capability) etc., and the amount of background data available were considered, the alloy Rene 80 was chosen for this program. Rene 80 is used in many present and advanced engines and most of these have thin walled cast turbine blades.

Every major supplier of vacuum cast superalloy turbine blades has successfully produced Rene 80. Over one hundred heats, over 450,000 kg (~ 1,000,000 lbs) have been melted. Castability is similar to older nickel-base alloys, and no new problems have appeared.

The Rene 80 specification includes a high temperature solution heat treatment in vacuum, and a coating thermal cycle as part of the full heat treatment, whether or not coatings are required. The latter treatment eliminates the variable of the presence or absence of a coating thermal cycle encountered with other alloys. The alloy composition is PhaComp controlled, insuring reliable and reproducible stability behavior.

The two pre-eminent types of protective coatings for nickel-base superalloys are the aluminide and MCrAlY types. The aluminide coatings are in use by virtually every engine manufacturer, while the MCrAlY coatings are newer and have less service. Laboratory tests indicate the MCrAlY coatings, which are ~ 50% thicker, have the capability of providing three to ten times the life of aluminide coatings (ref. 10) but presently have the disadvantage of about 10 times higher cost of application. The predominance of the aluminide coating experience and the prospective superiority of the MCrAlY type required that both coatings be investigated.

Many commercial aluminide coatings are available. While they all depend on the compound NiAl (or Ni_2Al_3) with other dissolved elements (Cr, Ti, etc.) for their effectiveness, the processing methods, process controls, thermal cycles and final compositional balance are different. It is no surprise that no single coating has proven best on all alloys and under all test conditions. General Electric engine experience indicates that the Codep B-1 coating is superior to other aluminide coatings on a larger variety of high strength nickel-base superalloys including Rene 80, and is in fact replacing several other coatings in existing engine applications.

The application of the MCrAlY coatings has not been as widespread as the aluminides because of their recent development. Good experience has been obtained with CoCrAlY coatings having a nominal composition of about 25% Cr, 12% Al, 0.5% Y, balance cobalt

(ref. 10). This coating has been evaluated on Rene 80, Rene 77, U500, X-40 and TD NiCr and specifically on thin wall castings of Rene 77 and Rene 80, in oxidation and hot corrosion tests as coated pins and coupons up to 2000 hours over the 760C-1025C range. The coating has shown good performance in these tests. Consequently, this coating was chosen for inclusion in the program.

To provide maximum possible correlation with expected turbine blade thin walled behavior, the castings used for test specimens simulated blade size, shape, thermal history, etc., as much as possible. After an investigation of experiences with various cast specimen shapes, a slight modification of an earlier thin walled cast specimen was selected and is shown in Figure 2. The size and wall thicknesses are representative of several air-cooled turbine blades. While most blades would have ribs, reinforcements, etc., on the inside, they would interfere with obtaining test specimens here. The rounded edge simulates a blade leading edge, and provides specimens for thermal fatigue tests (the leading edge of turbine blades is the location most prone to thermal fatigue). Each of the flat faces can provide a short sheet type test specimen suitable for tensile, rupture, and fatigue tests.

The mechanical property specimen machined from the flat sides of the castings is shown in Figure 3. The most critical dimensions are those specifying the axiality of the gage length, the gage section width, and the bow of the specimen. Although not indicated on the sketch, the bow was held to a maximum of 0.035 cm over the total length of the specimen. Deviations greater than permitted would add excessive additional bending stresses to the specimens. Under tensile loading, an eccentricity of 0.0025 cm causes an initial 2.4% increase in the stress at the center edge of the gage section (before stress relaxation occurs). Stresses due to bowing are more difficult to calculate due to the straightening that the axial load causes, but are of smaller magnitude.

The rounded "leading edge" of the casting was machined to a depth of 0.762 cm from the front edge, and served as both a thermal fatigue specimen and a ballistic impact specimen.

Materials and Specimens Used

All specimens used in the program were cast from a single heat of Rene 80 (No. BV231) by Jetshapes, Inc., using a master heat manufactured by Special Metals. A description of the casting process provided by the vendor is as follows:

A single cavity die was used with 3 different thickness cores to make the 3 different wall thicknesses required. Gating was cut in the die. After injection and dressing 16 pieces were set up per sprue (4 pieces per runner). A standard shell system was employed for mold making. Pour temperatures of 1454-1482C were used for all specimens, with a mold temperature of 1093C. After casting, the ceramic was removed and specimens cut-off from the gating system, sand blasted to clean and remove cores, marked with identification numbers, flat sides slit from castings, and inspected (visual, standard fluorescent penetrant and X-ray radiographic methods required in specification for airfoils).

The yield was not very high, but sufficient specimens for the program were easily obtained. The identification numbers that were stamped on each flat face and leading edge of each specimen were useful for the maintenance of specimen identity throughout the program and are referred to wherever necessary. Unfortunately, records were not kept of which serial numbers came from which mold, and therefore the numbers represent only an approximate chronological casting sequence.

Photographs of reconstructed castings of each thickness are included in Figure 4. The thinnest specimen (Figure 4a) clearly shows some bowing that occurred after the sides were slit from the casting. The bow was not mechanically straightened; flattening was performed later during heat treatment.

Thickness measurements and visual inspection were made on each specimen received. Several specimens were rejected for a thickness variation more than $\pm$ 0.005 cm. A sample of 19 specimens, representing each thickness as well as flat and leading edge portions was run through X-ray and fluorescent penetrant inspection. The results agreed with the vendor supplied information and no mechanical defects were found in the areas destined to become test specimen gage sections. Several surface defects ("pock-marks") were noted in regions near the gates. The surfaces of each of these specimens were macro-etched with a solution of 100 ml HCl, 50 ml H_2O_2 and 100 ml H_2O for 30 seconds in order to determine grain size (specification requires surface grain size to be between 0.04 cm and 0.016 cm). Representative appearances are shown in Figure 5. The 0.075 cm specimens (Figure 5a) had a surface grain size of 0.04 cm at the center with slightly larger grains of 0.08 cm near the gate areas. The leading edge section had uniform 0.04 cm grains all over. The thicker specimens (Figures 5b-d) had surface grains of 0.08 to 0.16 cm near the center and in the leading edge, with some coarser columnar grains radiating from the gate area. As long as these grains did not reach the gage section of the test specimens, this condition was acceptable. Inspection of the X-ray films of each specimen received (supplied by the vendor) revealed that the grain size and shape were clearly visible, and that some of the thicker specimen flat pieces did have columnar grains through the center. All of these pieces were rejected and not used in the program. Each of the above samples were cut in several longitudinal and transverse cross sections to inspect for internal defects. Nothing more than a rare micro-shrink or micro-porosity of under 2% of thickness was found except in one 0.15 cm specimen where a single hole (possibly enlarged by polishing) of 0.008 cm was present. The microstructure was normal for Rene 80, and will be presented in a subsequent section.

Surface finish appeared normal for turbine blade castings. Readings on a Brush "Surfindicator", Model BL 110 yield the following values in RMS microinches:

		Specimen Thickness and Identification No.								
		0.075 cm			0.11 cm			0.15 cm		
Location	Direction	33	29	86	K	L	V	4	17	96
Outside	∥ to length	70	60	80	85	85	75	70	55	55
	⊥" "	70	65	80	90	80	80	45	70	90
Cored side	∥" "	70	75	80	85	80	80	70	60	55
	⊥" "	70	85	80	90	75	80	50	75	75

The 0.075 cm rounded nose section #0, parallel to its length, read 75-80. According to the vendor, normal turbine blade surface finishes are about 70, therefore the test specimens are reasonably similar. The 0.15 cm specimens showed a relatively larger variation than the others, probably due to the occasional "touch up" belt sanding of these specimens to remove surface projections by the vendor.

Chemical analyses were run by the vendor on one specimen, and by General Electric Co. on 11 specimens representing the various thicknesses. Results are listed in Table I, with the specification requirements for comparison. The $\overline{N}_{v3}$ is the PhaComp control number based on a special calculation similar to that described in ref. 7. Presumably, Rene 80 material with a $\overline{N}_{v3}$ below 2.32 will not form σ phase on exposure to elevated temperatures. No significant differences exist among the various analyses, and all are within the specification limits.

The vendor-provided mechanical property data for the specification requirements (on standard size 0.64 cm diameter bars) is in Table II. One reduction of area value of 13.8% is below the nominal minimum of 15%, but the specification permits a lower value if the average of it and all other tests is above the minimum.

In summary, the casting vendor produced acceptable quality thin section castings from Rene 80 that met all the specification and program requirements.

The machining, heat treating and Codep B-1 coating of specimens was done by Walbar, Inc. Specimens were machined to Figure 3 dimensions as follows: the holes were drilled in the cast flat blanks; groups of drilled blanks were clamped together using pins through the holes for alignment; the contour of the gage section was form-ground, and the ground edges individually cleaned up after unclamping the group of specimens. The flat sides were not touched. The bowed specimens still remained bowed. Flattening was accomplished during the first step of the required heat treatment (described below) by placing a flat weight on a stack of specimens resting on a flat plate. The high temperature permitted the weight to literally creep-form the specimens. After this treatment all specimens were within the flatness specified.

Rene 80 has a four step heat treatment:
1218C, 2 hours, in vacuum, rapid cool
1093C, 4 hours, in vacuum, rapid cool
1052C, 4 hours, in vacuum (or in coating process)
843C, 16 hours, in vacuum

All specimens (thin flat sections, leading edges and standard size bars) were put through the first three steps at the same time. The third step is the Codep B-1 coating process time and temperature (coating applied by a pack process in a hydrogen atmosphere). Rather than have the non-Codep coated specimens treated in vacuum at somewhat different heating and cooling rates than the Codep coated specimens, all specimens were run in the Codep processing furnace. The specimens not meant for Codep coating were masked to prevent coating pick-up. After this treatment, the bare and Codep B-1 coated specimens were aged (the fourth step).

The CoCrAlY coating was applied to specimens by a vapor deposition process. Unfortunately, only about a dozen specimens could be coated simultaneously, necessitating many separate runs to produce the total number needed for the program, with possibly

attendant differences in coating parameters. It should be noted that due to the fixture grip holding the specimens, one end of each specimen (outside the gage length area) was not coated. After coating a one hour diffusion treatment at 1052C in vacuum was given before the normal fourth heat treatment.

To determine coating thickness, 18 assorted Codep B-1 and 8 CoCrAlY coated specimens were sectioned at various locations and metallographically measured using a filar eyepiece at 400X. These specimens were used as calibration standards for a Dermitron coating thickness gage (at Walbar), and all other pieces were then non-destructively inspected for coating thickness. The results are summarized in Table III. Every Codep B-1 coated specimen fell within the required thickness range, and exhibited remarkable uniformity over all the sections inspected. The Dermitron had some trouble reading the thickness on the curved leading edge (it read too high); on the flat surfaces its readings were good. A total of six of the CoCrAlY coated specimens had greater thicknesses than specified (spread out among the three specimen thicknesses) and were not used for mechanical property tests.

The coatings were analyzed by electron microprobe for chemistry and by x-ray diffraction and microscopy for structure. The detailed results will be shown later in comparison to exposed material, and a brief summary will be given here. For the Codep B-1 coating, an average of four different specimens provided the following chemical analysis in the additive layer: Al ~ 33%, Cr ~ 2%, and Ti ~ 0.5%, with little difference among the samples. The microstructure revealed the normal additive layer and diffusion zone of about equal thickness, with a few Al_2O_3 particles entrapped in the additive layer, and the usual σ phase and carbide particles in the diffusion zone (phases verified by microprobe analysis). The additive layer, by x-ray diffraction, was found to be entirely NiAl, with a small amount of α Al_2O_3.

The CoCrAlY coatings were more variable, as the coating thickness measurements imply. On four samples, the average Cr content varied from ~ 18 to 30% and the Al content from ~ 10 to 15% (balance largely Co). Microstructurally, a two-phase additive layer constituted the major portion of the coatings. A noticeable diffusion zone of about 1/5 the coating thickness was found in three of the specimens, while the fourth had a barely distinguishable zone. This represents an additional indication of the variability of the coating.

The phases in the CoCrAlY additive layer are CoAl and a face-centered cubic matrix, with a very small amount of α Co (hexagonal) present. Microprobe analysis of the diffusion zones showed a thin NiAl layer with a σ, carbide rich zone below. Occasional oxide streaks and "spatter" defects were found on many areas in the CoCrAlY additive layer. Generally they did not penetrate to the base metal and would not be considered damaging. A non-destructive inspection technique does not exist to detect those that are damaging, and as became evident later during exposures, some damaging ones did exist.

In summary, the Codep B-1 coating was entirely satisfactory on all specimens, while the CoCrAlY coatings exhibited greater variability. Some were rejected for high coating thickness.

EXPOSURE AND TEST PROCEDURES

Exposure Conditions and Procedures

The operating stresses in turbine blades are such that even the newest cast nickel-base superalloys do not have sufficient strength for long time service (over 1000 hours) at temperatures above 982C. Air cooling is used to keep metal temperatures to this level, even though the gas temperatures, due to hot streaks, interference with cooling air flow, etc., may reach well over intended use levels. 1093C was selected as the maximum exposure temperature representing such a possibility, for a time of 500 hours. The results of a high temperature exposure cannot be considered to represent a longer time at lower temperatures. To represent a reasonable temperature for realistic engine exposures, 982C was selected. Long life in engines is expected at this level. Prior tests show that the metallurgical effects at this temperature, 982C, occur in relatively short times, certainly before 200 hours. The same tests indicate no serious degradation of the Codep B-1 coating in 1000 hours exposure (in air). These data suggest that an exposure time of 1000 hours is desirable. The 982C exposure was divided into two groups: cyclic exposure unstressed, and static exposure under stress. The 1093C exposure was only cyclic and unstressed.

The cyclic exposures were carried out in a jet fuel burning rig (the same used in the hot corrosion testing performed here). The construction and operational details are described in ref. 11. The specimens were placed in a rotating fixture (30 rpm) in the stream of the products of combustion of JP-5 fuel (air fuel ratio of 30:1). Figure 6 is a photograph of bare and Codep B-1 coated specimens (after exposure) in the fixtures. Gas velocity was rather low, in the order of Mach 0.04 (6-20 meters per sec.). Every hour during the working day the whole fixture was removed and placed in a compressed air blast. Cooling from the exposure temperature to under 94C was accomplished within 2 minutes. Heating time to within 5C of the exposure temperature was about 10 minutes, and exposure time was calculated from this point. Full temperature was attained in under an additional 5 minutes. Temperatures were maintained to ± 6C of the nominal and a recording temperature indicator provided actual thermal history. Temperature was controlled from a stationary thermocouple placed above the top center of the rotating fixture. Initial calibration of this couple was made by placing three thermocouples on a specimen (center, top and bottom of gage section) placed in the rotating fixture with a full load of specimens. Slip rings on the bottom of the fixture shaft enabled temperature measurements to be taken during rotation. Variations up and down the specimen, during rotation, and with time did not exceed ± 6C. This operation was performed for each of the exposure temperatures. It was presumed that the difference in indicated temperatures between the stationary control thermocouple and the rotating thermocouples would remain essentially constant, and the actual exposure runs did not contain the thermocoupled specimen. Three burner rigs were used: one for the 1093C exposures, and two for the 982C exposures. Every ~ 50 hours, each specimen was removed from the fixture, visually inspected, and weighed to provide oxidation weight change data. If surface deterioration seemed sufficient to affect later testing capability (as in Figure 6b), exposures were terminated before the desired times.

The stressed exposures for 1000 hours at 982C were done in ordinary open air electric furnace, lever-arm type stress rupture test stands. Temperature was maintained within ± 3C. Stress was selected to produce failure in ~ 5000 hours, and was 55 MN/m^2 initially. After early stress rupture results indicated lower-than-expected lives, this exposure stress was dropped to 48 MN/m^2. The stress on the few specimens that were already in exposure (up to 118 hours) at the higher stress was lowered, and they and all the others run at the lower stress. No thermal cycling was done, and at the completion of the 1000 hours the specimens, particularly the bare and CoCrAlY coated specimens, appeared to have much less surface damage than comparable specimens from the cyclic exposure. Only the 0.15 cm thick specimens were used for the stressed exposures.

Mechanical Property Test Procedures

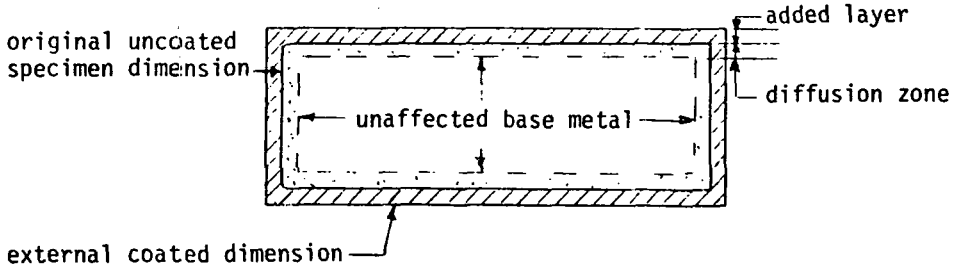
Tensile Tests

Tensile tests were performed in accordance with ASTM procedures E8-66 and E21-66T at room temperature, 760C, 982C and 1093C for both thin section and standard size cast bars. The 0.11 cm thick castings were tested only at room temperature and 982C. Testing was done in air at a strain rate of 0.005 mm/mm/min. to yield and 0.05 mm/mm/min. to failure. A few of the 1093C tests used head motion to determine yield strength; all others used standard extensometers. Ultimate tensile strength, 0.2% yield strength and elongation were measured (and reduction of area for standard size bars). For the coated samples, strengths were calculated based on three differenct cross sectional areas (see sketch below).

1. External dimensions (total cross sectional area including both base metal and coating).

2. Original uncoated specimen dimensions (added coating material and coating diffusion zone both ignored).

3. Unaffected base metal dimensions (dimensions inside of coating diffusion zone used, as determined from typical metallographic samples).



The coatings are usually quite weak compared to the base alloy and method 1 assesses this full penalty to the coated specimen. Method 2 is generally used for design purposes which implies no additional load carrying capacity to the added coating material, but includes the weakened diffusion zone as part of the sample. Method 3 recognizes the poor strength of the entire coating (diffusion zone plus added layer) and is most useful in evaluating the properties and changes in properties of the base alloy itself.

For Codep B-1 coated specimens, the coating thickness was presumed to be the average (from Table III) for the particular specimen thickness. The greater variability of the CoCrAlY coating thickness required that each individual specimen be corrected using its own Dermitron gage measurement.

Measurements of specimen dimensions were difficult on some of the exposed bare and CoCrAlY coated pieces due to heavy attack. For bare specimens the thinnest-appearing remaining area was used as a basis for calculating stresses, and several readings taken across the section. For CoCrAlY coated samples, if the actual minimum thickness measured after exposure was less than the original bare metal thickness (of each individual specimen) it was presumed that no coating remained and no correction for stress was made; if the thickness was greater than the bare metal thickness (each specimen individually considered again), the additional thickness was presumed to be coating and the stress corrected for that thickness. Nevertheless, due to uneven attack, these values are not as reliable as measurements on clean samples, and will reflect as greater variability in strengths.

Stress Rupture Tests

Stress rupture testing was performed at 760C, 982C and 1093C in accordance with ASTM E139-66T procedures. Test stresses were calculated based on overall specimen dimensions (method 1 described previously). The two lower temperature tests were done using the standard lever arm of the stress rupture test stands. The 1093C tests required such low loads for the thin sections that the lever arm was not used; weights were hung directly on the specimen grip extension. The 0.11 cm thicknesses were tested only at 982C. The stresses initially chosen were 627 MN/m^2 at 760C, 172 MN/m^2 at 982C and 48 MN/m^2 at 1093C. These represent somewhat lower stresses than required to cause failure in about 100 hours for standard size bars. The first failures at these conditions took place in less than about 50 hours, therefore for further testing the stresses were decreased, respectively to 565 MN/m^2, 144 MN/m^2 and 34.5 MN/m^2. Conclusions based on rupture failures at short times would not provide for a realistic guide for gas turbine applications. To avoid the usage of too many of the spare specimens available, only a few conditions were duplicated by repetition of the lower stress test. In order to compare (in the final graphs) all rupture lives at the same level of stress, the life obtained at the higher stress was extrapolated to a life at the lower stress by following a curve parallel to the master isothermal stress-rupture curve for Rene 80. A similar extrapolation was used to obtain comparative lives for coated specimens based on original and base metal thickness, (methods 2 and 3 described previously). After exposure, the same specimen measuring problems occurred for the rupture tests as for the tensile tests mentioned above.

Mechanical Fatigue Tests

Mechanical fatigue is not usually an important factor in large hollow or air-cooled blades, but in solid thin blades it becomes a vital property. Furthermore, coatings which affect the outer surfaces have a greater influence on bending fatigue and would be expected to exert a still greater effect on thin specimens. This has been noted in testing turbine blades in fatigue. Prior test data indicate little difference in strengths for Rene 80 from room temperature to about 816C, therefore tests were run at room temperature only. Four-specimen S-N curves were obtained to determine the 10^7 cycle fatigue strength. Since thinner specimens were expected to show the greatest effects, the 0.075 cm thickness only was tested. Sonntag SF2 machines at a frequency of 1800 cycles per minute were used. A load-deflection trial for each piece was run to determine the necessary deflection to set at the oscillating end of the test specimen. Cycles to failure were recorded.

Thermal Fatigue Tests

Thermal fatigue is a recognized design factor for gas turbine blades. Rates of temperature change, superimposed restraint, thermal conductivity, specific heat, ductility, coefficient of expansion and creep strength of the material are all factors that influence thermal fatigue behavior. Although there are no universally accepted test procedures, General Electric Co. has developed and used a test rig called SETS (Simulated Engine Thermal Shock) which has proven capable of rating the thermal fatigue properties of superalloys in agreement with engine experience. The SETS tester has a rotating holder which accepts up to 8 specimens. The holder indexes the specimens in front of gas-fired burners, which heat the entire front of the specimen to the desired temperature and maintain that temperature for the desired time. Then the tester indexes the specimens in front of a small diameter compressed air jet which cools a spot on the front of the specimen very rapidly, and the remainder of the specimen more slowly. Temperature is measured with a model 250 Ircon infrared pyrometer, calibrated initially against sample thermocoupled specimens. The cycle parameters used in the present program are: heating time of 10 seconds to the maximum temperature of 1093C; holding time of 50 seconds, and cooling time to under 204C of 20 seconds. These have been found to be reasonable conditions to simulate high temperature turbine blade behavior. The specimens were 5 cm long sections of the leading edge of the casting, Figure 2, ground to a depth of 0.762 cm. To provide suitable restraint (as a blade would have), a Rene 80 cast plate 0.14 cm thick was TIG welded across the open back of the leading edge. The welding did not produce any noticeable change in appearance or structure at the leading edge. During the test, the specimens were inspected every 50 cycles for cracks up to a total of 250 cycles, then every 250 cycles up to 1000 cycles, and thereafter every ~250-500 cycles up to a maximum of 4000 cycles. At each inspection, each specimen was ranked with a special crack severity index number:

0 - No damage or cracking
1 - General oxidation or pitting of surface, no cracks
2 - 1 to 3 cracks of up to 0.5 cm long
3 - 4 or more cracks up to 0.5 cm long
4 - 1 to 3 cracks of 0.5 - 1.0 cm long
5 - 4 or more cracks 0.5 - 1.0 cm long
6 - 1 to 3 cracks greater than 1.0 cm long
7 - 4 or more cracks greater than 1.0 cm long

(Note: The Codep coated specimens, which did not crack, were rated merely by degree of coating degradation.)

The normal cracks are all transverse cracks through the leading edge, but the bare specimens all produced (late in the test after transverse cracks already existed) longitudinal cracks directly up the center of the leading edge. Only the 0.075 cm thick castings were tested. The effects of both coatings and both exposures were examined. Due to the differences in surface conductivity and total thickness of the coated specimens, it was necessary to run the bare and each of the types of coated specimens in separate runs.

Ballistic Impact Tests

Impact strength (or foreign object damage resistance) is another property of interest. This is a region in which least standardization of test procedures and engine correlations exist. A ballistic impact test, using an air rifle and steel pellet has been used to provide qualitative comparisons of damage caused by a given impact energy. The curved edge sections of the castings serve as specimens impacted directly on the "leading edge". A pellet size of 0.445 cm, weighing 0.356 gms was used. Impact energy was varied by changing the air pressure. Velocity of the pellet was measured by an electronic timer and impact energy calculated as $1/2\ mv^2$. The damage done by the pellet was rated in terms of the deformation produced, the type and severity of the cracking produced, and by the adherence or spalling of the coatings. Tests were performed at room temperature (to simulate foreign object damage at starting) and at 982C (to simulate impact during engine running). The elevated temperature was obtained by induction heating, with the pellet fired between the heating coils. The length of the leading edge specimen permitted several shots to be taken on each piece. Velocities were 30-160 m/sec. (99-530 ft/sec.).

Oxidation and Hot Corrosion Tests

Oxidation and hot corrosion resistance are clearly of great importance to turbine blade life; the coatings are used for protection. The exposures, described previously, provide a combustion products oxidation test. Weight change data every ~ 50 hours during the course of the exposures represent one method of reporting oxidation information and is expressed in terms of mg. per square cm of surface area. However, more useful mechanical information is obtained by measurements of actual metal lost during oxidation and the depth of sub-surface attack. The latter measurements were obtained only after completion of the exposures by use of a filar eyepiece on a microscope. The coated samples, where coating remained intact, do not afford useful metal loss data for oxidation. The hot corrosion (sulfidation) tests used by industry are not standardized. The burner rigs, in which the exposures were run, were developed in conjunction with the Navy Marine Engineering Laboratory for hot corrosion testing, and have proven very useful in rating alloys and coatings and in basic mechanism studies. Compared to the exposure runs, the only change is the injection of a standard (ASTM D665-60, Part 17, pg 248, 1970) sea water solution, and cycling once a day to room temperature rather than every hour during the working day. The choice of amount of sea water is a compromise: too high an amount leads to unrealistically high salt concentrations, too little (but similar to engine intakes) requires too long a time to cause attack for laboratory purposes. A level that has proven satisfacotry and is used in all coating evaluations provides a concentration of 5 ppm sea salt in the corrosion atmosphere (approximately 5 times greater than the highest levels encountered in engine experience), and was therefore selected for this program as well. The temperature chosen was 927C, as used in the standard coating evaluation test. Higher temperatures, > 982C, do not permit condensation of the major corrosive constituent, Na_2SO_4, while lower temperatures do not cause coating-base metal diffusion effects to occur rapidly enough and also tend to lower the attack rate. Weight changes were not taken at all, since the adherence of variable quantities of salts and the uncontrolled spalling make interpretation too difficult. Metal loss and sub-surface depth of attack measurements are the methods for describing attack on the bare alloy and on penetrated coated samples. Time for initial coating failure (appearance of a blister or dark spot) is reported. Only the 0.15 cm thick specimens were tested. Some of the specimens were the tensile type specimens, and some were simple 0.64 cm wide flat strips. Specimens with and without the coatings and unexposed and exposed (both temperatures) were hot corrosion tested.

In all the tests described, duplicate specimens were run at each condition (four in mechanical fatigue), except for some isolated cases where specimens were inadvertently lacking due to losses of pieces during aborted processing or an exposure run.

TEST RESULTS

Tensile Tests

The complete tensile test results are reported in Table IV. For ease in comparison, the average strength data have also been expressed in terms of percent change from the 0.635 cm standard bar values and are listed in Tables V and VI for 0.2% yield and ultimate tensile strengths, respectively. The percent elongation is compared in Table VII. Strengths for coated samples are based on original metal thickness (method 2), since this is the method normally used for design. There are many effects that can be noted, and these are summarized in groups as follows:

A. Bare Rene 80

1. Effect of section thickness

   a. Slight differences exist among the three thicknesses at any temperature in yield strength, except at 982C, but all are below standard size bars.

   b. At room temperature and 760C, the greater the thickness, the lower the ultimate strength; at the other temperatures, the reverse is true.

   c. At room temperature and 760C, the greater the thickness, the lower the ductility. At 1093C, the reverse occurs.

2. Effect of exposures

   a. The 982C exposure caused great loss in ultimate strengths at room temperature and 760C, while very little effect was noted at 982C. Yield strength was also lowered greatly at room temperature. At 1093C test temperature, ultimate and yield strength were higher.

   b. The 1093C exposure caused less loss of strength at room temperature, 760C and 982C than the 982C exposure, but resulted in a greater loss in strength at 1093C.

   c. The 1093C exposure possibly caused an increase in room temperature elongation, otherwise both 982C and 1093C exposures lowered elongation up to 982C. At 1093C test temperature, ductilities were virtually the same after both exposures.

3. Exposure/thickness effects

   Strengths and ductilities retain the same ranking with thickness after exposure that they had prior to exposure.

B. Codep B-1 Coated Rene 80

1. Effect of section thickness

   a. Thinnest specimens have highest strengths at room temperature; about equal at elevated temperature.

   b. Elongation was higher for the thin specimens at room temperature and 1093C, with little difference at the other temperatures.

2. Effect of exposures

   a. The exposures raised the yield strength of Codep B-1 coated material at all test temperatures except for the 982C exposure which lowered the room temperature yield an average of 12%. The 1093C exposure resulted in marked improvements at room temperature, 760C and 982C.

   b. The 982C exposure lowered the room temperature ultimate strength an average of 23%, with smaller losses at 760C and 982C. The 1093C exposure produced little change in ultimate strength except at 982C where an increase of ~ 15% occurred.

   c. Exposures tended to decrease elongations at the three lower test temperatures, but increased elongation at 1093C. There was little difference in effect between the two exposures.

3. Exposure/thickness effects

   a. After 982C exposure, there was little difference in strength between the different thicknesses at room temperature and 760C, while the thicker specimens had higher strengths at 982C and 1093C. The 1093C exposure produced somewhat higher strengths in the thinner specimens at room temperature and 760C, with no discernable effect at 982C and 1093C.

   b. No significant differences in elongation with thickness were caused by either exposure, except possible higher elongation in the thicker specimens at 982C and 1093C after 982C exposure.

C. CoCrAlY Coated Rene 80

1. Effect of section thickness

   a. Thin sections had greater strengths at all temperatures except 982C.

   b. Elongation was greater for the thinner specimens at all temperatures except at 1093C.

2. Effect of exposures

   a. Exposures reduced strengths at all test temperatures, except that the 1093C exposure raised the strengths at 982C for the 0.15 cm specimens.

b. Elongation was greatly decreased by the exposures at the three lower temperatures. At 1093C, both exposures still caused reductions for the thin section, while the 982C exposure indicated an improvement for the thickest section.

3. Exposure/thickness effects

a. Thicker specimens had higher strengths after both exposures at all test temperatures except at 1093C after 982C exposure.

b. No significant thickness effects on elongation after exposure exist except at 982C and 1093C after the 982C exposure, where the thicker specimens have greater elongation.

D. Effect of Codep B-1 Coating

1. Unexposed

a. The strengths of coated pieces were about equal to those of bare specimens.

b. The coating decreases elongation at 760C for the 0.075 cm specimens.

2. After exposures

a. The strengths of coated samples were equal to or higher than uncoated samples after exposures.

b. Elongations of coated samples were equal to or higher than uncoated samples after both exposures, except at room temperature after the 1093C exposure, when they were lower.

E. Effect of CoCrAlY Coating

1. Unexposed

a. Strengths of CoCrAlY coated specimens were always equal to or greater than those of bare specimens.

b. Elongation was less for coated samples at room temperature and about equal at elevated temperatures.

2. After exposure

a. Yield and ultimate strengths after 982C exposure for the coated samples were similar to those of bare samples up to 982C. At 1093C they were lower. The 1093C exposure produced erratic results, with yield strengths about the same at room temperature and 982C (possibly higher for the 0.15 cm coated samples). At 1093C the yield strengths were higher for the coated samples. Ultimate strength was equivalent at room temperature, but lower for the coated samples at the elevated temperatures after 982C exposure. The 1093C exposure caused lower

ultimate strengths at room temperature, 760C and 982C for the coated material (except possibly the 0.15 cm thickness at 982C). At 1093C, ultimates were equivalent.

b. Elongation after exposure was less than the uncoated specimens at all temperatures; excepting the 1093C elongation after 982C exposure for the 0.15 cm thickness.

F. Effect of Stress During 982C Exposure

For the limited number of 0.15 cm thick specimens tested, the following results occurred.

a. Strengths of the uncoated and the CoCrAlY coated specimens were 5 to 20% lower after the stressed exposure than after the unstressed exposure, except for the CoCrAlY specimens at 982C, which were equivalent. No noticeable differences existed between the strengths of the Codep B-1 coated stressed and unstressed exposed samples.

b. The stressed and unstressed exposed samples had equivalent elongations at room temperature for the bare and coated conditions. At 982C, the bare was still similar, but the Codep B-1 was lower and the CoCrAlY higher in the stressed specimens.

G. General Summary of Tensile Results.

Thin sections have lower strengths than standard size test bars, particularly at elevated temperatures, with equivalent elongation. Coatings tend to improve strengths (based on uncoated substrate cross sectional areas) at higher temperatures without affecting elongation. Exposures lower strengths and low temperature elongation of uncoated material. The Codep B-1 coating greatly protects against these losses during exposures, while the CoCrAlY coating was erratic in behavior.

In the preceding results, whenever failures took place at or near the gage length marks, it was presumed that the true elongation would have been somewhat greater than measured. Several CoCrAlY coated specimens failed in the shoulder section or were tested incorrectly and results for these are not included. The coated material strengths were compared on the basis of original metal dimensions. If overall external dimensions were used, the coated strengths would appear lower compared to the uncoated material and if base metal dimensions were used, the strengths would appear higher. Thinner specimens would lose or gain relatively greater amounts than the thicker specimens. The exposure effects would be unchanged.

Stress Rupture Tests

The complete results of the stress rupture tests are included in Table VIII. Stresses for the coated samples are listed based on the three methods mentioned previously, but the tests were run with the stress calculated on the external dimensions (Stress column 1). Actual test lives are listed in Life column 1. Where stresses for the uncoated samples were used other than the desired levels of 565 MN/m^2, 144 MN/m^2 and 34.5 MN/m^2 at 760C, 982C and 1093C respectively, lives were extrapolated to the equivalent at these

stresses. The coated specimen lives were also extrapolated to these stress values from their effective stresses as listed in Stress columns 2 and 3, as described under Test Procedures. For comparison, figures 7 to 15 show the variation of life with thickness, with lives from column 2 of Table VIII used. Unexposed and exposed specimen results are shown on the same graph, but separate plots are made for the bare and coated samples with the unexposed, bare material curve drawn on each of the coated material figures. Unfortunately, some of the initial test specimens were not gripped firmly enough near the pin, and some deflection occurred at the grip ends which may have caused additional stresses in the test section. These specimens are indicated in both the Table and the figures, and it may be presumed that higher lives should have been obtained on them. After the grip ends were properly held, no unusual curvature was noted in any failed piece. Many of the exposed specimens failed on loading. Where elongations could be measured, they invariably had very low values. However, the difficulty of measuring true metal thickness on many of the exposed samples may have contributed by allowing a false higher specimen thickness measurement to result in a higher test stress than intended.

The data based on stress calculated from original metal thickness for coated samples may be grouped and summarized as follows:

A. Bare Rene 80 (Figs. 7-9)

1. Effect of section thickness

   a. The greatest apparent reductions in life (unexposed) compared to the standard size bar were at 760C, with smaller losses at the higher temperatures. The range of loss was from about 10:1 for 0.075 cm samples at 760C to 2:1 for the 0.15 cm samples at 1093C.

   b. The lives of the 0.15 cm specimens were generally about double the lives of the 0.075 cm specimens.

   c. Rupture elongation tended to be higher for the 0.075 cm specimens than the thicker ones, but less than that of the standard bars.

2. Effect of exposures

   a. The 1093C exposure caused greatest loss in rupture life at 760C and the least loss at 1093C. The 982C exposure had almost no effect except for a loss at 760C for the 0.15 cm specimens.

   b. All exposures drastically lower 760C ductility, but do not affect ductility at the higher temperatures very much.

3. Exposure/thickness effects

   a. Thicker specimens had greater lives than thin specimens after both exposures except at 760C for the 982C exposure.

   b. Elongation tends to be somewhat greater for the thickest specimens at 982C and 1093C after both exposures.

B. Codep B-1 Coated Rene 80 (Figs. 10-12)

1. Effect of section thickness

   a. Thicker specimens had greater rupture lives at all test temperatures, but the average ratio is less than noted for bare material.

   b. There was little effect of thickness on rupture elongation, although at 1093C, the 0.075 cm samples were higher than the 0.15 cm samples.

2. Effects of exposures

   a. Losses in life of ~50% due to 1093C exposure occurred at 760C. No losses (possibly improvements) were found at 982C and 1093C. The 982C exposure produced life losses of ~80% for the 0.075 cm specimens at 760C and 982C, with a much smaller loss (~30%) at 1093C. No losses due to 982C exposure were caused for the 0.15 cm samples.

   b. Neither exposure affected rupture elongation significantly at 982C or 1093C. Elongation at 760C was lowered, except for one 0.15 cm specimen after 982C exposure.

3. Exposure/thickness effects

   a. Thickness effects were exaggerated by the exposures; the thin specimens had lower lives relative to the thicker specimens after exposures than before, except for the 1093C exposure at 760C test temperature.

   b. Elongation after exposures tended to be equal or higher for the 0.15 cm specimens than for the 0.075 cm specimens.

C. CoCrAlY Coated Rene 80 (Figs. 13-15)

1. Effect of section thickness

   a. Rupture life effects were the same as for Codep B-1 (Bla above).

   b. No significant differences in rupture elongation with thickness was noted.

2. Effect of exposures

   a. Rupture life was reduced greatly by all exposures at the two lower test temperatures, and less at 1093C. The 1093C exposure produced the greatest losses.

   b. Exposures generally reduced ductility at all test temperatures, but least at the highest temperature.

3. Exposure/thickness effects

   a. Same effects on life as for Codep B-1 (B3a above) with no exceptions.

   b. Elongations after exposures were about equal for all section sizes except after the 1093C exposure at the 1093C test temperature, where the 0.15 cm samples had much higher elongations than the 0.075 cm samples.

D. Effect of Codep B-1 Coating

1. Unexposed

   a. Life is lowered by Codep B-1 coating by ~75% at 760C, ~40% at 982C, with no loss at 1093C.

   b. Ductility lowered at 760C; lesser effects at the higher test temperatures.

2. After exposures

   a. The coated samples had much less loss of rupture life after 1093C exposure than did the bare specimens resulting in higher absolute lives. After the 982C exposure, the 0.075 cm coated specimens had greater losses, but not the 0.15 cm specimens.

   b. Ductility of Codep B-1 coated samples after exposure was higher than that of bare specimens particularly at the two higher test temperatures.

E. Effect of CoCrAlY Coating

1. Unexposed

   a. No effect on rupture life.

   b. Ductility improved at two lower temperatures, little effect at 1093C.

2. After exposure

   a. Somewhat greater losses in rupture life after exposures than with bare specimens except for the 0.15 cm specimens at 1093C, where no losses occurred.

   b. The 1093C exposure causes somewhat more ductility loss in the CoCrAlY coated samples, but the 982C exposure does not.

F. Effect of Stress During 982C Exposures

For the limited number of 0.15 cm specimens tested, the following results occurred:

a. The stressed samples had lower rupture lives bare or coated at both test temperatures, 760C and 982C. Losses were greatest at 760C and were greatest

for the bare specimens and least for the Codep B-1 coated samples at both test temperatures.

b. Rupture elongation may be somewhat lower at 760C for the stressed exposed specimens, but at 982C the bare and Codep B-1 coated specimens show no difference, while the CoCrAlY coated specimens may still have lower elongation after stressed exposure.

G. General Summary of Stress Rupture Results

Thin sections lose appreciable stress rupture life with greater losses for thinner specimens at 760C and with smaller losses as the test temperature increases. Codep B-1 coating lowered life at 760C, with less or no loss at higher temperatures, while CoCrAlY coating did not lower life. Exposure at 1093C further lowers uncoated Rene 80 life, more at 760C than at 1093C and more for the thinnest specimens. 982C exposure is much less detrimental. Codep B-1 coating provides better resistance against losses during the 1093C exposure, but generally not against the 982C exposure. The CoCrAlY coating was not as effective. Elongations at 760C are also greatly lowered by exposures, but not elongations at 982C and 1093C.

If coated specimen stresses were calculated by method 3 (on remaining base metal thickness), appreciable improvement in the relative ranking of the Codep B-1 coated samples would result.

Mechanical Fatigue

Table IX contains the mechanical fatigue test results. The reversed bending stresses are the calculated stresses at the point of actual failure, based on the full specimen thickness (no subtraction of coating thicknesses). From the cycles to failure, S-N curves were drawn (not shown), and the 10^7 cycle strength read, or estimated from the curves.

The bare, unexposed fatigue strength is comparable to average data previously obtained for Rene 80 on 0.635 cm diameter standard specimens. Codep B-1 coating lowered the strength slightly, while the CoCrAlY coating appears to have raised the strength (two specimens only available for this test with consequent lower reliability). The 982C exposure lowered fatigue strengths of the coated samples, but unusually high values were obtained for the bare specimens. The 1093C exposure lowered all fatigue strengths, with the bare material being the poorest.

Thermal Fatigue

The thermal fatigue test results are shown in Table X in terms of number of cycles at which the first crack appeared, number of cycles for cracks to grow to 0.5-1.0 cm in length, and number of cycles for cracks to exceed 1.0 cm in length. Both coatings improved the overall thermal fatigue behavior of Rene 80, with the Codep B-1 coating providing the greatest life. Both exposures lowered the thermal fatigue resistance of bare material. The Codep B-1 coated specimens with longer thermal exposures did not lead to failures, while one of the CoCrAlY coated specimens with the 1093C exposure did incur a decrease in thermal fatigue.

Photographs of some of the specimens after 4000 cycles are shown in Figure 16. The cracks seen are in the normal transverse direction. One of the two unexposed CoCrAlY coated specimens (#55) suffered severe spalling of the coating at the top, and a thermal fatigue crack initiated in the remaining bare area. This specimen and subsequent specimens in the ballistic impact tests that exhibited CoCrAlY coating spalling, were all products of a single coating run (no flat specimens were in the run). If it weren't for the spalling, the unexposed CoCrAlY coated specimens would not have had cracks up to the 4000 cycle mark. The two specimens exposed at 1093C, one CoCrAlY and one Codep B-1 coated, appear to have had erosion along the coating on the leading edge. The CoCrAlY specimen had cracks in the eroded region, while none were present in the Codep B-1 specimen.

Ballistic Impact

The ballistic impact test results are listed in Table XI. The impact energy for each test is shown, together with the diameter of the depression made and the observation of cracks on each side of the specimen. From the results of several impacts on each of the two duplicate specimens for each condition, the "average" impact energy to cause cracks in the parent metal was estimated. Cracking is more severe on the back of the specimen (the tensile stress side), and the ratings are determined by this. The diameter of the depression caused by the impact invariably increases with the energy of the impact, and does indicate a greater amount of deformation at the higher energies, but not necessarily in a linear fashion. Photographs of typical impact appearances are shown in Figures 17 and 18. Uncracked impacts, front and back are illustrated in the lower impressions in Figure 17, and cracks on the upper impressions. Craze cracking and spalling of the CoCrAlY coating are shown in Figure 18.

At room temperature and 982C tests, the results show that both coatings are better than bare material before and after exposure in terms of protecting the base metal from cracking. However, both coatings are craze cracked at low impact energies. Impact energies at 982C for all specimens were below that for bare material at room temperature. Impact values for the coated specimens, as compared to unexposed, were least affected at room temperature after the 1093C exposure.

Oxidation and Hot Corrosion

The exposures at 982C and 1093C provide oxidation data as weight change with exposure time and as metal loss and oxide penetration measurements. The weight change data are plotted in Figures 19 to 24 for each temperature and bare and coated material separately. The values are averages for all the specimens of a given thickness in each run (from 6 to 18). Note that spalled products were lost, and not included in weights. Bare Rene 80 (Figures 19 and 22) showed similar behavior at both temperatures with an initial weight gain of between 2 to 4 mg/cm^2, followed by a rapid loss. Slight differences existed between thicknesses, with the 0.075 cm specimens having the least weight loss. The light sand blasting after each run removed the lightly adherent scales, and contributed from 2 to 5 mg/cm^2, additional loss.

Codep B-1 coated specimens at each temperature (Figures 20 and 23) showed very low weight gains only (~ 0.2 to 0.6 mg/cm^2), although after 450 hours at 1093C, it seemed that weight losses were impending. Slight peaks and valleys may indicate protective oxide spalling and regenerating. At 982C the CoCrAlY specimens (Figure 21) had initial gains of 1-2 mg/cm^2, but after > 600 hours, weight losses occurred. While much poorer than the Codep B-1 behavior, the CoCrAlY coating was much better in oxidation resistance than bare

Rene 80 at this temperature. However, at the higher exposure temperature (Figure 24), the CoCrAlY coating behaved very similar to the bare metal, with about equal weight loss after twice the exposure time. The 0.075 cm CoCrAlY coated specimens had the least weight loss, as did the bare specimens.

Metal loss for bare specimens after the 982C exposure (754 hours) was from 0.0025 to 0.005 cm in thickness. Additional sub-surface attack (oxides) existed to a depth of 0.015 cm below the remaining metal surface for a total effective loss per side of about 0.017 cm. After the 1093C exposure (168 hours), the metal thickness loss was much higher, from 0.020 to 0.029 cm, but the sub-surface attack was only 0.0025 cm for a total loss per side of from 0.013 to 0.017 cm. Metal loss seemed to be slightly less for the thinnest specimens. For the Codep B-1 coated specimens, no effective metal loss occurred in any sample. The CoCrAlY coated samples were more difficult to evaluate. Where coating still remained (more on some specimens than on others), no metal loss took place. Where the coating was gone, the attack resembled that on the bare pieces.

Table XII presents the hot corrosion test metal loss information for specimens removed at different test times. Bare specimens had the expected sulfidation type attack, with appreciable external metal loss, and sub-surface sulfide/oxide attack. The depth of sulfidation type attack increased with previous oxidation exposure, the rate of attack being greater for the stressed specimens than the unstressed ones. Most of the attack takes place early, with a decrease in rate of attack with time (parabolic type ?). The Codep B-1 specimens without any previous exposure were examined after the coating had been spent. It can be seen that the total attack at equal times is greater on the coated than on the bare specimens (a phenomenon that has been found in prior tests). Where coating was still present in the cross section inspected, very little attack occurs after the 982C exposures. The 1093C exposure resulted in the greatest attack on Codep B-1 coated samples. The CoCrAlY coating provided the greatest protection, with no attack through the coating on unexposed or on unstressed 982C exposed samples. The stressed exposure at 982C and the 1093C exposure produced the greatest deterioration in coating resistance. The external metal loss measured for the coated specimens that still seemed to have a coating is due to attack of the coating itself. Diffusion of the coating with the bare metal underneath would cause growth of the coating thickness. Therefore, although there exists an external metal loss (coating loss) the apparent thickness of the coating may still seem to be the same as before the test.

The parameter normally used to rate coatings in hot corrosion tests is the time to appearance of the first failure. Failure means the occurrence of a blister, or the discoloration produced by base metal oxide formation. On this basis the following is the list of coating lives:

Coating	Exposure	Time Period in Which First Failure Occurred, hrs
Codep B-1	unexposed	202-271
"	982C (1800F), 962 hrs	146-165
"	982C (1800F), 1000 hrs, stressed	61-127
"	1093C (2000F), 532 hrs	42-61
CoCrAlY	unexposed	> 473.5
"	982C (1800F), 962 hrs	146-165
"	982C (1800F), 1000 hrs, stressed	61-127
"	1093C (2000F), 532 hrs	146-165

The initial superiority of the CoCrAlY coating to hot corrosion attack is clear and verifies previous data. It was noted that several of the CoCrAlY coated specimens, particularly during the high temperature exposure, tended to produce little bumps that permitted base metal attack, Figure 25. These are associated with some of the initial defects.

METALLURGICAL ANALYSIS

Initial Structures

Typical as-cast microstructures of the different thicknesses are shown in Figures 26 and 27, unetched and etched*, respectively. The 0.11 cm and 0.15 cm specimens looked virtually identical. The points of interest are:

1. The primary MC carbides are much finer and more uniformly distributed in the thin castings.
2. The MC carbides are present right out to the surface.
3. Coring is evident in all thicknesses, but the dendritic pattern is clearest in the 0.075 cm casting. Relative grain size (grains across thickness) is about the same for the various thicknesses.
4. The thicker pieces show many patches of coarse eutectic γ', while the thinnest has none, or possibly very fine patches.
5. The size and distribution of the fine γ' is similar in all thicknesses.
6. Grain boundaries are not too clear, but may have some particles in them.

After the normal heat treatment, Figure 28 shows the unetched and etched structures. Several changes are evident:

1. Eutectic γ' has virtually disappeared.
2. Grain boundaries clearly show particles ($M_{23}C_6$ type carbides, mainly).
3. A very fine, one grain deep, recrystallized grain layer exists at the surface, with its grain boundaries outlined possibly by the same $M_{23}C_6$.
4. The MC carbides have decreased in concentration near the surface, particularly in the 0.075 cm sample. The MC carbides elsewhere are unchanged.

In order to identify the phases present in the Rene 80 after the normal heat treatment, two separate electrolytic extractions were made in accordance with the recommendations of ASTM E-4 Task Group (Reference 12): one with 10% HCl in methanol, and the other with 1% citric acid + 1% $(NH_4)_2SO_4$ in water. The latter provides some quantitative estimate of γ' present, while the former dissolves γ' and yields carbides and other intermetallic phases.

*The etchant used in all cases, unless otherwise specified is 92% HCl, 5% H_2SO_4, 3% HNO_3.

Identification was done by X-ray diffraction film techniques. The results are in Table XIII. All specimen sizes contained 43-45 weight % of γ', with a lattice parameter of 3.589Å. The HCl extraction for the thin castings only showed the MC carbides, a smaller amount of $M_{23}C_6$ and possibly some M_6C. These results are normal for heat treated Rene 80.

Structures of the coatings are shown in Figures 29 and 30 for Codep B-1 and CoCrAlY, respectively. Unetched, the Codep B-1 coating exhibits the normal single phase additive layer (NiAl) with occasional entrapped α Al_2O_3 particles, and a diffusion zone of almost equal thickness. The diffusion zone consists of fine "fingers", heavily interspersed with MC carbide particles. The fingers are Al-rich Ni_3Al or NiAl and a σ-type phase (see below for microprobe analyses). The region just under the diffusion zone is relatively free of MC carbides. Etching reveals that an additional narrow region containing acicular or plate-like phases exists between the diffusion zone and base alloy. The γ' of the alloy comes right up to the edge of this region with no apparent transition.

The CoCrAlY coating (Figure 30a) has a thick two-phase additive layer and a "diffusion zone" which resembles a complete Codep coating (its own "additive" layer and finger-like diffusion zone). The true additive layer of the CoCrAlY coating has several sharp separations or thin oxide inclusions, which are considered harmless if they do not reach through to the base alloy. In some specimens, two of these inclusions seem to meet in a Vee. The Vee is actually a section of a cone produced by a splatter particle during the coating process and is relatively easily raised and removed during high temperature cyclic exposure, leaving behind a thin spot in the coating (see Figure 25 for surface appearance after exposure). One side of one sample lacked the noticeable diffusion zone, Figure 30b, otherwise the coating was entirely similar to the others. The Codep-like diffusion zone may have resulted from a thin layer deposited through the mask when the samples were heat treated in the Codep process prior to CoCrAlY coating.

Hardness Measurements

Table XIV lists the Vickers microhardness numbers of the matrix, diffusion zone, and additive layer of both types of coated specimens. The matrix hardnesses are taken approximately 0.005 to 0.010 cm below the indentations measured in the coating. The Codep B-1 coating specimens have slightly harder base alloy values than the CoCrAlY, due probably to the additional overaging caused during the CoCrAlY process. The additive layers of the CoCrAlY specimens varied from 580 to 820 in hardness. Subsequent microprobe analyses indicated that the very high hardnesses occurred in coatings with considerably higher Cr content than the others. The additive layers of the Codep B-1 coatings are slightly harder than the base metal and near the level of the lower CoCrAlY additive layers. The diffusion zone hardness for the CoCrAlY coatings corresponds in value (and in chemistry, see below) to the Codep additive layer. Of all the regions measured, the Codep B-1 diffusion zone, rich in MC and σ is the hardest, over 900 Vickers.

Coating Compositions

Two methods were employed to describe the coating composition: X-ray diffraction on the exterior surface and electron microprobe analysis on cross sections of the coatings. The X-ray results describe the type of compounds while the probe provides the amounts of each metal element present. Table XV contains the X-ray information taken on the flat

surfaces of the gage section of the tensile test type specimens (and one leading edge specimen). Bare specimens were included so that γ or γ' in the coatings could be distinguished from matrix γ/γ'. The thickness of the coatings are well over the 90% absorption level for the radiation used (Fe filtered Co radiation at 40 kv, 10 ma). Codep B-1 coating showed only NiAl plus a small amount of α Al_2O_3 (from the intentionally entrapped particles). The major phases in the CoCrAlY coating are CoAl and a γ type phase having a smaller parameter than the base alloy. A small amount of α Co was detected by X-ray, although only two phases could be seen metallographically. The CoAl parameter is smaller than the NiAl parameter of the Codep coating.

A JXA 3A probe, with two goniometers recording simultaneously, was used to scan for the distribution of all important elements from the base alloy out to the edge of the coating. Four traces were made (2 elements at a time) over the same path at an angle of 45° to the surface to measure Al, Ti, Co, Cr, Mo, W and Ni. Recording of the output was made at a scale of 0.01 mm (on the specimen) = 4 cm (on the chart), or a ratio of 1:4000. Probe spot size was ~ 0.002 mm. Composition in weight % was calculated by linear extrapolation using the base alloy as a standard up to about the additive layers, and an external NiAl standard for Codep B-1, and a CoCrAlY standard for the CoCrAlY coating additive layer. In the region at the boundary of the diffusion zone and additive layers, a sliding average of the two was used. In most cases, the agreement between the base alloy standard and the external standard was very good.

For the Codep B-1 coating, Figures 31, 32 and 33 show the variation of the three most important alloying elements for the additive layer: Al, Cr, and Ti respectively. In the additive layer Ni, plus a small amount of Co, is essentially the balance. The diffusion zone contains Mo and W as well, and really poses a problem in plotting composition. The values for Al, Cr and Ti shown are intended to represent the "base composition" in the diffusion zone. The presence of MC carbides were indicated by simultaneous Ti+Mo+W peaks with corresponding dips in the other elements, and the σ phase fingers indicated by peaks in Cr+Mo+W with dips in Ni, Ti and Al. Therefore, the curves do not show overall average levels of the elements in this region. Occasional Al peaks (and Ni dips) in the additive layer occurred when αAl_2O_3 particles were hit. Five specimens were analyzed, four of which had very similar additive layer compositions of ~ 35% Al, 0.5 to 1% Cr and 0.2 to 0.4% Ti. The fifth had lower Al and higher Cr and Ti. In all cases, the Al content was well over the 20-22% considered the minimum necessary. The greater variations of Cr and Ti noted in the diffusion zone are related to the difficulty in obtaining the "base composition" there, and the "finger" size has a great effect on the results. All the variations found are within the normal ranges for this coating.

Microprobe analysis results on four CoCrAlY coated specimens for Al, Cr and Ni are shown in Figures 34, 35 and 36 respectively. In the additive layer, Co is the balance. Three of the specimens (resembling Figure 30a in microstructure) had diffusion zones which were essentially Codep type coatings. For example, compare Al and Cr content variations in the diffusion zone and additive layer in Figures 31 and 32 with Al and Cr variations in the diffusion zone of Figures 34 and 35 for specimens No. 85, 17 and P. The fourth sample, No. 29 had the structure shown in Figure 30b, without a visible diffusion zone, and without noticeable variations in element content in the microprobe traces. Nickel was also present in the coating at a much higher level than the others. The "Codep coating" diffusion zone in the CoCrAlY coatings were complete with MC carbide and σ phase elemental peaks. The additive layer microstructurally is two phase, and in the microprobe

scans this was indicated by alternating Cr peak/Al valley, Al peak/Cr valley regions all across the layer which agrees with the CoAl + cubic Co-Cr X-ray diffraction results. In the plots, the average values of each are shown. Co remained relatively uniform. The Al range of 10 to 15% is normal, while the Cr contents were split into two groups: one at ~ 19%, the other near 30% for the major portion of the additive layer. The low Cr level is near the minimum required.

Fracture Structures (Tensile, Stress Rupture, Thermal Fatigue and Ballistic Impact

Typical tensile test fractures for unexposed bare Rene 80 bar and thin castings and coated thin castings are illustrated in Figures 37 to 39. The basic features of the fractures were the same, regardless of section size. Room temperature fractures were intergranular (Figures 37a, b). Etching revealed the presence of a fine grain recrystallized surface layer on the standard size bar as well as the flat specimens (Figure 37b, 38b). The 760C failures resembled the 982C and 1093C failures (Figures 37c and 38a, b), intergranular (or inter-dendritic) plus surface cracks, but with fewer cracks. Oxidation and alloy depletion are evident on their surface, and down the surface crack of the 1093C sample, Figure 38b. Both types of coated samples had many coating cracks in tests at room temperature and 760C as shown in Figures 39a, b, while at the higher temperatures neither of the coatings cracked in spite of cracks in the base metal, Figure 39c. The CoCrAlY coating occasionally separated from the surface during testing whereas the Codep B-1 coating did not. Failures were largely intergranular or inter-dendritic, although an isolated segment was transgranular as in Figure 39a. At 1093C, internal cracks other than the major failure were common, while at 982C they were less prevalent, and very rare at lower temperatures.

After exposures, the fractures of the bare specimens were the same as for the unexposed specimens, except for the lower temperature tests after the 1093C exposure. These had some surface cracking associated with the deep oxidation attack. The only difference noted in the exposed Codep B-1 coated fractures was the existence of coating cracks after the higher temperature tensile tests unlike the unexposed samples. The CoCrAlY coatings did not show cracks at the low test temperatures for the exposed samples, but some cracks were present in the 1093C tensile test pieces.

Fractures in stress-rupture tests on unexposed material resembled the tensile fractures at the same test temperatures. Bare specimen rupture fractures are shown in Figures 40 and 41, Codep B-1 coated in Figures 42 and 43 and CoCrAlY coated in Figures 44 and 45. Fractures were intergranular, with a rare transgranular segment mostly limited to 760C tests. No difference in appearance existed between specimen sizes. Bare material did suffer some oxidation attack during testing, and cracks were found in the attacked surface (Figure 41a). Intergranular surface cracks existed in the bare material 760C fractures and internal rupture cracks at the two higher temperatures. At 760C the Codep B-1 coated specimens had many coating cracks (Figure 42a); above 760C both coatings were ductile and protective to the surfaces. Internal rupture cracks which did not go through the coatings were common (Figures 42a, b, 43a, 44a, b, 45a, c). In Figure 45c, a rupture crack at a grain boundary in an early stage of development is visible. The adherence of the CoCrAlY coating was considerably better in the stress-rupture tests than in the tensile tests, (even though the metal-coating interface was being attacked as in Figures 45a, b).

Exposed specimens had stress-rupture failures which resembled the unexposed specimen failures. The exception was the 760C tests on Codep B-1 coated material exposed at 982C under stress. These did not have any coating cracks. All bare exposed specimens had greater oxidation attack than the unexposed, but no difference in fractures was found.

Heavy oxidation of thermal fatigue specimens made fractures difficult to assess, (Figure 16). A small thermal fatigue crack can be seen in Figure 46a for a bare unexposed sample. Gross oxidation has proceeded almost across the leading edge. The 1093C exposed Codep B-1 and CoCrAlY coated specimens did have coating erosion on the leading edge. A section through the Codep B-1 coated piece is shown in Figure 46b. No thermal fatigue cracks exist; just surface oxidation.

The ballistic impact tests, at low energies, caused "craze" cracks in the coatings at room temperature which did not progress into the base alloy, (Figures 47a, b). The Codep B-1 coating cracks appear to go below the visible diffusion zone, but go only through the acicular phase of the diffusion zone visible on etching (see Figure 29). At higher energies the cracks propagate through the specimen intergranularly (Figures 47c, d) or start transgranularly and then go intergranularly (Figures 47e, f).

Structures After Exposures

The two exposure conditions caused changes in the internal metallurgical structure of the Rene 80. Unetched, the only noticeable effect of the exposures particularly at 1093C was to decrease the amount of MC carbides. This was most evident in the Codep B-1 coated samples, since they were exposed for the longest times. Figure 48a, after 587 hours at 1093C may be compared to Figure 28b. Etching revealed further changes due to exposure. Figures 48b and c show the effects of 982C exposure on bare and Codep B-1 coated samples respectively. Grain boundaries have large two phase regions; $M_{23}C_6$ and γ', while the size of the γ' inside the grains has grown (compare to Figures 28c, d and 29c). The short time necessary for a tensile test (~1/4 hour) at 1093C is sufficient to eliminate much of the $M_{23}C_6$ at the grain boundaries and to further coarsen the interior γ', Figure 48d. Exposure at 1093C, Figure 49a, causes coarser internal γ', and produces fewer grain boundary phases in bare and CoCrAlY coated material. The Codep B-1 coated specimens had large globular γ' in grain boundaries somewhat heavier near the surface after this exposure, Figures 49b and c.

Phase analysis after exposure was performed as before, and the results included in Table XIII. The MC carbide amount did not decrease after the 982C exposure for bare Rene 80, but did decrease for both bare and Codep B-1 coated material after 1093C exposure. The $M_{23}C_6$ carbide was heaviest after the 982C exposure and least (almost none) in the bare specimens exposed at 1093C, while moderate amounts were still present after the latter exposure in the Codep B-1 coated specimens. Exposure at the higher temperature resulted in greater amounts of M_6C. The weight of γ' recovered was less for the exposed, bare material than for unexposed material. The Codep B-1 coated specimens maintained greater γ' after exposure. The γ' recovery was clearly higher in the thicker, exposed specimens for each condition. Lattice parameters did not change greatly, perhaps greater for γ' in the exposed Codep B-1 samples, and greater for MC in the exposed bare samples.

The exposures caused great changes in the surface structures of the bare material and in the coatings and the structure just below the coatings. Typical surface appearance of bare specimen surfaces are shown in Figure 50. Deep penetration of coarse and acicular oxides exists, and the oxidized regions are devoid of γ' (oxidized carbides may be present) after the 982C exposure, Figure 50a. The depth of oxides in the 1093C exposed samples, Figure 50b, was considerably less as noted previously. Presumably, the heavily oxidized regions spalled, since total metal loss was high. A wide layer without γ' is between the attacked surface and the normal base alloy structure.

The surfaces were investigated further in two ways by X-ray diffraction. The products of the exposures were analyzed by scraping the surfaces and running the products in a powder camera. These results are listed in Table XV. Short times at 982C formed mostly NiO and TiO_2, with some Cr_2O_3 and spinel (both NiCo-Cr and NiCo-Al types). Longer times produced further NiO and NiCo-Cr spinel, while TiO_2 and Cr_2O_3 disappeared in preference to an M_2O_3 which may contain Ti, Cr and Ni as the metallic elements (no ASTM standard index card exists for the parameter found). The stressed exposure, even though it represents a longer time, had only TiO_2 and Cr_2O_3. The other X-ray method applied was diffraction directly on the specimen surface, using a goniometer. Although intended more for the coated samples, this was done on cleaned bare specimens also, and the results were included in Table XVI. Both exposures produced surface layers with a smaller lattice parameter γ/γ' than the unexposed samples. Very likely, the γ' free surface layers visible in Figures 50a, b have matrix γ only with the smaller parameter, and the diffraction depth does not exceed the de-alloyed layer.

The apparent loss of MC carbides and possible other compositional changes after exposure were investigated by performing chemical analyses on unexposed and exposed samples of both bare and Codep B-1 coated (with the coating ground off). Results in Table XVII show some differences in several elements. The 982C exposure for bare material actually had higher C (carburization from the combustion products?) and lower Al, Ti and Cr, all constituents of the oxides found on the surface (Table XV). However, the 1093C exposure clearly caused depletion of C as well as the other three. No significant changes in any element except Al were found in exposed Codep B-1 coated samples, since the coating does insulate the base alloy from the external atmosphere. The Al level may have increased slightly due to diffusion from the Al-rich coating.

Significant changes in the coatings were produced by the exposures. Figures 51 and 52 show Codep B-1 and CoCrAlY coatings, respectively, after exposures. The 982C exposure agglomerates the "fingers" in the diffusion zone and increases the depth of the acicular and grain boundary phases (Figures 51a and b). The additive layer itself shows two phases (besides the α Al_2O_3 particles), whereas it was single phase initially. The lighter colored phase (Figure 51a) has about the same appearance as the matrix, and is γ or γ' rather than NiAl. At 1093C, the same changes take place to a greater degree (Figures 51c and 49b). Here, though, even the acicular sub-diffusion zone phases are agglomerated. CoCrAlY coating changes are shown in Figure 52. The lower temperature exposure agglomerates somewhat the darker phase in the additive layer (the CoAl), while the diffusion zone has gone from a two-layer structure (see Figure 30a) resembling the Codep coating to a clear, γ' free, layer containing darker agglomerated particles (Figure 52a). Etching attacks CoAl and NiAl severely, and the etched photographs indicate the attack on the CoAl in the additive layer and the NiAl in the diffusion zone. The 1093C exposure virtually eliminates the CoAl and NiAl phases completely. A larger γ' free layer is produced than at the lower temperature.

Exposure effects on the coatings were investigated by X-ray diffraction and microprobe also. The oxidation products were scraped from the surface and identified by X-ray diffraction, Table XV. Only the CoCrAlY coating products are listed, since the Codep B-1 did not have enough surface oxide to analyze by this technique. The analysis of the CoCrAlY products includes mixed material from poor sites (defects) as well as intact areas, unless otherwise noted. Short times at 982C produced mainly CoO, with very little NiO and NiCo-Cr spinel. Some α Co from the coating was present. After further exposure Al_2O_3 appeared (then decreased), NiO and the spinel increased, and CoO eventually decreased. The major initial oxide at 1093C was Al_2O_3, which decreased with time while CoO, NiO and the spinels increased. Specimen No. 37 products from two areas (a "good" and a "bad") were analyzed. The "good" area had CoO, Al_2O_3 and spinels (along with α Co from the coating). The "bad" area had less CoO, Al_2O_3 and NiCo-Al spinel, while NiO appeared.

X-ray diffraction directly on the coating surface provided interesting data (Table XVI). While the unexposed Codep B-1 coating had only NiAl and some Al_2O_3, the exposures produced γ/γ', while reducing the amount of NiAl. The loss in NiAl was greater after the higher temperature exposure. Al_2O_3 may have increased, due to its formation on the surface. The lattice parameter of the γ/γ' was higher than the parameter of the bare material with the same temperature exposures, indicating that the γ/γ' detected is probably not the base alloy. The 1093C exposure changed the CoCrAlY coating somewhat similarly; the CoAl disappeared, Al_2O_3 was present and the γ/γ' parameter was higher than that on the Rene 80 after exposure.

Microprobe analysis provided further details of the coating changes. Figures 53, 54 and 55 plot Al, Cr and Ti content variation, respectively, for two Codep B-1 coated specimens after each exposure. Comparisons with unexposed samples (Figures 31, 32 and 33) show that the 982C exposure lowers Al content in the additive layer to ~ 18% which is near the minimum required to retain some NiAl. At the same time, the Al content is raised internally so that the matrix level is not reached for over 50 microns from the additive layer boundary, whereas before exposure this depth was ~30 microns. Cr and Ti levels decreased in the diffusion zone area and increased in the additive layer. The depth before reaching matrix content was greater for these elements also. The 1093C exposure reduced Al to under 10% in the additive layer, which is below the level required for NiAl. The apparent diffusion zone depth increased, but the Al content was only slightly higher than the matrix here. A thinner additive layer indicates losses due to oxidation. Diffusion raised Ti levels to about the matrix content throughout the coating and Cr was raised in the additive layer (higher than after 982C exposure) at the expense of the original diffusion zone. The diffusion zones after the exposures had somewhat fewer Cr-Mo-W rich particles (σ phase) which extended further into the matrix. MC carbides (Ti-Mo-W rich particles) were gone from the 1093C exposed specimens, while still present to a lesser degree in the others. Microprobe scans were made on two of the large white particles in grain boundaries below the coating (Figure 51a). These were identified at Al, Ti, Ni rich, probably γ' encouraged by inward Al diffusion.

Microprobe results for Al, Cr and Ni in the exposed CoCrAlY coated samples are shown in Figures 56, 57 and 58, respectively (compare to Figures 34, 35 and 36 for unexposed CoCrAlY coatings). The greater variability encountered in the composition and thickness of the unexposed CoCrAlY coatings was emphasized still more by the exposures. The 1093C exposure drastically lowered the Al content to below matrix levels. Ni was raised to over 35%, while Cr was lowered slightly. Loss of the second coating phase (CoAl) was indicated by the lack of peaks and valleys in the Al and Cr traces. Oxides (Al, Ti rich) were

identified between the additive layer and the alloy, and occasionally in the additive layer (see Figure 52b). Overall additive layer thickness was reduced. The 982C exposure coarsened, but did not eliminate the CoAl phase. For one specimen (#22), two large areas of the CoAl, now (CoNi)Al, phase were left, and are indicated by the peaks in Al and Ni, and the dips in Cr at the same locations. The other specimen (#6) resembled Figure 52a and had many (NiCo)Al particles in the additive layer. On the graphs, these particles are represented by the upper dashed lines for Al and Ni and the lower for Cr. The Co-Cr base is represented by the lower Al-Ni lines and the upper Cr line. The full compositions of the two phases in weight percent are:

	Co	Ni	Cr	Al	Ti	Mo	W
(CoNi)Al	39.7	20.5	13.0	21.5	2.5	1.9	0.9
Co-Cr base	43.0	12.0	39.0	3.4	0.5	0.7	1.4

MC carbide retention after exposures was similar to the Codep B-1 coating.

Structures After Hot Corrosion Tests

Hot corrosion attack on the bare Rene 80 produced the normal structure, Figure 59a, of fine Cr-rich sulfide particles advancing well below the heavy surface oxides. Previously exposed specimens started with surface and sub-surface oxides (see Figure 50), and the hot corrosion test proceeded to produce the sulfides below the deepest existing oxides, Figure 59b. The sulfides penetrated most deeply at grain boundaries.

The structures of every one of the Codep B-1 coated specimens after hot corrosion testing were of two types: either the coating was intact and unchanged or the coating was gone and normal "bare" type attack occurred, Figures 60a and b, respectively. The CoCrAlY coating response was somewhat similar. Where the coating spalled, attack was normal. Where the coating was intact, the only visible change was the deepening and broadening of the originally existing cracks or thin oxide defects (see Figure 30). Figure 61a, b illustrate their appearance. The exposures themselves did not cause so noticeable a change (see Figure 52).

The surface products of corrosion were analyzed by x-ray diffraction just as were the exposure products, and the results listed in Table XVIII. Almost every specimen had Na_2SO_4 present. Since it is the outermost product, it is most likely to spall and be lost, and this is presumably the reason it was not detected on a few of the specimens. The major oxide on the bare specimens was NiO, with varying amounts of spinels and M_2O_3. The only clear difference between oxidation products (from Table XVII) and hot corrosion products is in the formation of M_2O_3 rather than $TiO_2 + Cr_2O_3$ during hot corrosion. All coated samples had Al_2O_3 present in the scale, and most had Al-containing spinels and TiO_2. The presence of TiO_2 (very little or no Ti in coating) is indicative of a change in behavior due to the hot corrosion, as TiO_2 was not commonly detected after oxidation. Some NiAl from the Codep B-1 coating was included in several of the scrapings. M_2O_3 was found on the surfaces of the Codep B-1 specimens, but not the CoCrAlY specimens (it was not found in oxidized CoCrAlY specimens). There was appreciable variation in the amounts of NiO or CoO in the scale. Generally, where the coatings were sound, very little NiO/CoO was present. When coatings seemed deteriorated, larger amounts were found.

DISCUSSION OF RESULTS

Mechanical Properties

Geometry Effects on Tensile Properties

Although the thin sheet type of specimen is expected to have lower tensile properties than the larger round specimens due to geometry, quantitative evaluation methods of the differences are not available. However, some prior work on the effects of grain size on tensile properties of cast nickel-base superalloys makes it possible to separate this variable from the data. In the earlier work, standard size test bars, 0.64 cm dia., of various grain sizes from 0.02 cm to 0.95 cm were tested at room temperature and 816C. Ultimate tensile strength and 0.2% yield strength at R. T. dropped rapidly with increasing grain size and essentially leveled out at a grain diameter of 0.64 cm (grain diameter equal to specimen diameter). The finest grain size specimens had ~ 20% higher Y. S. and ~30% higher U. T. S. than the coarsest. At 816C, these differences were reduced to under 10%. Applying these results to the standard size bars and 0.15 cm thick specimens of the present work, due to grain size alone, the 0.15 cm specimens should have been 2 to 3% stronger than the standard bars at room temperature. Actually, the standard bars were 4 to 7% stronger. Assuming the other major metallurgical variables that may affect tensile strengths (γ' and carbide size and distribution) were the same, it is inferred that the geometry effect itself amounts to a 6 to 10% loss in strength. From the prior grain size data, the thinnest specimens tested here, 0.075 cm thick, should be about 4-1/2% higher in U. T. S. and 3-1/2% higher in Y. S. than the 0.15 cm specimens. The present data shows the U. T. S. ~ 13% higher and no difference in Y. S. Considering the small amount of data and the further geometrical increment, these values are not unreasonable.

As the temperature is raised, fine grained material should lose its strength advantage and eventually become poorer above the equi-cohesive temperature. If the geometry effect is independent of temperature (an unknown), the present results show that the fine grain strength advantage is lost by about 760C, and coarse grain material remains stronger above this temperature. The prior work on other alloys indicated that the crossover was over 816C for the standard size round bars. The small amount of data makes it difficult to assess the agreement, although possibly the crossover temperature is geometry dependent, and is lower for the flat specimens.

Conventionally, fine grain size is expected to result in higher ductilities at room temperature. Although the prior work showed little effect of grain size on ductility for multi-grain cross sections in cast superalloys, the present tests do show greater ductility for the 0.075 cm specimens (finest grain size) than for the thicker specimens at room temperature and 760C. It is not known whether this is a grain size or a geometry effect. The thinnest specimens retained their ductility advantage up to 982C, which is the region of the normally expected equi-cohesive temperature.

Coating Effects on Tensile Properties

The effects of the Codep B-1 coating on tensile properties are negligible. The coating itself is NiAl, which has relatively low strength and nil ductility at low temperatures, but does become ductile at about 649C (ref. 13). Other work has indicated that the transition temperature is as high as 816C depending on the actual coating composition. As observed, low ductility at low temperatures leads to coating cracking as soon as the specimen yields. Fortunately, the cast nickel-base superalloys are not notch sensitive, and the coating cracks do not propagate into the alloy. At high test temperatures, the coating becomes very ductile and acts merely as surface protection; it appears to have no contribution to strength.

The CoCrAlY coating, with its much greater thickness, did have some effect on tensile properties when calculated based on original metal thickness. At all temperatures, strengths were higher than bare material and particularly for the thinnest specimens. This would be expected, as the coating is hard and can contribute strength which would be most noticeable on the thinnest pieces where the coating represents a greater proportion of the cross section. Like the Codep B-1 coating, the CoCrAlY composition has low ductility at low temperature and good ductility at high temperature. The CoAl in the CoCrAlY is identical in structure with the NiAl of the Codep, and very similar in behavior. The F.C.C. matrix around the CoAl phase is basically metallic in behavior, but cannot resist the spread of cracking from the many closely-spaced CoAl particles at the low temperatures. The existence of the relatively thick cracked surfaces in the room temperature tests may have caused the lower overall ductility. At the intermediate temperatures, little effect was noted, and at 1093C, ductility was improved due to both surface oxidation protection and the thick non-cracking load-carrying nature of the coating at this temperature.

Exposure Effects on Tensile Properties

The two exposure temperatures produce different substrate metallurgical effects as well as oxidation attack and would therefore affect tensile properties differently. At 982C, large amounts of grain boundary $M_{23}C_6$ are formed and some growth of γ' occurred. Low temperature ductility and strength should be lowered by this combination, while high temperature properties could be improved. On the other hand, 1093C dissolves $M_{23}C_6$ and grows and partially dissolves γ'. On cooling, fine γ' is precipitated. As a result; low temperature strength and ductility at all temperatures should be improved. To evaluate the bare specimen behavior, the effects of oxidation have to be added to these metallurgical factors. The exposures cause inward diffusion of oxygen and nitrogen, especially down grain boundaries, which generally lower ductilities, and possibly increase high temperature strength. At the same time, the depletion of Al and Ti noted from the surface region would decrease or eliminate the γ' thereby lowering the strength and improving the ductility at the surface. Carbon (and carbides) is also lost by reaction with air, further lowering strength. The lack of quantitative or even relative estimates of all the preceding items makes it impossible to predict all the effects found. For some test conditions, all the predictions are the same; the 982C exposure should lower strength and ductility at room temperature and probably at 760C and the data show this to take place. While the oxidation-affected depth would be greater after the 1093C exposure, the metallurgical factors point to a less detrimental effect on room temperature properties, which the data confirmed.

One means of comparing the metallurgical vs. oxidation effects is by noting the differences in properties with section thickness. The metallurgical changes, of course, are similar for all sizes, while the oxidation should have much greater effect on the thinnest sections. In virtually every tensile property at each test temperature, the bare thinnest specimens after exposure show the lowest values even though initially the thin specimens in many cases were better. For example, in bare specimens at room temperature after 982C exposure, Y.S. was decreased 28% for the 0.075 cm thickness and 19% for the 0.15 cm; U.T.S. decreased 31% for the thinnest and 20% for the thickest; elongation reduced ~85% for the thinnest and ~ 54% for the thickest. Clearly, the exposure to air in itself is a major detriment for Rene 80, and is a reason for coating.

Another method of evaluating the oxidation aspect of the exposure is to compare the bare specimens to specimens on which the surface is protected from the air by the Codep B-1 coating. The diffusion between the coating and base alloy during the 982C exposure is not too great, so that the coating may be considered somewhat inert. Virtually every tensile property at each test temperature after this exposure is higher for the coated than bare specimens. Actually, for test temperatures of 760C and higher, the Codep B-1 coated specimens after exposure at 982C have equal or higher strengths than the bare, unexposed material while elongation at temperatures up to 982C becomes less. Therefore, it is concluded that the major metallurgical effects of the 982C exposure lower strengths up to 760C by ~10%. The remainder of property losses are due to contamination from the atmosphere, and vary from losses of 2 to 3% in strength for the 0.15 cm specimens to losses of 11 to 20% for the 0.075 cm specimens.

The Codep B-1 coating was protective during the 1093C exposure. Carbon loss is blocked by the coating. The inward diffusion of Al, especially along grain boundaries, permitted formation of additional γ'. This has a major strengthening effect at low and moderate temperatures, with a consequent reduction of elongation, compared to bare specimens which lose γ' at the surface. The data shows all strength levels for Codep B-1 coated specimens after this exposure were about equal to or higher than for bare, unexposed specimens, while elongation was decreased up to 982C. Moreover, strengths and elongations to 982C were changed to a greater extent for the thin specimens, where the same total amount of Al diffusion (from the coating) affects a greater percentage of the cross section.

The CoCrAlY coating did not provide complete protection during the exposures. For many specimens, a local or more general failure occurred, causing the specimens to behave as if they were bare. Specimens on which the coating remained intact produced properties similar to the Codep B-1 coated samples.

Effects of Stress during Exposure on Tensile Properties

Stress during exposure tends to accelerate the metallurgical and surface reactions. On the other hand, the absence of cycling in the present stressed exposures would permit adherence (and protection) of oxides that might have spalled during cycling. Other work (on standard size bars) has indicated that the greatest part of 982C exposure effects takes place in the first 50 to 250 hours, therefore the accelerating influence of the stress would be relatively unimportant in a 750-1000 hour exposure. The depth and effect of oxygen or nitrogen diffusion might be increased in spite of the non-cyclic nature of the stressed exposure. That the latter type of effect is more likely the controlling factor is indicated by the slight additional losses suffered by the bare stress-exposure samples compared to almost no changes in the Codep B-1 samples.

Geometry Effects on Stress Rupture

Stress rupture life is affected by most of the same variables that affect tensile properties. Grain size is an important factor again. Prior work on standard size test bars (on other nickel-base superalloys) has indicated a loss of rupture life at about 927C of 25 to 50% as grain size decreased from 0.64 cm to 0.039 cm. The differences in life between the thin specimens and standard size bars noted in the present work are greater than grain size alone could account for. MC carbide size and distribution may have some effect. The geometrical effect undoubtedly causes a major part of the losses. It was deduced from the tensile properties that a 6-10% loss in strength may be attributed to geometry for the 0.15 cm thick specimens. If the same strength loss applies to the stress rupture test, it becomes equivalent to life losses of from 50-67% at 760C to 5-15% at 1093C (using master stress rupture curves for Rene 80). The present data does show the greatest losses at 760C and smaller losses at the higher temperatures; however, the losses are still somewhat more than the combination of grain size and geometry would explain.

Surface Effects on Stress Rupture

It has been shown that test specimens machined all over had higher rupture lives than specimens with a cast surface. Part of the improvement is due to the specimen having flatter, smoother surfaces which would help the accuracy and alignment of the test. Part is the result of removing the fine recrystallized grains and de-alloyed layer at the surface, both of which would be detrimental to rupture life. A comparison of the present results on cast-surface Rene 80 may be made with the machined specimen results for wrought U700 tested at 982C shown in Figure 1. Plotting the wrought U700 curve and Rene 80 data on the same basis of % of life of standard size bars yields Figure 62. Both bare and coated Rene 80 data are included. The Rene 80 curve is lower by 30% at the 0.075 cm thickness and by 20% at the 0.15 cm thickness. The testing methods employed were identical for each of the materials. The lower relative values for Rene 80 are largely due to the machining vs. cast surface effect, and in part due to the finer grain size of the Rene 80 thin specimens relative to the standard bar grain size (the U700 specimens all had the same grain size). Both effects would indicate that a smaller difference should exist as the thickness increases, as the data shows.

Testing Effects on Stress Rupture

Another source of rupture life loss may be the test specimen/test method dimensional and alignment problems. Although all specimens were machined within the required tolerances, there could be 5% additional bending stresses at the maximum limits. Alignment of test fixtures, friction in the loading system, etc., may accumulate additional stresses. The initial misalignment stresses would be reduced during creep of the specimen, but a reduction in life would ensue. Similar absolute amounts of misalignment of larger specimens would cause smaller additional stresses and less life losses. In the present programs, the tests at 1093C used direct loading of the specimens (eliminating the lever-knife edge system), which tends to reduce test fixture problems. Tests at this temperature did show the least differences between the thin casting and standard bars, which in part may be a result of the fixturing. If misalignment stress were reduced during creep, then the relative creep rates at the different temperatures and stresses would clarify some of the noted effects, as might rupture tests at lower stresses (longer time). Unfortunately, the present program did not include such work.

In a further attempt to evaluate the effects of mechanical test problems, several nominal 0.075 cm cast blanks that had been rejected for excess thickness variation were heat treated, then machined all over (including the flat faces) to the same specimen design. Some of the machined specimens were tested by the normal stress-rupture method (lever arm) at 760C and 982C, and some using direct loads. The machined specimens tested by the lever method had over double the lives of the cast-surface specimens at 760C and about 50% longer life at 982C. The specimens tested with direct loading had about 25% greater lives than the lever tested specimen. The improvement at 982C due to machining would raise the cast surface Rene 80 data close to the machined U700 curve (Figure 62); the additional improvement of the direct loading test would place the Rene 80 at or over the U700 curve.

The conclusions from the few available tests are that some of the losses in stress-rupture life noted in the program are due to mechanical testing variables; more at 760C than at 982C. Based on this, and using the data from Figure 7-15, an estimation of the life of cast thin sections (non-machined surfaces) compared to standard size bars is shown in Table XIX. Appreciable losses are indicated for the thinnest section at the lowest temperature; decreasing losses with increasing section thickness and test temperature.

Exposure Effects on Stress Rupture

Bare specimens were affected by the 982C exposures at 760C test temperature, whil virtually no effect was noted at 982C and 1093C. The 1093C exposure was extremely harmful at all test temperatures. The dissolving of the grain boundary $M_{23}C_6$ carbide, loss of some MC carbide, de-alloyed surface layer, coarse grain boundary γ', etc., were all detrimental to rupture life. No metallurgical reactions occurred that were beneficial. In addition, because of the metal loss from oxidation, the specimens become thinner than the nominal dimensions increasing the geometric strength loss factor. The effective thickness of the specimens due to grain boundary oxidation is really less than that measured externally, causing the true stress applied to be higher than calculated. The combination of these effects was more severe on the thinnest specimens at the higher test temperatures. At 760C both thicknesses were severely affected and failed on loading.

Coating Effects on Stress Rupture

The Codep B-1 coating results in over 50% loss in rupture life at 760C, ~40% loss at 982C and ~10% increase in life at 1093C compared to bare specimens, based on stresses calculated from original metal dimensions. The coating produces a diffusion layer which consists of NiAl and σ regions, which like the added coating material is brittle up to as high as 816C and is weak. If the stresses were calculated on the remaining base metal thickness (method 3), the losses at 760C and 982C would just about disappear. At 1093C, the protection afforded by the coating against oxidation effects outweighs the net section effect and permits longer life.

The CoCrAlY coating, as with the tensile properties, is relatively thick and can contribute some strength. Consequently, no losses in life occurred compared to bare material.

The Codep B-1 coating provided excellent protection against rupture life loss due to exposure at 1093C for the same reasons as in the tensile tests. After 982C exposure, some loss occurred in 760C and 982C for the 0.075 cm specimens particularly. This loss may be due to the embrittling effect of the additional sub-surface phases formed as a result of diffusion at the exposure temperature. If stresses were based on the unaffected metal thickness remaining, the losses would be reduced or eliminated. The phases were not harmful to ductility at 982C and 1093C.

The variability of protection during exposure afforded by the CoCrAlY coating resulted in greatly differing rupture lives. Samples with intact coating behaved as did the Codep B-1 samples; where coating was deteriorated, results resembled those of bare specimens.

Effects of Stress during Exposure on Stress Rupture

Stressing specimens during the 982C exposure did result in a measurable lowering of rupture life compared to unstressed specimens for both bare and coated material. A major part of the loss is the fraction of life used up in the stressed exposure itself, about 25%. The remainder must be due to the acceleration of reactions and possibly changes in phase morphology caused by the stress. As in the tensile tests, the losses were somewhat less for the coated samples.

Mechanical Fatigue

The type of mechanical fatigue test run in bending virtually eliminates the geometrical effects noted for the tensile and stress rupture tests since only the surface is stressed to the maximum level. Testing stops when a crack has been initiated. Fine grain size is generally believed to provide higher room temperature fatigue strength in wrought material, but this has not been proven for cast nickel-base superalloys. The thin section fatigue strength was equivalent to standard bar fatigue strength for the bare specimens. Prior tests on Codep coated bars and turbine blades have shown fatigue strength losses proportional to coating thickness. A loss of about 4% was found with the present thinner coatings. The only two CoCrAlY coated specimens available for test indicated a higher fatigue strength than contemplated. This is insufficient data to be certain of the result.

The 982C exposure resulted in unusually high fatigue values for the bare specimens. The irregularity of the attacked surface made stress calculations and detection of cracking difficult. The 1093C exposure probably because of spalling, had much less oxidation products than the 982C exposure (see Figure 50a, b). Consequently, its loss in strength is a more accurate representation of the effect exposure temperature has. Most of the loss is undoubtedly the result of the formation of the de-alloyed, weak surface layer (maximum stress in bending is at the surface). Both coatings provided protection most noticeable after the 1093C exposure. De-alloying is prevented, but diffusion has lowered the coating hardnesses and its surface strength, contributing the loss noted. Coating diffusion was less at the 982C exposure, and changes in fatigue strength are relatively slight.

Thermal Fatigue

Protection from oxidation is the major beneficial effect of coatings on thermal fatigue, as attack at a thermally induced crack tip causes rapid crack growth. The higher thermal conductivity of the coatings tends to reduce thermal gradients along the surface which reduces the thermal strains induced by the test cycling. Since the thermal cycling causes strain, the surface must be ductile enough to withstand the strains without cracking. The coatings are not ductile at low temperatures, below approximately 760C, and if large tensile strains were applied in this temperature region, cracking would occur. Under the present thermal fatigue conditions, the maximum tensile strains occur above the coating brittleness region. Both 982C and 1093C exposures lowered the thermal fatigue resistance of the bare samples, most likely by providing initial grain boundary oxidation spikes that required relatively few cycles to become cracks. The 1093C exposure lowered the number of cycles

to initiate cracks in the CoCrAlY coating. The oxidation and broadening of the coating "defects" (Figure 52b) during exposure seem to be the major reason. Possibly the first cracks seen were only coating cracks and not base metal cracks. The rate of crack growth was lower for these specimens than for the bare specimens and may be associated with the initial cracks existing only in the CoCrAlY coating.

Ballistic Impact

The ballistic impact tests, like the thermal fatigue tests, provide relevant comparisons only for the conditions used. The energy variation was obtained by changing velocity; if constant velocity with varying mass was employed, or if a sharp rather than a round impact shape or impact angles other than 90° were used, the absolute and possibly relative values might be different. The coatings provided effective protection to the base metal even though they are brittle at room temperature and possibly at 982C at the high effective strain rate caused by the projectile. Two factors permit this: energy is dissipated in cracking the coating, and the base alloy is not crack sensitive (cracks in coating do not readily propagate into the alloy). The mechanical integrity of the base alloy is not damaged, but if the coating cracks are wide enough, oxidation or corrosion at the bottom of the cracks may take place.

Both temperature exposures are harmful to room temperature impact strength, as would be expected, since the impact strength represents an energy to fracture (similar to the area under the tensile stress-strain curve at that deformation rate), which is dependent on both strength and ductility. For the 0.075 cm specimens, room temperature tensile strength was reduced by both exposures, while ductility remained about the same or was lowered. Losses at the 982C test temperature were not as drastic in ballistic impact, as in the tensile strength-ductility combination. The impact energy losses at room temperature for the coated specimens due to the 982C exposure are mainly due to the lowering of the portion of the energy absorbed by the base alloy, as the coating properties themselves are only slightly altered. Exposure at 1093C does reduce the coating hardnesses (see Table XIV) at room temperature which should increase coating ductility and allow improvement in their energy absorption. This is reflected by the higher energies required to craze crack the coatings at room temperature after the high temperature exposure, and the overall increase in energy needed to crack the base alloy. The coating ductilities at 982C are not improved by the exposure, as they are ductile initially. Overall, and particularly after exposure, the CoCrAlY coated specimens had the highest ballistic impact strengths, largely because of the greater thickness of coating.

Oxidation and Hot Corrosion

The weight change data obtained during the exposures shows that Rene 80 is not outstanding in oxidation resistance (weight losses of over several mg/cm^2 are not desirable), with maximum permissible exposure times of under 500 hours at 982C and under 80 hours at 1093C. At the times of removal from exposures (754 and 168 hours, respectively) the total depth of attack on the surface (metal surface loss plus additional sub-surface attack) was about 0.017 cm. This is excessive for turbine application of cast thin section superalloys. The relatively poor oxidation behavior of Rene 80 is attributed to its high Ti/Al ratio, which is greater than any of the other high strength nickel-base superalloys. This results in TiO_2 and Ti containing M_2O_3 oxides, plus large amounts of NiO (see Table XV). The latter is invariably non-protective, and the former either non-protective or subject to spalling during the cycling. The stress exposure (no cycling) did not have NiO; only Cr_2O_3, which can be protective, and TiO_2. The slightly lower weight losses noted for the thinnest pieces may be due to their lower stiffness; they tended to bend or warp on cycling which can minimize oxide spalling.

The Codep B-1 coating was completely protective at both exposure temperatures. The thin surface oxide was difficult to detect. Only Al_2O_3 was identified on the surface after long exposure times. For the length of test time, the internal coating diffusion reactions have not been noted to affect surface oxides. The CoCrAlY coating was not consistent in behavior due to the existence of occasional defects. Oxidation would take place at these points and spread across the surface, lifting off the coating. The overali weight changes include these locally attacked as well as undamaged areas. On the average, the CoCrAlY coated specimens had lower weight losses than bare specimens, but the figures really include areas which had very little attack (as verified in the microstructure samples) as well as spots just as poor as the bare metal. This combination is reflected in the detection of both "good" protective oxides (Al_2O_3 and some spinels) and "poor" oxides (NiO and CoO).

The amount of hot corrosion attack on the bare material is similar to that found in earlier tests under the same conditions. The microstructural appearance has the usual deep Cr-rich sulfides penetrating most rapidly in grain boundaries. The depth of attack after 473.5 hours in the hot corrosion test at 927C was about the same as after 754 hours in the oxidation exposure at 982C, which is an indication of the greater severity of the hot corrosion test. While the absolute amounts of attack for the exposed specimens was greater than for the unexposed specimens, it should be remembered that some of the increased attack is the result of the oxidation exposures themselves. Considering this, the chemistry and phase changes caused by the oxidation exposures did not alter the hot corrosion behavior noticeably.

The usual precursor of hot corrosion, Na_2SO_4, was found on the surface plus copious amounts of NiO and some spinel and M_2O_3 oxides. The oxidation exposures did not alter the major corrosion products. No TiO_2 was present, although it had been identified after some of the oxidation exposures.

Until they fail, coatings prevent hot corrosion attack of the substrate. First failure for Codep B-1 averaged 271 hours, which is about 25% lower than the average of prior tests and the present coating thickness is about 20% thinner than the prior coatings. After failure, the rate of attack is more rapid than on uncoated Rene 80. By 328 hours the depth is greater than after 473.5 hours for the bare material. The accelerated attack after failure of an aluminide coating has been found before on Rene 80 and other nickel-base superalloys. No tests have been specially performed to explain the phenomenon but is appears to be related to the diffusion reaction between the coating and the metal's grain boundaries. Enrichment of the boundaries in Al (indicated by the microstructure appearance) and depletion in Cr (not proven) would cause such an effect. The exposures decreased the time to initial failure although the sections taken for microscopic examination (Table XII) did not pass through failure sites. The decrease in coating life was greater for the 1093C exposure as would be expected from the microstructure, surface X-ray diffraction and microprobe results. Al decreases most after the higher temperature exposure, Ni_3Al is more apparent in appearance in the additive layer and X-ray diffraction shows less NiAl and more Ni_3Al. Since Ni_3Al has poor hot corrosion resistance, once it appears at the surface rapid attack and penetration of the coating occurs. The stressed 982C exposure lowered coating life more than the unstressed. Increased diffusion under stress would explain more rapid coating deterioration.

The CoCrAlY coating was superior to the Codep B-1 coating in the hot corrosion test, as it has been in previous comparisons. Whether this is due to a greater thickness or to intrinsically better coating corrosion resistance cannot be answered. The thermal exposures lowered CoCrAlY coating life also, partly by diffusion and partly by enlarging the spike type defects. One of the benefits that the CoCrAlY coating has in regard to stability with time is the high Cr level. When the CoAl phase is diffused out, the remaining Co-Ni base still retains high Cr (over 20%) which forms a reasonably good corrosion resistant alloy.

The surface products of corrosion on both coated alloys were similar: initial protective Al_2O_3, spinels of the Al and Cr containing varieties, NiO/CoO and of course Na_2SO_4. Surprisingly, very small amounts of TiO_2 were present (this was very rare after the exposures) on both coatings and some M_2O_3 on the Codep B-1 only. NiO/CoO and M_2O_3 are not found where complete protection exists. In several of the Codep B-1 samples, NiAl was present. It must have been loosened and separated by attack around or underneath remaining coating areas, since on unattacked specimens (i.e. the exposed-only specimens) none could be removed by scraping.

CONCLUSIONS

Tensile Properties

1. The geometrical effects of thin sections result in room and elevated temperature tensile strength losses of 5 to 10% compared to standard size bars with no loss in ductility.

2. The fine grain size obtained in thin castings alleviates this strength loss at low temperatures, but results in greater losses (up to 25%) at high temperatures.

3. Exposure in air at 982C lowers 0.2% yield strength by 20% and ultimate strength by 40% for the 0.075 cm specimens at room temperature. The losses are only half as much for 0.15 cm specimens. Losses are less at 760C and no losses occur at 982C or 1093C. Elongation is also greatly reduced up to 760C, with lesser reductions at 982C and no loss at 1093C.

4. The 1093C air exposure caused smaller losses in strengths (even some gains) up to 982C, but losses of 10 to 30% at 1093C. Room temperature elongation was raised, while 760C and 982C elongations were lowered and no change occurred at 1093C.

5. Coatings do not detrimentally affect the low temperature tensile properties of thin sections.

6. The Codep B-1 coating completely protected specimens from property losses due to atmospheric attack during exposure. The 982C exposure caused internal metallurgical changes which lowered coated specimen properties at room temperature only. The 1093C exposure produced noticeable strengthening effects and some ductility losses at low temperatures.

7. The CoCrAlY coating was not consistent in providing protection to the specimens during high temperature exposures.

Stress Rupture Properties

1. The combination of geometry and metallurgical structure resulted in stress rupture life losses which were greatest for the thinnest sections and the lowest test temperature. Reductions ranged from 80% for the 0.075 cm thickness at 760C to 40% for the 0.15 cm thickness at 982C and 1093C, for stresses producing lives of approximately 100 hours.

2. Exposure of bare metal at 1093C further reduces stress rupture life at all temperatures with losses decreasing as test temperature increases. The 982C exposure effect is much less.

3. Coatings show slight losses for these short time (100 hour) rupture lives at 760C and 982C, and slight improvement at 1093C.

4. Codep B-1 coating affords protection against life loss due to exposure at 1093C. Coated specimen lives are from 2 to over 8 times that of bare specimens. Some losses after 982C exposure occurred for the 0.075 cm specimens at 760C and 982C.

5. The CoCrAlY coating was not consistent in providing protection to the specimens during high temperature exposures.

Mechanical Fatigue

1. Thin castings high cycle fatigue strengths are comparable to standard size bars at room temperature.

2. Exposure at 1093C lowers the bare specimen fatigue strength by 40%. The 982C exposure effects are inconclusive.

3. The Codep B-1 coating slightly lowers, while CoCrAlY slightly raises unexposed fatigue strength.

4. Exposure at 1093C lowers Codep B-1 and CoCrAlY coated specimen fatigue strength by about 20%. The 982C exposure has smaller effect.

Thermal Fatigue

1. Coating improves thermal fatigue cracking resistance; Codep B-1 by a factor of over 2, and CoCrAlY less than 2.

2. Exposures lower thermal fatigue crack resistance of bare material while coated material maintains or improves it.

Ballistic Impact

1. Ballistic impact strength at room temperature is ~4 times the strength at 982C.

2. Exposures at 982C and 1093C lower room temperature ballistic impact strength by >90% and 982C impact strength by much less.

3. Coatings improve resistance to ballistic impact cracking of the alloy by 50 to 100% at room temperature and 982C. The coatings themselves may craze crack at lower impact energy values, but these cracks do not propagate into the base metal.

4. The 982C exposure lowers strength of coated Rene 80 as it does bare material. Ballistic impact strength is only slightly affected by 1093C exposure.

Oxidation and Hot Corrosion

1. Codep B-1 coating provided complete oxidation protection during the 1000 hour cyclic (and static stressed) exposures at 982C and the 500 hour cyclic exposure at 1093C. Weight gains of 0.2 to 0.6 mg/cm^2 occurred. Bare specimens were oxidized, showing weight losses of 8 to 36 mg/cm^2 in shorter times. CoCrAlY coatings were protective for about 600 hours at 982C, then showed weight losses (still considerably better than bare). At 1093C, the CoCrAlY coating was less effective, averaging about half the losses of bare specimens.

2. Both coatings prevent hot corrosion attack of the base metal until they fail, while bare material shows attack after a short time.

3. The Codep B-1 coating life at the hot corrosion conditions used (927C, 5 ppm sea salt) was 271 hours; CoCrAlY coating life was over 473 hours.

4. Prior specimen exposures increased the rate of corrosion attack on bare metal and lowered the coating lives by a factor of 1-1/2 to 5.

Structures

1. Unexposed Rene 80 contains γ', MC and a small amount of $M_{23}C_6$ in its structure. Exposure at 982C increases the amount of $M_{23}C_6$. Exposure at 1093C produces some M_6C and decreases the amount of MC. The latter exposure also produces a surface layer with lowered γ' and carbide content.

2. The Codep B-1 coating added layer consists of NiAl with dispersed α Al_2O_3 particles. Exposures at 982C and 1093C progressively lower the NiAl content by transformation to Ni_3Al. Aluminum content was lowered from 31% to 18% and 6% respectively.

3. The CoCrAlY coating added layer is largely a γ-type matrix with large particles of CoAl dispersed uniformly plus a small amount of α Co. Exposure at 982C and 1093C progressively decrease the CoAl phase and lower aluminum from 12% to 10% and 3%, respectively.

4. Microhardnesses of the added layer and the inter-diffusion zone of both coatings decreased with exposures.

RECOMMENDATIONS

Of all the properties investigated, those with the most direct application to turbine blade design are tensile and stress rupture. The laboratory thermal fatigue and ballistic impact tests, while showing the advantages of coatings and the effects of exposure, do not provide quantitative data that are simple to transfer to blade design. The oxidation and hot corrosion tests similarly provide comparative information, as engine conditions may vary considerably from the test conditions. However, the large effects noted on strength, especially on stress rupture life (used directly in design), have indicated that further work is necessary. Suggested items for additional data and investigations of thin cast sections are:

1. Obtain more tensile and stress rupture data (on different heats of material) to substantiate the major effects noted and provide reliable design data.

2. Verify effects on other nickel-base superalloys.

3. Extend section size to lower thicknesses to establish further geometry and coating effects.

4. Develop specimen design and test techniques to reduce experimental errors.

5. Determine effects of lower temperature, long-time exposures on property and coating behavior.

6. Obtain accurate creep data at several stress levels to help explain test temperature effects.

7. Evaluate effects of newer, lower inter-diffusion rate coatings.

8. Test various grain sizes at each specimen thickness.

9. Compare laboratory test data to engine operating experience.

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Table I Chemical Analyses of Rene 80 Specimens

Specimen	Spec. No.	Composition, weight %														
		Al	Ti	Cr	Co	Mo	W	Mo+W	Mn	Si	Fe	S	B	Zr	C	$\bar{N}_{v3}$
Vendor Anal.	-	3.11	5.10	13.88	9.70	3.90	3.89	7.79	0.05	0.10	0.17	0.005	0.017	0.03	0.15	2.298
Gate mat'l., 0.11 cm (0.045 in)	15	3.10	5.10	13.70	9.50	4.00	3.97	7.97	0.10	0.11	0.11	0.004	0.016	0.03	0.16	2.28
0.075 cm (0.030 in)	0*	3.20	5.03	14.00	9.50	3.95	3.91	7.86	0.11	0.14	0.13	0.002	0.016	0.045	0.166	
"	29	3.10	4.95	14.20	9.45	4.00	3.85	7.85	0.10	0.105	0.14	0.003	0.015	0.03	0.162	
"	33	3.18	5.05	13.90	9.45	4.00	3.97	7.97	0.10	0.14	0.14	0.002	0.015	0.035	0.168	
"	86	3.10	4.95	14.00	9.47	3.95	3.98	7.93	0.10	0.14	0.14	0.002	0.015	0.03	0.158	
0.11 cm (0.045 in)	K	3.10	5.00	14.20	9.45	4.00	3.96	7.96	0.10	0.12	0.14	0.002	0.015	0.033	0.168	
"	L	3.10	5.00	14.00	9.45	4.00	3.88	7.88	0.10	0.105	0.14	0.003	0.015	0.03	0.164	
"	V	3.10	4.95	14.09	9.45	3.95	3.95	7.90	0.10	0.10	0.14	0.004	0.015	0.033	0.156	
0.15 cm (0.060 in)	4	3.15	5.00	14.05	9.47	4.00	3.85	7.85	0.09	0.12	0.13	0.003	0.016	0.035	0.160	
"	17	3.05	4.90	14.05	9.47	4.00	3.80	7.80	0.10	0.12	0.14	0.003	0.017	0.033	0.164	
"	96	3.15	4.95	13.85	9.50	3.95	3.80	7.75	0.10	0.12	0.13	0.003	0.017	0.04	0.166	
C50TF28 Spec. Req't.		2.80/3.20	4.80/5.20	13.70/14.30	9.00/10.00	3.70/4.30	3.70/4.30	7.70 min.	0.20 max.	0.20 max.	0.20 max.	0.015 max.	0.010/0.020	0.02/0.10	0.15/0.19	2.32 max.

All specimens as-cast

* Rounded "leading edge" specimen. All others below this specimen are from center of flat sides of castings.

Table II Tensile and Stress Rupture Tests, Rene 80, Heat BV231
Vendor Data, Standard Size Bars

Tensile Tests

	Test Temp.		0.2% Y.S.		U.T.S.		Elong. %	R.A. %
	°C	°F	MN/m^2	psi	MN/m^2	psi		
Test 1	871	1600	607	88,100	820	118,900	12	13.8
" 2	"	"	659	95,700	811	117,700	11	16.9
" 3	"	"	605	87,900	789	114,300	11½	17.6
C50TF28 min requirement	"	"	482	70,000	620	90,000	-	15.0

Stress Rupture Tests

	Test Temp.		Test Stress		Life	Elong. %	R.A. %
	°C	°F	MN/m^2	psi	hrs.		
Test 1	982	1800	189.5	27,500	38.5	9	12.4
Test 2	"	"	"	"	47.5	9	16.1
C50TF28 min requirement	"	"	"	"	23	-	5.0

Table III Coating Thickness Ranges, Codep B-1 and CoCrAlY on Rene 80 Specimens

Coating Type	Specimen Thickness cm	(inch)	Coating Thickness Range Sectioned Specimens cm	(mils)	All Specimens cm	(mils)
Codep B-1	0.15	(0.060)	0.0038/0.0048	(1.5/1.9)	0.0041/0.0051	(1.6/2.0)
"	0.11	(0.045)	0.0038/0.0051	(1.5/2.0)	0.0041/0.0051	(1.6/2.0)
"	0.075	(0.030)	0.0043/0.0056	(1.7/2.3)	0.0043/0.0051	(1.7/2.0)
"	"	" *	0.0033	(1.3)*	0.0051/0.0053	(2.0/2.1)*
CoCrAlY	0.15	(0.060)	0.0063/0.0132	(2.5/5.2)	0.0059/0.0157	(2.3/6.2)
"	0.11	(0.045)	0.0097/0.0117	(3.8/4.6)	0.0069/0.0157	(2.7/6.2)
"	0.075	(0.030)	0.0069/0.0117	(2.7/4.6)*	0.0063/0.0134	(2.5/5.3)

* Leading edge specimens

Specification coating thickness ranges:

F50TF8D - Codep B-1 0.003/0.0064 cm (1.3/2.5 mils)

F50TF16B - CoCrAlY 0.0051/0.0127 cm (2.0/5.0 mils)

Sectioned specimens measured with filar eyepiece at 400X on microscope.

All specimens measured using Dermitron coating thickness gage.

Table IV Rene 80 Tensile Test Results

A. Room Temperature

Spec. Type or Thickness cm (inch)	Specimen Condition	Spec. No.	0.2%Y.S. MN/m^2 (ksi) (1)	0.2%Y.S. MN/m^2 (ksi) (2)	0.2%Y.S. MN/m^2 (ksi) (3)	U.T.S. MN/m^2 (ksi) (1)	U.T.S. MN/m^2 (ksi) (2)	U.T.S. MN/m^2 (ksi) (3)	Elong. %
Std Size	Bare	-	802 (116.3)	same	same	939 (136.2)	same	same	5
"	"	-	847 (123.0)	"	"	906 (131.5)	"	"	2*
0.075 (0.030)	"	19	760 (110.2)	"	"	1000 (145.4)	"	"	7.8
"	"	35	776 (112.8)	"	"	1027 (149.0)	"	"	9.1*
0.11 (0.045)	"	A	796 (115.6)	"	"	980 (142.3)	"	"	6.5*
"	"	X	775 (112.5)	"	"	987 (143.2)	"	"	8.1
0.15 (0.060)	"	9	784 (113.8)	"	"	945 (137.1)	"	"	5.2*
"	"	90	768 (111.5)	"	"	822 (119.9)	"	"	2.5
0.075 (0.030)	Codep B-1	11	700 (101.5)	753 (109.1)	793 (115.0)	899 (130.4)	966 (140.2)	1019 (147.7)	7.7
"	"	-1	734 (106.6)	789 (114.6)	832 (120.8)	970 (140.8)	1043 (151.4)	1099 (159.5)	8.3
0.11 (0.045)	"	8	765 (111.0)	800 (116.1)	830 (120.4)	1025 (148.7)	1072 (155.5)	1112 (161.3)	9.9
"	"	-2	768 (111.4)	803 (116.5)	833 (120.9)	993 (144.1)	1039 (150.7)	1077 (156.3)	7.9*
0.15 (0.060)	"	2	737 (107.0)	761 (110.4)	779 (113.1)	929 (134.9)	959 (139.2)	982 (142.6)	6.0*
"	"	100	725 (105.1)	748 (108.5)	766 (111.1)	775 (112.4)	800 (116.0)	819 (118.8)	2.3
0.075 (0.030)	CoCrAlY	-12	790 (114.6)	948 (137.5)	975 (141.4)	880 (127.8)	1056 (153.4)	1086 (157.7)	4.5
0.15 (0.060)	"	5	754 (109.3)	839 (121.7)	839 (121.7)	779 (113.0)	867 (125.8)	867 (125.8)	2.5
0.075 (0.030)	Bare + 754 hrs	28	564 (81.7)	same	same	616 (89.3)	same	same	1.0*
"	@ 982C (1800F)	-8	616 (89.3)	"	"	655 (94.9)	"	"	1.5
0.11 (0.045)	"	R	533 (77.3)	"	"	556 (80.7)	"	"	2.0
"	"	11	690 (100.0)	"	"	740 (107.3)	"	"	2.0
0.15 (0.060)	"	45	685 (99.3)	"	"	758 (109.9)	"	"	1.5
"	" (758 hrs)	1	659 (95.6)	"	"	722 (104.7)	"	"	2.0
0.075 (0.030)	Codep B-1+989 hrs	15	646 (93.7)	694 (100.7)	732 (106.2)	681 (98.8)	732 (106.2)	772 (111.9)	8.7
"	@ 982C (1800F)	32	633 (91.7)	680 (98.6)	717 (103.9)	694 (99.3)	746 (106.7)	786 (112.5)	8.0
0.11 (0.045)	"	C	651 (94.5)	681 (98.8)	706 (102.5)	719 (104.2)	752 (109.0)	778 (113.0)	4.5
"	"	V	658 (95.4)	688 (99.8)	714 (103.5)	733 (106.3)	767 (111.2)	795 (115.3)	3.0
0.15 (0.060)	"	73	650 (94.3)	671 (97.3)	687 (99.7)	756 (109.8)	780 (113.3)	799 (116.1)	8.0
"	" (949 hrs)	40	667 (96.8)	688 (99.9)	705 (102.3)	774 (112.2)	799 (115.8)	818 (118.6)	5.0
0.075 (0.030)	CoCrAlY+990 hrs	22	524 (76.0)	576 (83.6)	576 (83.6)	529 (76.6)	582 (84.3)	582 (84.3)	0.7
"	@ 982C (1800F)	43	- -	- -	- -	593 (86.0)	700 (101.5)	700 (101.5)	1.2*
0.11 (0.045)	"	3	661 (95.8)	767 (111.1)	791 (114.7)	700 (101.4)	812 (117.6)	838 (121.4)	1.2
"	"	20	- -	- -	- -	504 (73.0)	526 (76.2)	533 (77.2)	0.5
0.15 (0.060)	"	6	- -	- -	- -	561 (81.4)	605 (87.7)	615 (89.2)	0.7*

See footnotes on page 64

Table IV Rene 80 Tensile Test Results (Cont.)

A. Room Temperature (Cont.)

Spec. Type or Thickness cm (inch)	Specimen Condition	Spec. No.	0.2% Y.S. MN/m^2 (ksi) (1)	0.2% Y.S. MN/m^2 (ksi) (2)	0.2% Y.S. MN/m^2 (ksi) (3)	U.T.S. MN/m^2 (ksi) (1)	U.T.S. MN/m^2 (ksi) (2)	U.T.S. MN/m^2 (ksi) (3)	Elong. %
0.15 (0.060)	Bare +~1000 hrs @ 982C	13	599 (85.6)	same	same	614 (89.1)	same	same	1.5
"	(1800F), stressed	31	577 (83.7)	"	"	636 (92.4)	"	"	2.0*
0.15 (0.060)	Codep B-1 + 1000 hrs @	33	681 (97.8)	703 (100.9)	720 (103.4)	767 (111.2)	792 (114.8)	811 (117.5)	7.0
"	982C (1800F), stressed	51	691 (100.2)	713 (103.4)	730 (105.9)	794 (115.0)	819 (118.7)	839 (121.6)	7.0
0.15 (0.060)	CoCrAlY + 1000 hrs @	3	- -	- -	- -	520 (75.4)	555 (80.5)	565 (81.9)	0.8*
"	982C (1800F), stressed	54	- -	- -	- -	559 (81.0)	598 (86.7)	609 (88.2)	1.0*
0.075 (0.030)	Bare + 168 hrs	2	641 (92.9)	same	same	836 (121.2)	same	same	11.5
"	@ 1093C (2000F)	74	674 (97.6)	"	"	878 (127.3)	"	"	8.2*
0.11 (0.045)	"	BB	741 (107.5)	"	"	942 (136.7)	"	"	11.4
"	"	1	775 (112.4)	"	"	1006 (145.8)	"	"	12.0
0.15 (0.060)	"	41	767 (111.1)	"	"	931 (135.0)	"	"	8.1
"	" (224 hrs)	10	784 (113.6)	"	"	983 (143.4)	"	"	11.0
0.075 (0.030)	Codep B-1 + 487 hrs	7	826 (119.8)	888 (128.8)	936 (135.7)	935 (135.5)	1005 (145.7)	1059 (153.5)	5.5*
"	@ 1093C (2000F)	-9	783 (113.5)	842 (122.0)	887 (128.6)	868 (125.8)	933 (135.2)	983 (142.5)	2.8
0.11 (0.045)	"	3	797 (115.5)	834 (120.8)	865 (125.3)	957 (138.8)	1001 (145.2)	1038 (150.6)	5.0
"	"	26	846 (122.8)	885 (128.4)	918 (133.2)	988 (143.2)	1033 (149.8)	1072 (155.4)	4.9
0.15 (0.060)	"	67	759 (110.0)	783 (113.5)	802 (116.3)	851 (123.3)	878 (127.2)	900 (130.3)	4.8
"	" (532 hrs)	27	816 (118.2)	842 (122.0)	863 (124.9)	899 (130.2)	928 (134.4)	950 (137.6)	5.0
0.075 (0.030)	CoCrAlY + 375 hrs	C	- -	- -	- -	566 (80.6)	656 (93.4)	666 (94.8)	1.5*
"	@ 1093C (2000F)	66	- -	- -	- -	456 (66.0)	521 (75.4)	530 (76.7)	2.0*
0.11 (0.045)	"	W	623 (90.4)	673 (97.6)	673 (97.6)	676 (98.0)	730 (105.8)	730 (105.8)	4.5
"	"	24	622 (90.3)	670 (97.3)	670 (97.3)	744 (107.8)	801 (116.1)	801 (116.1)	2.5
0.15 (0.060)	"	37	767 (111.2)	same	same	791 (114.7)	same	same	1.5*
"	" (349 hrs)	72	802 (116.2)	"	"	925 (134.0)	"	"	3.7

B. 760C (1400F)

Std Size	Bare	-	701 (101.8)	same	same	1059 (153.5)	same	same	13.0
"	"	-	681 (98.8)	"	"	1070 (155.2)	"	"	3*
0.075 (0.030)	"	30	636 (92.3)	"	"	926 (134.4)	"	"	10.7
"	"	84	614 (89.1)	"	"	847 (123.0)	"	"	12.1
0.15 (0.060)	"	16	631 (91.6)	"	"	946 (137.3)	"	"	6.4
"	"	114	626 (90.9)	"	"	912 (132.3)	"	"	3.3
0.075 (0.030)	Codep B-1	-3	584 (84.6)	628 (90.9)	662 (95.6)	855 (123.9)	919 (133.2)	969 (140.4)	3.6
"	"	-4	592 (85.8)	636 (92.2)	671 (97.2)	824 (119.4)	886 (128.4)	933 (135.3)	4.2
0.15 (0.060)	"	9	605 (87.8)	624 (90.6)	639 (92.8)	881 (127.8)	909 (131.9)	931 (135.1)	7.3
"	"	28	613 (88.9)	633 (91.7)	648 (94.0)	868 (125.9)	896 (129.9)	917 (133.1)	3.1

Table IV Rene 80 Tensile Test Results (Cont.)

B. 760C (1400F) (Cont.)

Spec. Type or Thickness cm (inch)	Specimen Condition	Spec. No.	0.2%$_2$Y.S. MN/m^2 (ksi) (1)	0.2%$_2$Y.S. MN/m^2 (ksi) (2)	0.2%$_2$Y.S. MN/m^2 (ksi) (3)	U.T.S. MN/m^2 (ksi) (1)	U.T.S. MN/m^2 (ksi) (2)	U.T.S. MN/m^2 (ksi) (3)	Elong. %
0.075 (0.030)	CoCrAlY	22	899 (130.2)	1060 (153.5)	1097 (158.8)	1117 (162.0)	1317 (191.0)	1363 (197.6)	7.5
0.15 (0.060)	"	18	764 (110.8)	810 (117.4)	817 (118.6)	988 (143.3)	1047 (151.9)	1057 (153.3)	7.0
0.075 (0.030)	Bare + 754 hrs	72	442 (64.1)	same	same	471 (68.2)	same	same	0.0*
"	@ 982C (1800F)	D	673 (97.6)	"	"	684 (99.2)	"	"	0.5
0.15 (0.060)	"	22	- -	- -	- -	581 (84.3)	"	"	1.0
"	"	92	653 (94.7)	same	same	660 (95.8)	"	"	2.5
0.075 (0.030)	Codep B-1 + 989 hrs	5	684 (99.3)	735 (106.7)	775 (112.5)	798 (101.2)	858 (108.8)	904 (114.7)	1.0
"	@ 982C (1800F)	38	611 (88.6)	657 (95.2)	692 (100.4)	727 (105.3)	782 (113.2)	824 (119.3)	2.5
0.15 (0.060)	" (949 hrs)	72	670 (97.2)	691 (100.3)	708 (102.7)	789 (114.2)	814 (117.9)	834 (120.7)	4.0*
"	" "	127	645 (93.6)	666 (96.6)	682 (98.9)	747 (108.2)	771 (111.7)	790 (114.4)	3.5*
0.075 (0.030)	CoCrAlY + 990 hrs	23	- -	- -	- -	396 (57.4)	415 (60.2)	423 (61.2)	1.0
"	@ 982C (1800F)	70	- -	- -	- -	506 (73.4)	582 (84.5)	601 (87.2)	0.5*
0.15 (0.060)	"	61	- -	- -	- -	515 (74.8)	541 (78.5)	541 (78.5)	1.5*
"	"	103	663 (96.2)	same	same	678 (98.4)	same	same	1.5*
0.075 (0.030)	Bare + 168 hrs	33	612 (88.8)	same	same	619 (89.7)	same	same	0.9
"	@ 1093C (2000F)	58	- -	- -	- -	507 (73.5)	"	"	0.9
0.15 (0.060)	"	73	- -	- -	- -	625 (90.6)	"	"	1.1
0.075 (0.030)	Codep B-1 + 487 hrs	27	810 (117.3)	871 (126.1)	918 (132.9)	921 (133.7)	990 (143.7)	1043 (151.5)	3.5
"	@ 1093C (2000F)	-10	839 (121.7)	902 (130.8)	951 (137.9)	872 (126.3)	937 (135.8)	988 (143.1)	2.5*
0.15 (0.060)	" (532 hrs)	50	789 (114.2)	814 (117.9)	834 (120.7)	860 (124.7)	888 (128.7)	909 (131.8)	2.0*
"	" "	82	736 (106.7)	760 (110.1)	778 (112.8)	803 (116.3)	829 (120.0)	849 (122.9)	5.0*
0.075 (0.030)	CoCrAlY + 375 hrs	B	- -	- -	- -	325 (47.1)	same	same	0.5
"	@ 1093C (2000F)	4	Broke in grip section						0.0*
0.15 (0.060)	" (349 hrs)	27	- -	- -	- -	718 (104.0)	"	"	1.0*
"	" "	39	- -	- -	- -	456 (66.2)	"	"	1.0*

C. 871C (1600F)

Std Size	Bare	-	438 (63.5)	same	same	695 (99.4)	same	same	13.0*
"	"	-	450 (65.4)	"	"	720 (104.5)	"	"	12.0*
0.11 (0.045)	Codep B-1 + 949 hrs								
	@ 982C (1800F)	Z	554 (80.4)	579 (84.1)	601 (87.2)	706 (102.3)	738 (107.0)	766 (111.0)	5.0

D. 982C (1800F)

Std Size	Bare	-	270 (39.2)	same	same	419 (60.8)	same	same	18.4
"	"	-	284 (41.2)	"	"	414 (60.0)	"	"	14.2

Table IV Rene 80 Tensile Test Results (Cont.)

D. 982C (1800F) (Cont.)

Spec. Type or Thickness cm (inch)	Specimen Condition	Spec. No.	0.2% Y.S. MN/m^2 (ksi) (1)	0.2% Y.S. MN/m^2 (ksi) (2)	0.2% Y.S. MN/m^2 (ksi) (3)	U.T.S. MN/m^2 (ksi) (1)	U.T.S. MN/m^2 (ksi) (2)	U.T.S. MN/m^2 (ksi) (3)	Elong. %
0.075 (0.030)	"	30	198 (28.7)	same	same	305 (44.3)	same	same	21.3
"	"	12	222 (32.2)	"	"	339 (49.2)	"	"	19.6
0.11 (0.045)	"	AA	237 (34.4)	"	"	347 (50.3)	"	"	16.5
"	"	6	252 (36.6)	"	"	399 (57.9	"	"	16.2
0.15 (0.060)	"	118	238 (34.5)	"	"	355 (51.5)	"	"	23.6
"	"	46	268 (38.9)	"	"	394 (57.2)	"	"	16.3
0.075 (0.030)	Codep B-1	81	204 (29.6)	219 (31.8)	231 (33.5)	349 (50.7)	375 (54.5)	395 (57.4)	13.4
"	"	-5	221 (32.1)	238 (34.5)	250 (36.4)	370 (53.7)	398 (57.7)	419 (60.8)	14.4
0.11 (0.045)	"	22	222 (32.2)	232 (33.7)	241 (34.9)	352 (51.1)	368 (53.5)	382 (55.4)	18.0
"	"	1	251 (36.4)	263 (38.1)	272 (39.5)	361 (52.4)	378 (54.8)	392 (56.9)	14.9
0.15 (0.060)	"	79	220 (32.0)	227 (33.0)	233 (33.8)	351 (50.9)	362 (52.5)	371 (53.8)	11.7
"	"	21	251 (36.4)	259 (37.6)	265 (38.5)	409 (59.3)	422 (61.2)	432 (62.7)	16.3
0.075 (0.030)	CoCrAlY	-13	206 (29.8)	246 (35.6)	254 (36.7)	301 (43.6)	359 (52.9)	371 (53.8)	25.8
0.15 (0.060)	"	58	249 (36.1)	277 (40.1)	279 (40.5)	375 (54.4)	417 (60.4)	420 (61.0)	13.5*
0.075 (0.030)	Bare + 754 hrs	4	221 (32.1)	same	same	309 (44.8)	same	same	4.7
"	@ 982C (1800F)	51	220 (31.9)	"	"	320 (46.4)	"	"	4.4
0.11 (0.045)	"	9	227 (32.9)	"	"	324 (47.0)	"	"	7.8
"	"	19	219 (31.8)	"	"	333 (48.3)	"	"	8.5
0.15 (0.060)	"	62	251 (36.4)	"	"	345 (50.0)	"	"	10.5
"	" (758 hrs)	12	237 (34.4)	"	"	353 (51.2)	"	"	4.0
0.075 (0.030)	Codep B-1 + 989 hrs	19	193 (28.0)	207 (30.1)	219 (31.7)	325 (47.1)	349 (50.6)	368 (53.4)	6.0*
"	@ 982C (1800F)	87	226 (32.8)	243 (35.3)	256 (37.2)	291 (42.2)	313 (45.4)	329 (47.8)	2.5*
0.11 (0.045)	"	T	266 (38.6)	278 (40.4)	289 (41.9)	346 (50.2)	362 (52.5)	375 (54.5)	5.5
0.15 (0.060)	"	33	232 (33.7)	239 (34.8)	245 (35.6)	334 (48.4)	345 (49.9)	353 (51.2)	15.0
"	" (949 hrs)	82	296 (42.9)	305 (44.3)	313 (45.3)	404 (58.6)	417 (60.5	427 (61.9)	18.0
0.075 (0.030)	CoCrAlY + 990 hrs	32	188 (27.2)	218 (31.6)	226 (32.6)	210 (29.3)	244 (34.0)	252 (35.2)	0.7*
"	@ 982C (1800F)	91	Broken during test set up						
0.11 (0.045)	"	14	222 (33.6)	same	same	326 (47.3)	same	same	6.2
"	"	31	254 (36.9)	"	"	330 (47.9)	"	"	2.0*
0.15 (0.060)	"	53	226 (32.8)	"	"	315 (45.7)	"	"	7.0
"	" (994 hrs)	88	193 (28.0)	207 (30.0)	208 (30.2)	272 (39.5)	291 (42.3)	294 (42.7)	3.0
0.15 (0.060)	Bare + 1000 hrs @	41	265 (38.4)	same	same	332 (48.1)	same	same	7.0
"	982C (1800F), stressed	77	196 (28.5)	"	"	323 (46.8)	"	"	11.0
0.15 (0.060)	Codep B-1+1000 hrs @	42	279 (40.5)	288 (41.8)	295 (42.8)	395 (57.4)	408 (59.2)	418 (60.7)	6.0
"	982C (1800F), stressed	57	280 (40.6)	289 (41.9)	296 (42.9)	356 (51.6)	367 (53.3)	376 (54.5)	2.0
0.15 (0.060)	CoCrAlY + 1000 hrs @	?	200 (29.0)	220 (31.9)	224 (32.4)	288 (41.8)	317 (45.9)	322 (46.7)	19.0*
"	982C (1800F), stressed	79	237 (34.4)	260 (37.8)	264 (38.4)	299 (43.4)	328 (47.7)	334 (48.4)	25.3

Table IV Rene 80 Tensile Test Results (Cont.)

D. 982C (1800F) (Cont.)

Spec. Type or Thickness cm (inch)	Specimen Condition	Spec. No.	0.2%$_2$Y.S. MN/m^2 (ksi) (1)	0.2%$_2$Y.S. MN/m^2 (ksi) (2)	0.2%$_2$Y.S. MN/m^2 (ksi) (3)	U.T.S. MN/m^2 (ksi) (1)	U.T.S. Mn/m^2 (ksi) (2)	U.T.S. MN/m^2 (ksi) (3)	Elong. %
0.075 (0.030)	Bare + 168 hrs	12	280 (40.6)	same	same	316 (45.8)	same	same	4.1
"	@ 1093C (2000F)	31	219 (31.7)	"	"	244 (35.4)	"	"	1.9*
0.11 (0.045)	"	2	290 (42.0)	"	"	345 (50.0)	"	"	3.2
"	"	30	291 (42.2)	"	"	346 (50.1)	"	"	3.4*
0.15 (0.060)	"	15	325 (47.1)	"	"	360 (52.2)	"	"	2.9
"	" (224 hrs)	50	279 (40.4)	"	"	342 (49.6)	"	"	7.0*
0.075 (0.030)	Codep B-1 + 487 hrs	3	353 (51.2)	379 (55.0)	400 (58.0)	409 (59.2)	440 (63.6)	463 (67.1)	11.5
"	@ 1093C (2000F)	62	384 (55.7)	413 (59.9)	435 (63.1)	446 (64.7)	479 (69.6)	505 (73.3)	6.2
0.11 (0.045)	"	11	264 (38.3)	276 (40.1)	286 (41.6)	371 (53.8)	388 (56.3)	403 (58.4)	11.0
"	"	22	329 (47.7)	344 (49.9)	357 (51.8)	411 (59.6)	430 (62.3)	446 (64.7)	6.5
0.15 (0.060)	"	87	380 (55.1)	392 (56.9)	402 (58.2)	460 (66.7)	475 (68.8)	486 (70.5)	8.5
"	" (532 hrs)	59	Tested at wrong temperature						
0.075 (0.030)	CoCrAlY + 375 hrs	F	235 (34.1)	same	same	235 (34.1)	same	same	1.5
"	@ 1093C (2000F)	64	183 (26.6)	"	"	183 (26.6)	"	"	1.5*
0.11 (0.045)	"	15	316 (45.8)	"	"	342 (49.6)	"	"	2.0
"	"	29	273 (39.6)	"	"	299 (43.4)	"	"	2.4*
0.15 (0.060)	"	42	350 (50.8)	"	"	350 (50.8)	"	"	1.0
"	" (349 hrs)	7	460 (66.7)	"	"	515 (74.7)	"	"	3.0

E. 1093C (2000F)

Std Size	Bare	-	112 (16.2)	same	same	181 (26.3)	same	same	16.1
"	"	-	130 (18.8)	"	"	190 (27.5)	"	"	16.2
0.075 (0.030)	"	5	103 (14.9)	"	"	158 (22.9)	"	"	6.6
"	"	40	98 (14.2)	"	"	151 (21.9)	"	"	13.8
0.15 (0.060)	"	21	92 (13.3)	"	"	163 (23.7)	"	"	13.5
"	"	80	96 (13.9)	"	"	175 (25.3)	"	"	11.4
0.075 (0.030)	Codep B-1	-6	97 (14.1)	104 (15.2)	110 (16.0)	171 (24.8)	184 (26.7)	194 (28.1)	14.7
"	"	-7	83 (12.0)	89 (12.9)	94 (13.6)	146 (21.2)	159 (22.8)	165 (24.0)	15.3
0.15 (0.060)	"	9-2	83 (12.0)	86 (12.4)	88 (12.7)	173 (25.1)	179 (25.9)	183 (26.5)	8.7
"	"	29	80 (11.6)	83 (12.0)	85 (12.3)	164 (23.8)	169 (24.6)	173 (25.2)	9.5
0.075 (0.030)	CoCrAlY	-6	123 (17.8)	147 (21.2)	153 (22.1)	163 (23.7)	194 (28.3)	202 (13.7)	13.7*
0.15 (0.060)	"	33	102 (14.8)	115 (116.6)	117 (16.9)	172 (25.0)	193 (28.1)	197 (28.6)	15.0
0.075 (0.030)	Bare + 754 hrs	12	95 (13.8)	same	same	144 (20.9)	same	same	9.6
"	@ 982C (1800F)	81	126 (18.2)	"	"	165 (23.9)	"	"	9.2
0.15 (0.060)	"	49	151 (21.9)	"	"	191 (27.7)	"	"	15.0
"	"	109	161 (23.4)	"	"	190 (27.5)	"	"	19.0

Table IV Rene 80 Tensile Test Results (Cont.)

E. 1093C (2000F) (Cont.)

Spec. Type or Thickness cm (inch)	Specimen Condition	Spec. No.	0.2% Y.S. MN/m^2 (ksi) (1)	0.2% Y.S. MN/m^2 (ksi) (2)	0.2% Y.S. MN/m^2 (ksi) (3)	U.T.S. MN/m^2 (ksi) (1)	U.T.S. MN/m^2 (ksi) (2)	U.T.S. MN/m^2 (ksi) (3)	Elong. %
0.075 (0.030)	Codep B-1 + 989 hrs	4-3	112 (16.3)	120 (17.5)	127 (18.5)	146 (21.2)	157 (22.8)	165 (24.0)	13.0*
"	@ 982C (1800F)	40	123 (17.9)	132 (19.2)	139 (20.3)	157 (22.8)	169 (24.5)	178 (25.8)	15.0*
0.15 (0.060)	" (949 hrs)	49	139 (20.2)	143 (20.8)	147 (21.4)	183 (26.5)	189 (27.3)	193 (28.0)	24.0
"	" "	93	154 (22.3)	159 (23.0)	163 (23.6)	186 (27.0)	192 (27.9)	197 (28.5)	15.5
0.075 (0.030)	CoCrAlY + 990 hrs	30	77 (11.1)	90 (13.0)	93 (13.4)	107 (15.5)	125 (18.1)	129 (18.7)	4.0
"	@ 982C (1800F)	51	110 (15.9)	113 (16.4)	117 (16.9)	121 (17.5)	125 (18.1)	129 (18.7)	3.2
0.15 (0.060)	" (994 hrs)	47	95 (13.8)	106 (15.4)	108 (15.6)	139 (20.1)	155 (22.4)	157 (22.8)	19.5
"	" "	79	81 (11.8)	89 (12.9)	91 (13.3)	132 (19.2)	145 (21.1)	149 (21.6)	25.5
0.075 (0.030)	Bare + 168 hrs	34	71 (10.3)	same	same	134 (19.5)	same	same	11.0
"	@ 1093C (2000F)	88	99 (14.3)	"	"	134 (19.5)	"	"	13.8
0.15 (0.060)	"	17	59 (8.6)	"	"	143 (20.8)	"	"	13.0
0.075 (0.030)	Codep B-1 + 487 hrs	13	109 (15.8)	117 (17.0)	123 (17.9)	163 (23.6)	175 (25.4)	185 (26.7)	16.0
"	@ 1093C (2000F)	80	78 (11.3)	84 (12.1)	88 (12.8)	131 (19.0)	141 (20.4)	148 (21.5)	14.0*
0.15 (0.060)	" (532 hrs)	76	113 (16.4)	117 (17.0)	119 (17.3)	155 (22.5)	160 (23.2)	164 (23.8)	23.5
"	" "	100	113 (16.4)	117 (17.0)	119 (17.3)	157 (22.8)	162 (23.5)	166 (24.1)	21.5
0.075 (0.030)	CoCrAlY + 375 hrs	3	Tested at wrong temperature						
"	@ 1093C (2000F)	-11	92 (13.4)	same	same	128 (18.6)	same	same	9.5
0.15 (0.060)	" (349 hrs)	38	106 (15.3)	"	"	159 (23.0)	"	"	7.0
"	" "	70	119 (17.3)	"	"	144 (20.9)	"	"	7.0

* Specimens failed at or outside gage length mark.

(1) Strengths calculated from overall specimen thickness.

(2) Strengths calculated from original specimen thickness before coating, or from overall specimen thickness if coating is lost.

(3) Strengths calculated from thickness of base metal below the coating and its diffusion zone, or from overall thickness if coating is lost.

"Same" indicates strengths are the same as listed in the (1) columns.

Table V Average Percent Change in 0.2% Yield Strength Compared to Standard 0.635 cm Bar

Test Temp °C	Spec. Thick. cm	Bare	Codep B-1 Coated	CoCrAlY Coated	Exposed at 982C						Exposed at 1093C		
					Bare 754 hrs	Bare 1000 hrs stressed	Codep B-1 989 hrs	Codep B-1 1000 hrs stressed	CoCrAlY 990 hrs	CoCrAlY 1000 hrs stressed	Bare 168 hrs	Codep B-1 487 hrs	CoCrAlY 375 hrs
R.T.	0.075	-7	-6	+14	-28		-17		-29		-20	+5	
	0.11	-5	-3	-	-26		-17		-7		-8	+4	-18
	0.15	-6	-7	+2	-19	-29	-17	-14	-	-	-6	+2	-5
760	0.075	-9	-8	+53	-19		+1		-		-11	+28	-
	0.15	-9	-9	+17	-5		-2		-4		-	+14	-
982	0.075	-24	-17	-11	-20		-19		-21		-10	+43	-25
	0.11	-12	-11	-	-19		0		-14		+5	+12	+7
	0.15	-9	-12	0	-12	-17	-2	+4	-2	-13	+9	+41	+46
1093	0.075	-17	-20	+21	-9		+4		-16		-30	-17	-24
	0.15	-22	-30	-5	+29		+25		-19		-51	-3	-7

Coated specimen strengths based on original specimen thickness, column (2) Table IV.

Table VI Average Percent Change in Ultimate Tensile Strength Compared to Standard 0.635 cm Bar

Test Temp °C	Spec. Thick. cm	Bare	Codep B-1 Coated	CoCrAlY Coated	Exposed at 982C						Exposed at 1093C		
					Bare 754 hrs	Bare 1000 hrs stressed	Codep B-1 989 hrs	Codep B-1 1000 hrs stressed	CoCrAlY 990 hrs	CoCrAlY 1000 hrs stressed	Bare 168 hrs	Codep B-1 487 hrs	CoCrAlY 375 hrs
R.T.	0.075	+10	+9	+14	-31		-20		-30		-7	+5	-36
	0.11	+7	+14	-	-30		-18		-28		+5	+10	-17
	0.15	-4	-5	-6	-20	-32	-14	-13	-14	-37	+4	-2	-6
760	0.075	-17	-15	+24	-46		-23		-53		-47	-9	-69
	0.15	-13	-15	-2	-42		-24		-43		-41	-19	-45
982	0.075	-23	-7	-14	-24		-21		-41		-33	+10	-50
	0.11	-11	-11	-	-21		-13		-21		-17	-2	-23
	0.15	-10	-6	0	-16	-21	-9	-7	-27	-23	-16	+14	+4
1093	0.075	-17	-8	+5	-17		-12		-33		-28	-9	-31
	0.15	-9	-7	+4	+3		+3		-19		-23	-13	-18

Coated specimen strengths based on original specimen thickness, column (2) Table IV.

Table VII Average Tensile Elongation, Percent

Test Temp °C	Spec. Thick. cm	Bare	Codep B-1 Coated	CoCrAlY Coated	Exposed at 982C						Exposed at 1093C		
					Bare 754 hrs	Bare 1000 hrs stressed	Codep B-1 989 hrs	Codep B-1 1000 hrs stressed	CoCrAlY 990 hrs	CoCrAlY 1000 hrs stressed	Bare 168 hrs	Codep B-1 487 hrs	CoCrAlY 375 hrs
R.T.	0.075	8.5*	8.0	4.5	1.3*		8.4		1.0*		9.9*	4.2*	1.8*
	0.11	7.3*	8.9*	-	2.0		3.8		0.8		11.7	5.0	3.5
	0.15	3.9*	4.2*	2.5	1.8	1.8*	6.5	7.0	0.7*	0.9*	9.6	4.9	2.6*
	Std Bar	3.5*											
760	0.075	11.4	3.9	7.5	0.3+		1.8		0.8*		0.9	3.0*	0.3*
	0.15	4.9	5.2	7.0	1.8		3.8*		1.5*		1.1	3.5*	1.0*
	Std Bar	8.0*											
982	0.075	20.5	13.9	25.8	4.6		4.3*		0.7*		2.5*	8.9	1.5*
	0.11	16.4	16.5	-	8.2		5.5		4.1*		3.3*	8.8	2.2*
	0.15	20.0	14.0	13.5*	7.3	9.0	16.5	4.0	5.0	22.1*	5.0*	8.5	2.0
	Std Bar	16.3											
1093	0.075	10.2	15.0	13.7*	9.4		14.0+		3.6		12.4	15.0*	9.5
	0.15	12.5	9.1	15.0	17.0		19.8		22.5		13.0	22.5	7.0
	Std Bar	16.2											

* specimen(s) failed at or outside gage length mark

Table VIII Stress-Rupture Data, Rene 80 Thin Section Castings

A. 760C (1400F)

Specimen Thickness cm (inch)	Specimen Condition	Spec. No.	Test Stress MN/m^2 (ksi) (1)	Test Stress MN/m^2 (ksi) (2)	Test Stress MN/m^2 (ksi) (3)	Life hrs. (1)	Extrapolated life, hrs** (2)	Extrapolated life, hrs** (3)	Elong. %
Std Size	Bare	-	565 (82.0)	same	same	205-268#	same	same	11.4
"	"	-	"	"	"	174-190##	"	"	17.5
"	"	-	"	"	"	339	"	"	11.7
0.075 (0.030)	"	74	627 (91.0)	"	"	3.5*	11.0*	11.0*	6.1
"	"	D	"	"	"	6.0*	19.0*	19.0*	13.5
"	"	I	565 (82.0)	"	"	20.0	same	same	9.3
"	"	VI	"	"	"	25.5	"	"	7.3
0.15 (0.060)	"	27	627 (91.0)	"	"	7.0*	24.0*	24.0*	7.5
"	"	99	"	"	"	10.0*	31.0*	31.0*	7.8
"	"	57B	565 (82.0)	"	"	21.5	same	same	6.0
"	"	57A	"	"	"	83.0	"	"	6.6
0.075 (0.030)	Codep B-1	13	627 (91.0)	675 (97.9)	710 (103.0)	0.2*	1.8*	5.0*	2.7
"	"	?	"	" "	" "	2.5*	18.0*	36.0*	3.1
0.15 (0.060)	"	16	"	651 (94.0)	663 (96.2)	0.9*	4.8*	6.5*	4.2
"	"	72	"	" "	" "	2.0*	10.0*	16.0*	3.6
0.075 (0.030)	CoCrAlY	?	565 (82.0)	686 (99.5)	707 (102.5)	3.0	28.0	46.0	14.8
0.15 (0.060)	"	6	"	614 (89.1)	624 (90.5)	27.0	65.0	82.0	8.9
"	"	99	"	611 (88.6)	621 (90.0)	13.0	30.0	40.0	8.7
0.075 (0.030)	Bare + 754 hrs	?	"	same	same	9.0	same	same	0.2
"	@ 982C (1800F)	45	"	"	"	29.0	"	"	1.2
0.15 (0.060)	"	3	"	"	"	0.6	"	"	0.8
"	"	51	"	"	"	11.7	"	"	1.5
0.075 (0.030)	Codep B-1 + 988 hrs	N	"	608 (88.2)	641 (93.0)	Failed in grip			
"	@ 982C (1800F)	48	"	" "	" "	0.5	1.1	2.6	0.9
0.15 (0.060)	"	22	"	584 (84.7)	597 (86.6)	Failed in grip			
"	"	47	"	" "	" "	67.7	89.0	110.0	8.2
0.075 (0.030)	CoCrAlY + 990 hrs	F	"	667 (96.8)	690 (100.1)	Failed on loading			
"	@ 982C (1800F)	63	"	638 (92.6)	660 (95.7)	" " "			"
0.15 (0.060)	"	7	"	584 (84.7)	594 (86.2)	" " "			"
"	"	37	"	" "	" "	" " "			"
0.075 (0.030)	Bare + 168 hrs @ 1093C (2000F)	M	"	same	same	" " "			1.2
"	"	36	"	"	"	" " "			1.0
0.15 (0.060)	"	11	"	"	"	" " "			0.9
"	Bare + 224 hrs @ 1093C (2000F)	15	"	"	"	" " "			-

No load for indeterminate time between these limits.

No load for indeterminate time between these limits plus 335 hrs at 341 MN/m^2 (49.5 ksi).

See footnotes on page 72

Table VIII Stress-Rupture Data, Rene 80 Thin Section Castings (Cont.)

A. 760C (1400F) (Cont.)

Specimen Thickness cm (inch)	Specimen Condition	Spec. No.	Test Stress MN/m^2 (ksi) (1)	Test Stress MN/m^2 (ksi) (2)	Test Stress MN/m^2 (ksi) (3)	Life hrs. (1)	Extrapolated Life, hrs** (2)	Extrapolated Life, hrs** (3)	Elong. %
0.075 (0.030)	Codep B-1 + 487 hrs	47	565 (82.0)	608 (88.2)	641 (93.0)	0.5	1.2	2.0	1.3
"	@ 1093C (2000F)	?	"	" "	" "	6.0	12.0	25.0	1.6
0.15 (0.060)	"	24	"	584 (84.7)	597 (86.6)	0.2	0.3	0.4	1.3
"	"	85	"	" "	" "	2.5	3.6	4.9	1.5
0.075 (0.030)	CoCrAlY + 375 hrs	?	"	same	same	Failed on loading			
"	@ 1093C (2000F)	32	"	"	"	" " "			
0.15 (0.060)	"	40	"	"	"	" " "			
"	"	112	"	"	"	1.0	same	same	1.2
0.15 (0.060)	Bare + 1001.1 hrs @	7	"	same	same	Failed on loading			
"	982C (1800F), stressed	34	"	"	"	" " "			
0.15 (0.060)	Codep B-1+1003.5 hrs @	78	"	584 (84.7)	597 (86.6)	4.0	5.1	7.3	0.3
"	982C (1800F), stressed	27	"	" "	" "	22.0	30.5	40.0	2.0
0.15 (0.060)	CoCrAlY + 1000 hrs @	13	"	604 (87.6)	614 (89.1)	Failed on loading			
"	982C (1800F), stressed	104	"	" "	" "	" " "			

B. 982C (1800F)

Std Size	Bare	-	144 (21.0)	same	same	108.8	same	same	17.3
"	"	-	"	"	"	115.0	"	"	7.7
0.075 (0.030)	"	88	172 (25.0)	"	"	8.8*	22.0*	22.0*	6.4
"	"	5	"	"	"	21.6	45.0	45.0	11.2
"	"	V	144 (21.0)	"	"	20.0	same	same	5.7
"	"	II	"	"	"	22.7	"	"	7.5
0.11 (0.045)	"	X	172 (25.0)	"	"	9.0*	20.0*	20.0*	10.0
"	"	94	"	"	"	9.7*	21.0*	21.0*	3.5
"	"	?	"	"	"	10.8*	24.0*	24.0*	9.2
0.15 (0.060)	"	76	"	"	"	36.8*	92.0*	92.0*	5.5
"	"	45	"	"	"	52.9	120.0	120.0	7.1
"	"	75	144 (21.0)	"	"	30.7	same	same	6.6
"	"	57	"	"	"	58.9	"	"	11.5
0.075 (0.030)	Codep B-1	7	172 (25.0)	185 (26.9)	195 (28.3)	2.4*	9.0*	14.0*	6.4
"	"	?	"	" "	" "	5.7*	19.5*	36.0*	13.2
0.11 (0.045)	"	T	"	181 (26.2)	187 (27.1)	5.8*	19.0*	28.0*	11.5
"	"	6	"	" "	" "	10.0*	31.0*	44.0*	5.3
0.15 (0.060)	"	102	"	178 (25.8)	182 (26.4)	9.0*	24.0*	41.0*	6.5
"	"	31	"	" "	" "	9.7*	26.0*	45.0*	9.6
0.075 (0.030)	CoCrAlY	?	144 (21.0)	179 (26.0)	185 (26.9)	10.0	30.0	45.0	7.6
"	"	?	"	176 (25.5)	181 (26 3)	14.1	34.0	50.0	12.3
0.11 (0.045)	"	19	"	169 (24.5)	172 (25.0)	18.2	37.0	50.0	12.3
"	"	28	"	172 (24.9)	176 (25.5)	20.0	45.0	61.0	12.2
0.15 (0.060)	"	52	"	161 (23.3)	164 (23.8)	34.1	55.0	67.0	12.1
"	"	96	"	157 (22.8)	161 (23.4)	35.5	56.0	69.0	7.8

Table VIII Stress-Rupture Data, Rene 80 Thin Section Castings (Cont.)

B. 982C (1800F) (Cont.)

Specimen Thickness cm (inch)	Specimen Condition	Spec. No.	Test Stress MN/m^2 (ksi) (1)	Test Stress MN/m^2 (ksi) (2)	Test Stress MN/m^2 (ksi) (3)	Life hrs. (1)	Extrapolated Life, hrs** (2)	Extrapolated Life, hrs** (3)	Elong. %
0.075 (0.030)	Bare + 754 hrs	74	144 (21.0)	same	same	19.9	same	same	4.6
"	@ 982C (1800F)	P	"	"	"	50.0	"	"	5.0
0.11 (0.045)	"	25	"	"	"	23.0	"	"	6.6
"	"	?	"	"	"	32.5	"	"	5.6
0.15 (0.060)	"	33	"	"	"	26.4	"	"	6.8
"	"	87	"	"	"	53.6	"	"	5.8
0.075 (0.030)	Codep B-1 + 988 hrs	92	"	156 (22.6)	164 (23.8)	1.5	2.2	3.5	5.4
"	@ 982C (1800F)	4	"	" "	" "	2.2	3.1	5.0	6.5
0.11 (0.045)	"	2	"	152 (22.0)	157 (22.8)	3.3	4.1	6.0	18.5
"	"	R	"	" "	" "	12.6	14.5	21.0	8.4
0.15 (0.060)	"	44	"	150 (21.7)	153 (22.2)	22.9	25.0	32.0	9.7
"	"	15	"	" "	" "	38.5	43.0	52.0	11.0
0.075 (0.030)	CoCrAlY + 990 hrs	3	"	same	same	2.5	same	same	2.7
"	@ 982C (1800F)	88	"	158 (22.9)	162 (23.5)	3.7	5.1	6.0	9.2
0.11 (0.045)	"	26	"	154 (22.3)	154 (22.3)	2.0	2.6	3.0	2.7
"	"	10	"	165 (23.9)	165 (23.9)	4.2	7.5	7.5	2.9
0.15 (0.060)	"	18	"	153 (22.2)	153 (22.2)	8.8	11.0	11.0	5.1
"	"	75	"	same	same	31.0	same	same	6.2
0.075 (0.030)	Bare + 168 hrs	7	"	same	same	1.3	same	same	3.7
"	@ 1093C (2000F)	31	"	"	"	2.0	"	"	4.3
0.11 (0.045)	"	17	"	"	"	4.6	"	"	4.6
"	"	BB	"	"	"	8.0	"	"	3.7
0.15 (0.060)	"	2	"	"	"	9.7	"	"	6.2
"	"	63	"	"	"	12.0	"	"	3.6
0.075 (0.030)	Codep B-1 + 487 hrs	23	"	156 (22.6)	164 (23.8)	7.3	10.3	12.5	3.4
"	@ 1093C (2000F)	?	"	" "	" "	7.0	10.0	12.0	3.5
0.11 (0.045)	"	27	"	152 (22.0)	157 (22.8)	32.2	41.0	49.0	14.1
"	"	7	"	" "	" "	49.5	61.0	69.0	11.4
0.15 (0.060)	"	53	"	150 (21.7)	153 (22.2)	27.3	31.0	42.0	6.9
"	"	38	"	" "	" "	67.4	75.0	89.0	12.5

Table VIII Stress-Rupture Data, Rene 80 Thin Section Castings (Cont.)

B. 982C (1800F) (Cont.)

Specimen Thickness cm (Inch)	Specimen Condition	Spec. No.	Test Stress MN/m^2 (ksi) (1)	Test Stress MN/m^2 (ksi) (2)	Test Stress MN/m^2 (ksi) (3)	Life hrs. (1)	Extrapolated Life, (hrs)** (2)	(3)	Elong. %
0.075 (0.030)	CoCrAlY + 375 hrs	?	144 (21.0)	same	same	Failed on loading			
"	@ 1093C (2000F)	48	"	"	"	" " "			
0.11 (0.045)	"	18	"	165 (24.0)	165 (24.0)	1.3	2.3	2.3	2.4
"	"	2J	"	same	same	4.0	same	same	2.7
0.15 (0.060)	"	80	"	"	"	0.4	"	"	2.5
"	"	43	"	"	"	2.3	"	"	2.7
0.15 (0.060)	Bare + 1001.1 hrs @	29	"	"	"	8.3	"	"	6.7
"	982C (1800F), stressed	46	"	"	"	11.0	"	"	9.7
0.15 (0.060)	Codep B-1+1003.5 hrs @	43	"	150 (21.7)	153 (22.2)	20.0	22.0	28.0	11.0
"	982C (1800F), stressed	24	"	" "	" "	35.0	39.0	45.0	11.2
0.15 (0.060)	CoCrAlY + 1000 hrs @	6	"	152 (22.1)	152 (22.1)	5.6	6.5	6.5	0
"	982C (1800F), stressed	68	"	147 (21.3)	147 (21.3)	9.7	10.0	10.0	4.0

C. 1093C (2000F)

Std Size	Bare	-	48 (7.0)	same	same	60.0	150.0	same	13.3
"	"	-	"	"	"	99.6	210.0	"	-
0.075 (0.030)	"	50	34.5 (5.0)	"	"	36.8	"	"	5.4
"	"	4	"	"	"	60.7	"	"	12.9
"	"	IV	"	"	"	68.4	"	"	14.2
"	"	III	"	"	"	70.0	"	"	8.1
0.15 (0.060)	"	61	48 (7.0)	"	"	9.0*	25.0*	25.0*	4.7
"	"	75A	34.5 (5.0)	"	"	72.0	same	same	-
"	"	120	"	"	"	81.0	"	"	3.2
"	"	75B	"	"	"	113.5	"	"	7.2
0.075 (0.030)	Codep B-1	71	48 (7.0)	52 (7.5)	54 (7.9)	26.0	60.0	72.0	8.4
"	"	71B	"	" "	" "	51.5	100.0	120.0	7.4
0.15 (0.060)	"	79	34.5 (5.0)	36 (5.2)	37 (5.3)	48.0	51.0	55.0	3.3
"	"	14	"	" "	" "	119.0	124.0	130.0	5.4
0.075 (0.030)	CoCrAlY	42	34.5 (5.0)	41 (5.9)	41 (5.9)	35.9	51.0	58.0	5.5
0.15 (0.060)	"	?	"	38 (5.5)	39 (5.6)	50.5	60.0	63.0	6.6
"	"	38	"	" "	" "	82.0	95.0	102.0	7.1
0.075 (0.030)	Bare + 754 hrs	81	"	same	same	48.0	same	same	5.0
"	@ 982C (1800F)	9	"	"	"	51.6	"	"	2.6
0.15 (0.060)	"	77	"	"	"	90.0	"	"	-
"	"	25	"	"	"	124.5	"	"	6.5
0.075 (0.030)	Codep B-1 + 988 hrs	80	"	37 (5.4)	39 (5.7)	37.7	41.0	50.0	3.6
"	@ 982C (1800F)	1	"	" "	" "	50.0	54.0	62.0	7.1
0.15 (0.060)	"	33	"	36 (5.2)	37 (5.3)	120.0	125.0	130.0	15.4
"	"	89	"	" "	" "	145.3	152.0	160.0	12.0

Table VIII Stress-Rupture Data, Rene 80 Thin Section Castings (Cont.)

C. 1093C (2000F) (Cont.)

Specimen Thickness cm (inch)	Specimen Condition	Spec. No.	Test Stress MN/m^2 (ksi) (1)	Test Stress MN/m^2 (ksi) (2)	Test Stress MN/m^2 (ksi) (3)	Life hrs. (1)	Extrapolated Life, hrs)** (2)	(3)	Elong. %
0.075 (0.030)	CoCrAlY + 990 hrs @ 982C (1800F)	?T	34.5 (5.0)	40 (5.8)	41 (5.9)	14.6	19.0	20.0	5.0
0.15 (0.060)	"	32	"	37 (5.3)	37 (5.3)	91.0	102.0	110.0	5.4
"	"	80	"	37 (5.3)	38 (5.5)	106.8	120.0	128.0	8.9
0.075 (0.030)	Bare + 168 hrs	L	"	same	same	5.6	same	same	-
"	@ 1093C (2000F)	37	"	" "	" "	19.0	"	"	10.1
0.15 (0.060)	"	48	"	" "	" "	54.5	"	"	-
0.075 (0.030)	Codep B-1 + 487 hrs	?	"	37 (5.3)	39 (5.7)	51.0	59.0	68.0	4.9
"	@ 1093C (2000F)	58	"	" "	" "	83.0	97.0	108.0	12.4
0.15 (0.060)	"	28	"	36 (5.2)	37 (5.3)	91.2	100.0	106.0	5.7
"	"	74	"	" "	" "	139.2	147.0	155.0	9.7
0.075 (0.030)	CoCrAlY + 375 hrs	N	"	same	same	3.3	same	same	0.4
"	@ 1093C (2000F)	26	"	"	"	6.0	"	"	0.2
0.15 (0.060)	"	57	"	35 (5.1)	36 (5.2)	43.7	46.0	49.0	10.5
"	"	69	"	same	same	132.0	same	same	7.2

* Specimen grip sections not held flat in grips. The 0.075 and 0.11 cm specimens did bend (presumably causing premature failure). The 0.15 cm specimens did not bend (except for spec. #102 Codep B-1 coated, tested at 982C).

** Life extrapolated from test life (column 1), based on stresses from Test Stress columns (2) and (3) respectively rather than the Test Stress actually used (column 1) for coated specimens.

(1) Stresses calculated from overall specimen thickness.
(2) Stresses calculated from original specimen thickness before coating or from overall specimen thickness if coating is lost.
(3) Stresses calculated from thickness of base metal below the coating and its diffusion zone, or from overall thickness if coating is lost.

Test stresses used for extrapolated life are 595 MN/m^2 (82 ksi) at 760C (1400F), 144 MN/m^2 (21 ksi) at 982C (1800F) and 34.5 MN/m^2 (5 ksi) at 1093C (2000F).

For bare specimens tested at other than these stresses, lives were also extrapolated and listed in columns (2) and (3).

"Same" indicates values are the same as in preceding column(s).

Table IX Mechanical Fatigue Results at Room Temperature, Rene 80 Thin Section Castings

Specimen Condition	Specimen No.	Reversed Bending Stress MN/m^2 (ksi)	Life cycles	10^7 Cycle Strength MN/m^2 (ksi)
Bare	35	474 (68.7)	0.716×10^6	
	17	444 (64.5)	2.054 "	
	78	403 (58.5)	8.468 "	
	H	338 (49.0)	15.039 "	~ 372 (54.0)
Codep B-1 Coated	75C	393 (57.0)	1.218 "	
	75	389 (56.4)	0.284 "	
	75B	345 (50.0)	15.700 " →	
	75A	310 (45.0)	17.550 " →	~ 359 (52.0)
CoCrAlY Coated	22	477 (69.3)	15.095 "	
	-12	345 (50.0)	10.000 " →	~ 482 (70.0)
Bare + 754 hours @ 982C (1800F)	68	379 (55.0)	14.746 " →	
	80	345 (50.0)	15.023 " →	
	32A	448 (65.0)	10.319 " →	
	32B	606 (88.0)	15.163 " →	> 551 (80.0)
Codep B-1 Coated + 989 hours @ 982C (1800F)	43	345 (50.0)	12.854 " →	
	C	338 (48.9)	0.916 "	
	11	324 (47.0)	10.003 " →	
	E	311 (45.0)	12.640 " →	~ 331 (48.0)
CoCrAlY Coated + 990 hours @ 982C (1800F)	38	581 (84.2)	0.003 "	
	?	542 (78.6)	0.383 "	
	L	536 (77.8)	0.164 "	
	45	345 (50.0)	12.136 " →	> 345 (50.0)
Bare + 168 hours @ 1093C (2000F)	5	426 (61.9)	0.545 "	
	J	380 (55.2)	0.357 "	
	M	377 (54.7)	0.206 "	
	26	265 (38.5)	0.991 "	~ 221 (32.0)
Codep B-1 Coated + 487 hours @ 1093C (2000F)	7	332 (48.2)	6.599 "	
	19	303 (43.9)	1.405 "	
	32	292 (42.3)	2.198 "	
	15	276 (40.0)	10.079 " →	~ 283 (41.0)
CoCrAlY Coated + 375 hours @ 1093C (2000F)	22	379 (55.0)	10.077 " →	
	67	310 (45.0)	10.161 " →	
	?	276 (40.0)	15.161 " →	
	61	240 (34.8)	0.367 "	> 276 (40.0)

Specimens are 0.075 cm (0.030 inch) thick.

→ Indicates no failure.

Table X Thermal Fatigue Test Results, Rene 80

Specimen Surface	Prior Exposure	Spec. No.	First crack cycles	Crack Growth to 0.5-1.0 cm, cycles	Crack Growth to over 1.0 cm, cycles
Bare	None	D	2500	2800	3500
"	"	41	1935	2100	2300
"	761 hrs @ 982C (1800F)	45	1500	1700	2000
"	"	F	1100	1200	1700
"	180 hrs @ 1093C (2000F)	6	1100	1400	1700
"	"	44	1500	1700	2000
Codep B-1 Coated	None	A	no cracks up to 4000 cycles		
"	"	27	"		
"	975 hrs @ 982C (1800F)	F	"		
"	"	6	"		
"	483 hrs @ 1093C (2000F)	M	"		
"	"	3	"		
CoCrAlY Coated	None	A	no cracks up to 4000 cycles		
"	"	55	2700	3000	> 4000
"	975 hrs @ 982C (1800F)	8	no cracks up to 4000 cycles		
"	"	D	"		
"	385 hrs @ 1093C (2000F)	Z	800	1400	> 2800*
"	"	K	2500	3500	> 4000

All specimens are 0.075 cm (0.030 inch) thick

Test cycle: heating time 10 sec. to 1093C (2000F), hold for 50 sec., cool by air blast to under 204C (400F) in less than 20 sec.

* Specimen removed from test at this time.

Table XI Ballistic Impact Test Results

Room Temperature Tests

Specimen Surface	Exposure Temp. °C (°F)	Exposure Time hrs	Spec. No.	Impact Energy N-m (ft-lbs)	Impact dia. cm (inch)	Specimen Cracks # front	Specimen Cracks # back	Energy to Crack Parent Metal N-m (ft-lbs)
Bare	none		1-	0.65 (0.48)	0.152 (0.060)	none	none	
				1.34 (0.99)	0.195 (0.077)	none	none	
				1.47 (1.08)	0.188 (0.074)	very small	very small	
				1.60 (1.18)	0.175 (0.069)	"	moderate	
				2.02 (1.49)	0.206 (0.081)	moderate	very large	
"	"		74	1.49 (1.10)	0.183 (0.072)	?	?	
				1.59 (1.17)	0.183 (0.072)	very small	very small	
				1.70 (1.25)	0.193 (0.076)	"	"	
				1.90 (1.41)	0.203 (0.080)	"	"	
				2.02 (1.49)	0.203 (0.080)	small	"	
				2.17 (1.60)	0.218 (0.086)	"	large	1.45 (1.07)
Codep B-1	"		M	2.45 (1.81)	0.211 (0.083)	none	coating craze	
				3.28 (2.42)	0.236 (0.093)	?	severe	
"	"		-3	0.65 (0.48)	0.152 (0.060)	none	coating craze	
				1.36 (1.00)	0.178 (0.070)	"	"	
				2.03 (1.50)	0.203 (0.081)	coating craze	"	
				2.44 (1.80)	0.213 (0.084)	?	" + ?	
				3.19 (2.35)	0.216 (0.085)	?	moderate	2.64 (1.95)
CoCrAlY	"		8	0.66 (0.49)	0.150 (0.059)	none	coating craze	
				1.36 (1.00)	0.170 (0.067)	coating craze	"	
				2.03 (1.50)	0.203 (0.080)	"	" + ?	
				2.68 (1.98)	0.218 (0.086)	moderate	" + small	
"	"		3-	0.18 (0.13)	0.076 (0.030)	none*	coating craze	
				0.65 (0.48)	0.140 (0.055)	" *	" *	2.03 (1.50)

Table XI Ballistic Impact Test Results (Cont.)

Room Temperature Tests (Cont.)

Specimen Surface	Exposure		Spec. No.	Impact Energy N-m (ft-lbs)	Impact dia. cm (inch)	Specimen Cracks #		Energy to Crack Parent Metal N-m (ft-lbs)
	Temp. °C (°F)	Time hrs				front	back	
Bare	982 (1800)	761	8	0.16 (0.12) 0.66 (0.49)	0.081 (0.032) 0.152 (0.060)	very small small	small large	
"	"	"	53	0.16 (0.12) 0.65 (0.48)	0.081 (0.032) 0.157 (0.062)	none small	moderate large	<0.16 (<0.12)
Codep B-1	"	975	K	0.16 (0.12) 0.66 (0.49)	0.094 (0.037) 0.152 (0.060)	coating + ? coating craze	coating + ? large	
"	"	"	23	0.16 (0.12) 0.66 (0.49)	0.097 (0.038) 0.150 (0.059)	coating craze coating + ?	coating craze large	0.16 (0.12)
CoCrAlY	"	"	H	0.16 (0.12) 0.65 (0.48) 1.36 (1.00) 2.02 (1.49)	0.094 (0.037) 0.150 (0.059) 0.178 (0.070) 0.203 (0.080)	none " coating ? "	none " " large	
"	"	"	10	0.16 (0.12) 0.66 (0.49)	0.086 (0.034) 0.145 (0.057)	none coating ? *	none large	1.08 (0.80)
Bare	1093 (2000)	180	2-	0.16 (0.12) 0.65 (0.48)	0.091 (0.036) 0.145 (0.057)	? small	moderate large	
"	"	"	9-	0.16 (0.12) 0.66 (0.49)	0.084 (0.033) 0.142 (0.056)	? ?	moderate large	<0.16 (<0.12)

Table XI Ballistic Impact Test Results (Cont.)

Room Temperature Tests (Cont.)

Specimen Surface	Exposure Temp. °C (°F)	Exposure Time hrs	Spec. No.	Impact Energy N-m (ft-lbs)	Impact dia. cm (inch)	Specimen Cracks # front	Specimen Cracks # back	Energy to Crack Parent Metal N-m (ft-lbs)
Codep B-1	1093 (2000)	483	B	0.65 (0.48)	0.145 (0.057)	none	none	
				1.36 (1.00)	0.185 (0.073)	"	coating mod.	
				2.02 (1.49)	0.208 (0.082)	coating ?	coating small	
"	"	"	4	0.66 (0.49)	0.155 (0.061)	none	none	
				1.37 (1.01)	0.173 (0.068)	"	coating ?	
				2.02 (1.49)	0.198 (0.078)	coating small	large	2.03 (1.50)
CoCrAlY	"	385	3	0.65 (0.48)	0.142 (0.056)	coating ?	none	
				1.37 (1.01)	0.175 (0.069)	coating small	"	
				2.00 (1.48)	0.200 (0.079)	none	coating ?	
				2.70 (1.99)	0.216 (0.089)	coating small	"	
				3.28 (2.42)	0.231 (0.091)	"	coating small	
				4.15 (3.06)	0.252 (0.099)	"	large	
				4.75 (3.50)	0.259 (0.102)	"	"	
"	"	"	-4	0.66 (0.49)	0.150 (0.059)	none	none	
				1.34 (0.99)	0.175 (0.069)	"	"	
				2.02 (1.49)	0.209 (0.079)	coating ?	"	
				2.70 (1.99)	0.213 (0.081)	coating small	coating ?	
				3.28 (2.42)	0.239 (0.093)	"	"	
				4.15 (3.06)	0.249 (0.098)	coating mod.	coating mod.	
				4.75 (3.50)	0.256 (0.101)	"	large	3.69 (2.72)

Table XI Ballistic Impact Test Results (Cont.)

Tests at 982C (1800F)

Specimen Surface	Exposure Temp. °C (°F)	Exposure Time hrs	Spec. No.	Impact Energy N-m (ft-lbs)	Impact dia. cm (inch)	Specimen Cracks # front	Specimen Cracks # back	Energy to Crack Parent Metal N-m (ft-lbs)
Bare	none		30	0.34 (0.25) 0.35 (0.26) 0.68 (0.50)	0.114 (0.045) 0.114 (0.045) 0.152 (0.060)	none " "	very small ? small	
"	"		82	0.34 (0.25) 0.66 (0.49)	0.124 (0.049) 0.145 (0.057)	" "	none very small	0.34 (0.25)
Codep B-1	"		5	0.34 (0.25) 0.68 (0.50)	0.114 (0.045) 0.152 (0.060)	" coating ?	coating craze "	
"	"		36	0.34 (0.25) 0.66 (0.49)	0.119 (0.047) 0.152 (0.060)	none "	" "	>0.68 (>0.50)
CoCrAlY	"		1	0.33 (0.24) 0.66 (0.49)	0.122 (0.048) 0.155 (0.061)	" "	none coating mod.	
"	"		6	0.33 (0.24) 0.66 (0.49)	0.124 (0.049) 0.142 (0.056)	" * " *	coating craze "	>0.68 (>0.50)
Bare	982C (1800)	761	3-	0.33 (0.24) 0.66 (0.49)	0.114 (0.045) 0.172 (0.068)	? moderate	large severe	
"	"	"	60	0.33 (0.24) 0.66 (0.49)	0.129 (0.051) 0.162 (0.064)	? moderate	large severe	<0.33 (<0.24)
Codep B-1	"	975	7	0.34 (0.25) 0.69 (0.51)	0.076 (0.030) 0.162 (0.064)	none "	none ctg.craze+mod	
"	"	"	3-	0.33 (0.24) 0.66 (0.49)	0.068 (0.027) 0.150 (0.059)	" "	none ctg.craze+mod	0.50 (0.37)

Table XI Ballistic Impact Test Results (Cont.)

Tests at 982C (1800F)

Specimen Surface	Exposure Temp. °C (°F)	Exposure Time hrs	Spec. No.	Impact Energy N-m (ft-lbs)	Impact dia. cm (inch)	Specimen Cracks # front	Specimen Cracks # back	Energy to Crack Parent Metal N-m (ft-lbs)
CoCrAlY	982 (1800)	975	5	0.34 (0.25) 0.68 (0.50) 1.38 (1.02)	0.124 (0.049) 0.155 (0.061) 0.193 (0.076)	none " coating large	none ctg.very small large	
"	"	"	51	0.34 (0.25) 0.68 (0.50) 1.38 (1.02)	0.124 (0.049) 0.150 (0.059) 0.203 (0.080)	none " "	none coating ? severe	1.03 (0.76)
Bare	1093 (2000)	180	1-	0.34 (0.25) 0.68 (0.50)	0.124 (0.049) 0.155 (0.061)	none very small	? large	
"	"	"	-5	0.34 (0.25) 0.68 (0.50)	0.124 (0.049) 0.168 (0.066)	none ?	? large	0.35 (0.26)
Codep B-1	"	483	0	0.34 (0.25) 0.66 (0.49)	0.114 (0.045) 0.147 (0.058)	none "	coating mod ctg. large + ?	
"	"	"	18	0.33 (0.24) 0.68 (0.50)	0.112 (0.044) 0.157 (0.062)	" "	none ctg. large + ?	0.68 (0.50)
CoCrAlY	"	385	7	0.34 (0.25) 0.66 (0.49) 1.40 (1.03)	0.114 (0.049) 0.155 (0.061) 0.203 (0.080)	" " "	none " ctg. craze + ?	
"	"	"	93	0.33 (0.24) 0.66 (0.49) 1.37 (1.01)	0.109 (0.043) 0.157 (0.062) 0.203 (0.080)	" " "	coating craze " severe	1.01 (0.75)

Size of cracks: very small <0.005 cm (<0.002 inch); small 0.005-0.012 cm (0.002-0.005 inch); moderate 0.012-0.038 cm (0.005-0.015 inch); large >0.038 cm (>0.015 inch); severe means cracks completely across impact indentation, and multiple large cracks.

Cracks are in parent metal unless specifically indicated as coating crack.

* Coating spalled.

Table XII Hot Corrosion Test Results

Surface Condition	Prior Exposure	Time in Test hrs	Spec. No.	External Metal Loss* cm (inch)	Max. Additional Penetration** cm (inch)	Remarks
Bare	None	61	E	0.0033 (0.0013)	0.0018 (0.0007)	Small subsurface sulfides present.
"	"	473.5	G	0.0079 (0.0031)	0.0102 (0.004)	Sulfides penetrating grain boundaries.
"	758 hrs @ 982C (1800F)	61	A	0.0167 (0.0066)	0.0114 (0.0045)	Many gold acicular subsurface particles, few sulfides.
"	"	346	19	0.0223 (0.0088)	0.0152 (0.006)	Like spec. A, but many sulfides.
"	1003 hrs @ 982C (1800F),stressed	61	25	0.0185 (0.0073)	0.0178 (0.007)	Many gold acicular particles, plus blocky subsurface oxides, few sulfides.
"	"	473.5	20	0.0244 (0.0096)	0.0203 (0.008)	Like spec. 25, but many sulfides.
"	229 hrs @ 1093C (2000F)	61	B	0.0190 (0.0075)	0.0127 (0.005)	Like spec. 25.
"	"	328	3-	0.0206 (0.0081)	0.0165 (0.0065)	Like spec. 20.
Codep B-1	None	328	23	0.0096 (0.0038)	0.0127 (0.005)	No coating present. Sulfides in grain boundaries.
"	"	435	C	0.0137 (0.0054)	0.0140 (0.0055)	Most of coating gone. Where coating is present there is no attack.
"	962 hrs @ 982C (1800F)	61	10	0.0030 (0.0012)	0 (0)	No attack through coating.
"	"	328	A	0.0030 (0.0012)	0 (0)	" " " "
"	1000 hrs @ 982C (1800F),stressed	61	44	0.0038 (0.0015)	0 (0)	" " " "
"	"	184	21	0.0046 (0.0018)	0 (0)	" " " "
"	532 hrs @ 1093C (2000F)	61	D	0.0053 (0.0021)	0 (0)	Attack (sulfides) in additive layer, but not through diffusion zone.
"	"	184	-2	0.029 (0.0114)	0.0178 (0.007)	Much coating gone. Where coating remains, sample resembles spec. D.

Table XII Hot Corrosion Test Results (Cont.)

Surface Condition	Prior Exposure	Time in Test hrs	Spec. No.	External Metal Loss* cm (inch)	Max. Additional Penetration** cm (inch)	Remarks
CoCrAlY	None	473.5	10	0.0013 (0.0005)	0 (0)	No attack through coating.
"	"	473.5	21	0.0020 (0.0008)	0 (0)	" " " "
"	962 hrs @ 982C (1800F)	61	11	0.0051 (0.0020)	0 (0)	" " " "
"	"	435	7	0.0066 (0.0026)	0 (0)	" " " "
"	1000 hrs @ 982C (1800F), stressed	61	2	0.0091 (0.0036)	0 (0)	" " " "
"	"	184	46	0.0127 (0.0050)	0.0076 (0.003)	Some attack at localized spots. Most coating still protective.
"	532 hrs @ 1093C (2000F)	61	D?	0.0124 (0.0049)	0 (0)	No attack through coating, coating single phase.
"	"	184	106	0.018 (0.0070)	0.0051 (0.002)	Attack in one area of cracked coating. Elsewhere coating still protective and is single phase.

Hot corrosion test in burner rig at 927C (1700F), 5 ppm salt. Specimens nominally 0.15 cm (0.060 inch) thick.

* Initial thickness measured by micrometer. Final metal thickness measured on metallographic cross section using micrometer stage microscope.

** Maximum additional penetration below remaining metal surface measured with filar eyepiece on microscope.

Table XIII Phase Analysis Results

Specimen		Exposure		Phases*							
Size cm (inch)	Surface	Temp. °C (°F)	Time hrs	γ' wt.%	γ' a_o, Å	MC am't.	MC a_o, Å	$M_{23}C_6$ am't.	$M_{23}C_6$ a_o, Å	M_6C am't.	M_6C a_o, Å
Std Size	Bare	none		45	3.589						
0.075 (0.030)	"	none		43	3.589	wm	4.307	w	-	?	-
0.15 (0.060)	"	none		43	3.589	wm	4.303	?	-	?	-
0.075 (0.030)	"	982 (1800)	754	22	3.589	wm	4.311	ms	10.71	-	-
0.11 (0.045)	"	" "	"	29	3.587	-	-	-	-	-	-
0.15 (0.060)	"	" "	"	N.D.	N.D.	wm	4.319	ms	10.72	vw	-
0.075 (0.030)	"	1093 (2000)	168	29	3.589	vw	-	vw	-	w	-
0.15 (0.060)	"	" "	"	38	3.587	w	4.313	?	-	vw	-
0.075 (0.030)	Codep B-1	" "	487	38	3.590	w	4.303	w	-	w	11.06
0.15 (0.060)	"	" "	"	41	3.592	vw	-	wm	10.75	wm	11.06

* M in carbides refers to Metal. Usually, the MC is (Ti,W,Mo)C; the $M_{23}C_6$ is $Cr_{21}Mo_2C_6$ and the M_6C is $(Ni,Co,Cr,W,Mo)_6C$.

Relative amounts are w - weak, m - medium, s - strong, v - very. N.D.-Not Determined.

γ' extracted in 1% $(NH_4)_2SO_4$ + 1% citric acid in water, carbides in 10% HCl in methanol.

X-ray diffraction identification used 114 mm Debye Scherrer camera, Co Radiation, Fe filter.

Table XIV Microhardness of Coatings Before and After Exposures

Coating	Exposure		Specimen Thickness	Spec. No.	Hardness*		
	Temp. °C (°F)	Time hrs	cm (inch)		Matrix	Diffusion Zone	Additive Layer
Codep B-1	None		0.15 (0.060)	B	490	909	588
	"		"	E	457	927	553
	982 (1800)	989	0.075 (0.030)	15	435	720	532
	"	"	0.15 (0.060)	73	383	752	461
	1093 (2000)	487	0.075 (0.030)	-9	450	565	392
	"	"	0.11 (0.045)	3	460	615	508
	"	"	0.15 (0.060)	67	438	594	367
CoCrAlY	None		0.11 (0.045)	17	434	-	790
	"		"	P	446	553	580
	"		0.15 (0.060)	85	430	-	581
	"		"	29	442	517	820
	982 (1800)	990	0.075 (0.030)	22	371	-	404
	"	"	0.15 (0.060)	6	376	-	430
	1093 (2000)	375	0.075 (0.030)	C	432	-	300
	"	349	0.15 (0.060)	72	456	-	365

* Hardness is in Vickers numbers, measured on Leitz Durimet using 50 gm weight. Each number is an average of two readings, one on each side of specimen.

Table XV Surface Products of Exposures

Spec. Cond.	Spec. No.	Exposure Conditions	Phases								
			CoO		NiO		Spinel		Al_2O_3	TiO_2	Others
			am't.	a_o, Å	am't.	a_o, Å	large	small	am't.	am't.	
Bare	109	982C, 225 hrs	-		m	4.183	vw	?	-	wm	Cr_2O_3 vw
"	A	" "	-		w	4.183	vw	vw	-	m	Cr_2O_3 w
"	49	" 770 hrs	-		ms	4.183	wm	-	-	-	M_2O_3 vw
"	109	" "	-		ms	4.183	wm	-	-	-	M_2O_3 vw
"	29& 46	" 1000 hrs, stress 48 MN/m^2	-		-		-	-	-	w	Cr_2O_3 wm
CoCrAlY	11	982C, 40 hrs	m	4.246	vw	4.180	vw	-	-	-	α Co vw
"	47	" 625 hrs	m	4.246	-	-	m	?	vw	-	-
"	7	" 990 hrs	m	4.234	vw	4.183	m	?	w	-	-
"	34	" "	w	4.215	m	4.186	m	-	vw	-	-
CoCrAlY	27	1093C, 50 hrs	-		vw	?	?	-	wm		Cr_2O_3?
"	39	" 150 hrs	w	4.236	?	-	wm	vw	?	?	-
"	27	" 364 hrs	w	4.215	m	4.186	m	?	-	-	-
"	39	" "	m	4.226	vw	4.183	wm	vw	vw	?	-
CoCrAlY	37	" 375 hrs	ms	4.220	-	-	m	vw	vw	-	α Co m
"	37	" "	wm	4.220	vw	4.186	m	?	?	-	-
"	32	" "	wm	4.220	vw	4.186	m	?	?	-	-

Notes: Spinel - large indicates $a_o \approx 8.32$Å $(Ni,Co)Cr_2O_4$ type.
Spinel - small " $a_o \approx 8.10$Å $(Ni,Co)Al_2O_4$ type.
Amounts: s - strong, m - medium, w - weak, v - very.
M_2O_3 - hexagonal structure lattice parameters between those of Cr_2O_3 and $NiTiO_3$.

CoCrAlY coated specimens @ 1093C, 375 hours, are from a different run than preceding 1093C exposures. Two different analyses on spec. #37 are from different appearing locations on same piece.

Table XVI X-Ray Diffraction Analysis of Surface Phases

Specimen			Exposure		Phases							
Size	Surface	No.	Temp.	Time	γ/γ'		NiAl		CoAl		αAl_2O_3	αCo
cm (inch)			°C (°F)	hrs	a_o, Å	Max.I	a_o, Å	Max.I	a_o, Å	Max.I	Max.I	Max.I
0.075 (0.030)	Bare	H,79	none		3.591	9	-	-	-	-	-	-
"	"	-8	982 (1800)	754	3.567	19	-	-	-	-	-	-
0.15 (0.060)	"	45	"	"	3.567	14	-	-	-	-	-	-
"	"	B,3	1093 (2000)	229	3.568	9	-	-	-	-	-	-
0.075 (0.030)	Codep B-1	M	none		-	-	2.887	46	-	-	3/4	-
" *	"	9	"		-	-		28	-	-	3/4	-
0.11 (0.045)	"	W	"		-	-		60	-	-	1-1/2	-
0.15 (0.060)	"	30	"		-	-		45	-	-	1-1/4	-
0.075 (0.030)	"	32	982 (1800)	989	3.587	4	2.872	25	-	-	1	-
0.15 (0.060)	"	73	"	"	3.591	5	2.872	30	-	-	1-3/4	-
0.075 (0.030)	"	8	1093 (2000)	487	3.593	2	2.870	13	-	-	1-1/4	-
0.15 (0.060)	"	24	"	"	3.584	14	2.872	12	-	-	1-1/2	-
0.075 (0.030)	CoCrAlY	22	none		3.574	9	-	-	2.869	9	-	1
0.15 (0.060)	"	33	"		3.566	18	-	-	2.866	12	-	1/2
"	"	21,106	1093 (2000)	532	3.592	8	-	-	-	-	2-1/4**	-

All diffraction patterns run on goniometer at same nominal conditions: Co radiation, Fe filter, 40 kv, 10 ma.

Bare specimens only belt sanded to remove surface oxides.

Each side of each sample run separately and results averaged.

Max. I is the peak height of the strongest diffraction line of each phase.

* Leading edge specimen; all others flat.

** Larger parameter than normal.

Table XVII Chemical Analyses After Exposures

Specimen Surface	Exposure Conditions	Thickness cm (inch)	Spec. No.	Composition, weight %							Spec. No.
				Al	Ti	Cr	Co	Mo	W	C	
Bare	None	0.075 (0.030)	30	3.10	4.98	14.05	9.55	4.05	3.95	0.160	84
"	"	0.15 (0.060)	16	3.15	4.98	14.05	9.49	4.05	4.00	0.155	114
"	754 hrs @ 982C (1800F)	0.075 (0.030)	72	2.90	4.50	14.00	9.47	4.30	4.15	0.221	D
"	758 hrs @ 982C (1800F)	0.15 (0.060)	22	3.05	4.80	13.85	9.47	4.20	4.05	0.215	92
"	168 hrs @ 1093C (2000F)	0.075 (0.030)	33	3.00	4.60	13.60	9.49	4.20	4.15	0.118	58
"	"	0.15 (0.060)	73	3.04	4.70	13.70	9.35	4.05	4.05	0.120	10
Codep B-1	None	0.075 (0.030)	-3	3.10	5.00	14.15	9.55	4.00	4.10	0.127	?-1
"	"	0.15 (0.060)	9-1	3.30	5.00	14.05	9.50	4.00	4.00	0.164	100
"	989 hrs @ 982C (1800F)	0.075 (0.030)	5	3.35	4.95	14.00	9.55	4.00	3.95	0.150	32
"	949 hrs @ 982C (1800F)	0.15 (0.060)	72	3.20	5.00	14.05	9.50	4.00	3.95	0.130	40
"	487 hrs @ 1093C (2000F)	0.075 (0.030)	-10	3.34	5.00	14.20	9.50	4.05	4.00	0.140	27
"	532 hrs @ 1093C (2000F)	0.15 (0.060)	50	3.30	4.98	14.00	9.55	4.00	4.00	0.146	27

All specimens have had standard heat treatment, and are broken halves of R.T. or 760C (1400F) tensile bars.

Carbon analyses were run on different specimens from other elements (specimen numbers shown).

Table XVIII Surface Products of Hot Corrosion Tests

Surface Condition	Prior Exposure	Time in Test hrs	Spec. No.	Phases									
				NiO/CoO		Spinel		Al_2O_3	TiO_2	M_2O_3	Na_2SO_4		NiAl
				am't	a_o, Å	large	small	am't	am't	am't	am't	type	am't
Bare	None	473.5	G	s	4.181	w	-	-	-	vw	w	III	-
"	758 hrs @ 982C (1800F)	346	19	s	4.181	m	-	-	-	?	vw	III	-
"	1003 hrs @ 982C (1800F), stressed	473.5	20	m	4.182	wm	-	-	-	wm	-	-	-
"	229 hrs @ 1093C (2000F)	328	3-	s	4.177	wm	vw	-	-	vw	?	-	-
Codep B-1	None	435	C	m	4.181	?	vw	w	vw	vw	vw	III	vw
"	962 hrs @ 982C (1800F)	61	10	vw	-	vw	-	w	?	-	-	-	-
"	"	328	A	m	4.180	w	vw	w	vw	w	vw	III	vw
"	1000 hrs @ 982C (1800F), stressed	184	21	wm	4.177	wm	vw	wm	vw	vw	vw	III	?
"	532 hrs @ 1093C (2000F)	61	D	w	4.177	-	wm	w	vw	w	-	-	vw
CoCrAlY	None	473.5	10	-	-	wm	wm	w	vw	-	wm	III	?
"	962 hrs @ 982C (1800F)	435	?	w	4.175	w	?	vw	vw	-	vw	III	-
"	1000 hrs @ 982C (1800F), stressed	184	46	wm	4.254	vw	vw	wm	-	-	vw	Then.+	-
"	532 hrs @ 1093C (2000F)	184	106	?	4.24	?	w	m	vw	-	vw	III	-

See footnotes following page

Footnotes to Table XVIII

Phases: Pure NiO a_o = 4.177A, CoO a_o = 4.260A. Complete solubility exists, with intermediate compositions having intermediate lattice parameters.

Large parameter spinel (a_o = 8.30-8.32A in Bare and Codep B-1; 8.22-8.30A in CoCrAlY specimens) are $(Ni,Co)Cr_2O_4$ type, with varying small amounts of Al replacing Cr. Small parameter spinel (a_o = 8.10-8.13A) is $(Ni,Co)Al_2O_4$ type.

Al_2O_3 is α Al_2O_3; TiO_2 is rutile.

M_2O_3 is hexagonal structure with parameters between those of Cr_2O_3 and $Ni{\cdot}Ti{\cdot}O_3$.

Na_2SO_4 was generally form III, with one occurrence of thenardite+ possibly meta-thenardite.

s = strong, m = medium, w = weak, v = very

Table XIX Proposed Stress-Rupture Life Effects for Thin Cast Superalloy Sections

Specimen Thickness Cm (Inches)	Test Temperatures °C (°F)	Per Cent of Stress-Rupture Life of Unexposed Standard Size Bars					
		Unexposed		Exposed 982C (1800F)		Exposed 1093C (2000F)	
		Bare	Coated	Bare	Coated	Bare	Coated
0.075 (0.030)	760 (1400)	20	15	10	10	2	10
	982 (1800)	40	40	35	35	4	35
	1093 (2000)	50	50	50	50	15	50
0.15 (0.060)	760 (1400)	40	35	20	40	2	10
	982 (1800)	60	60	50	50	15	60
	1093 (2000)	60	60	60	60	35	60

These values represent an estimation of stress-rupture life for the type of specimens used with specimen alignment and test fixture errors removed.

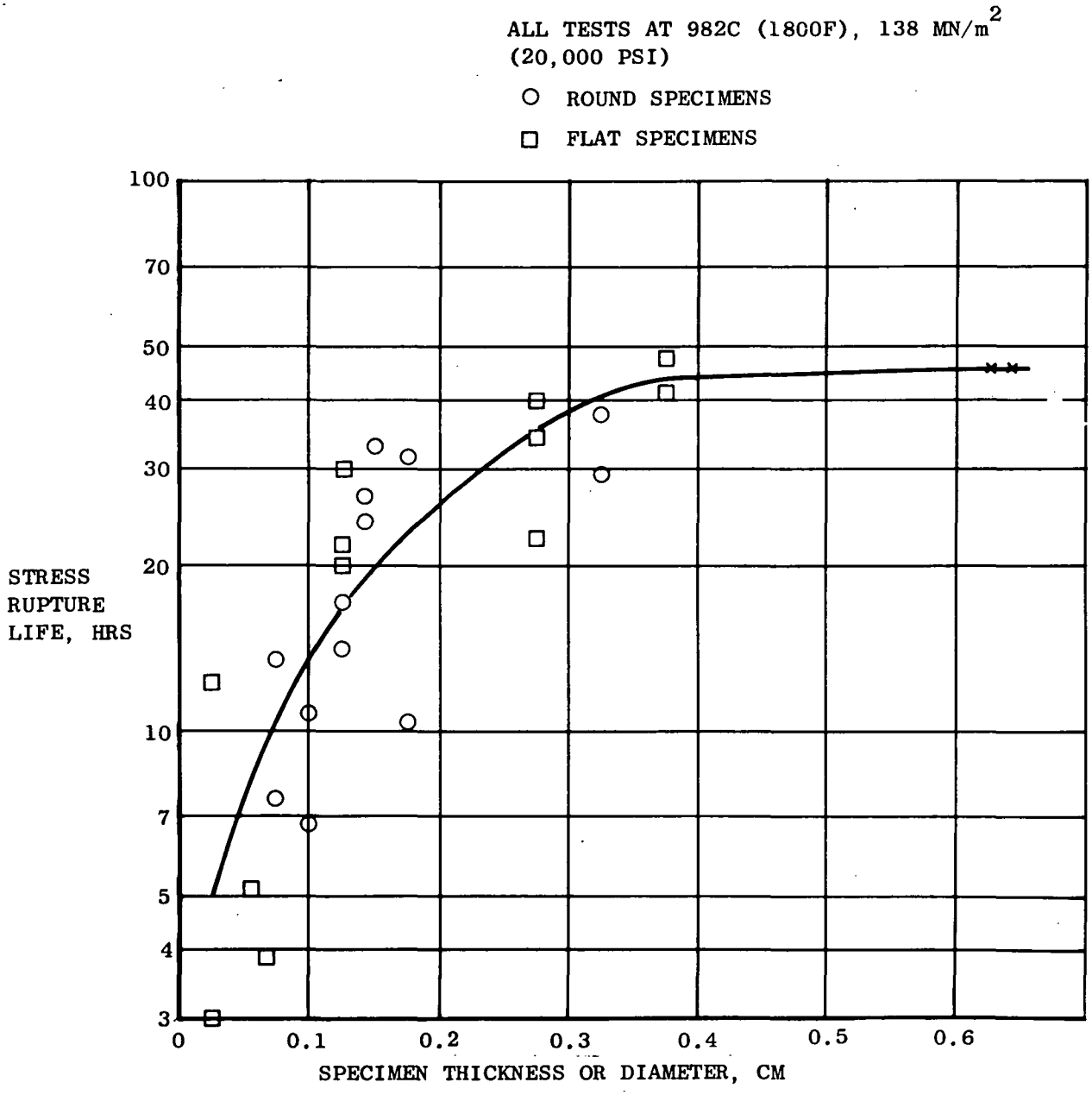


Figure 1 Effect of Section Size on the Stress Rupture Life of Wrought U700

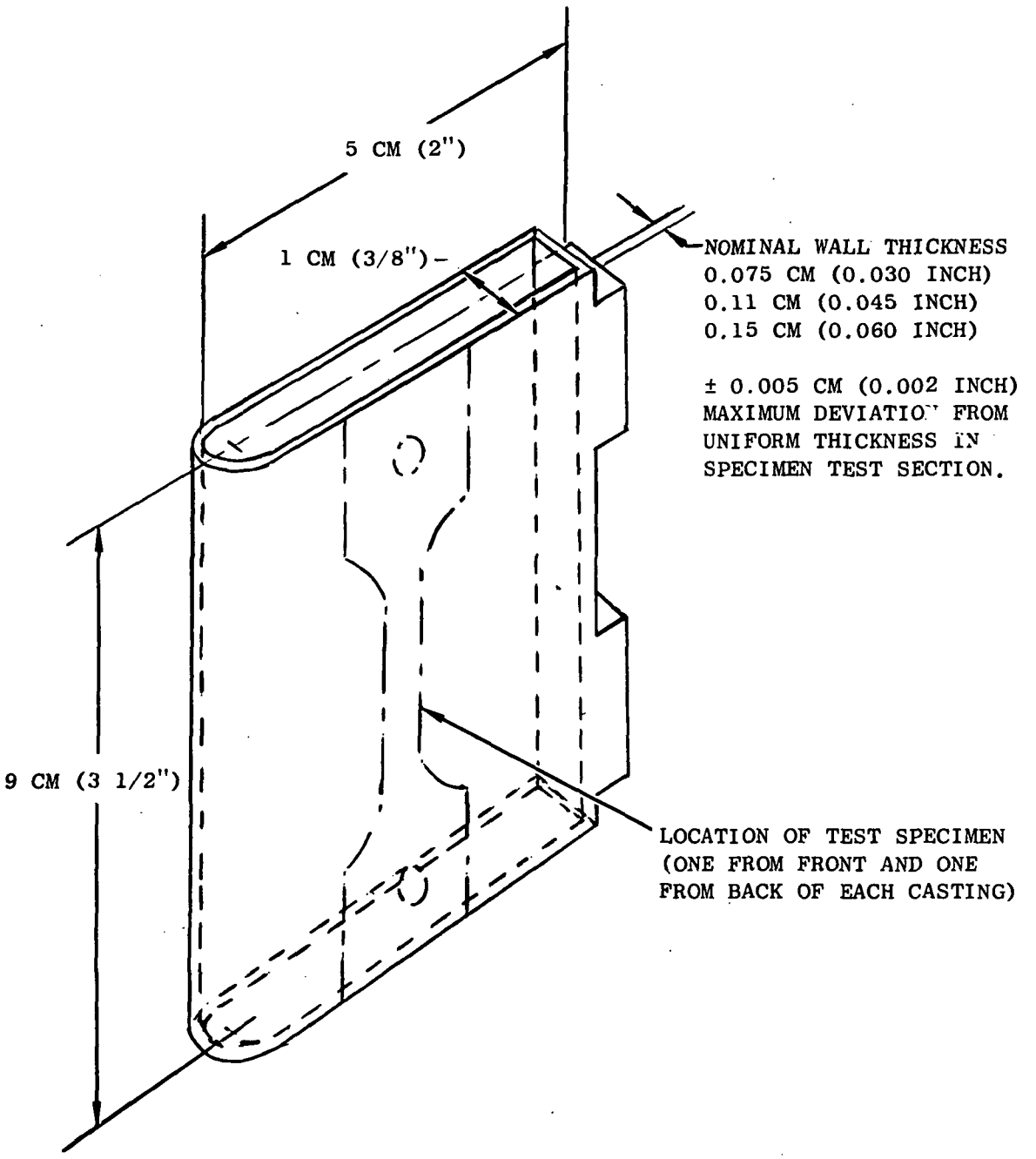
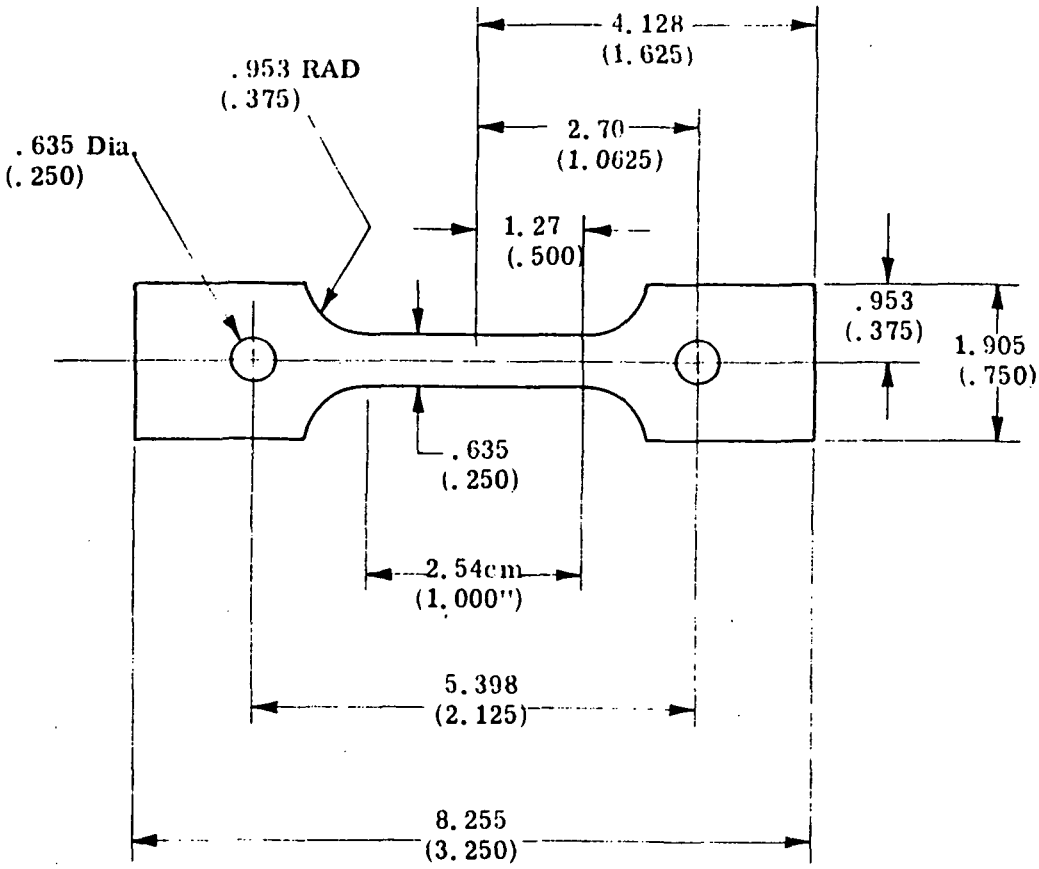


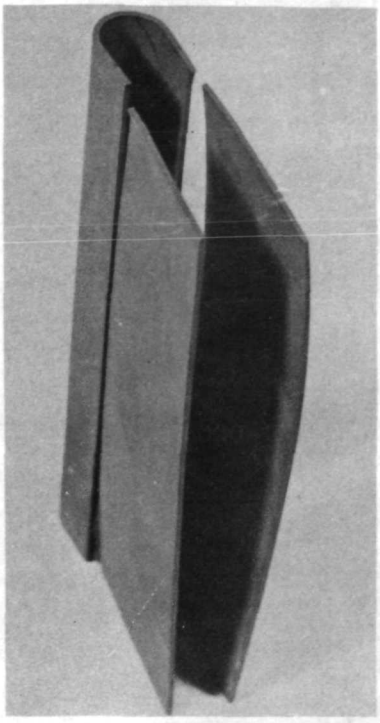
Figure 2 Thin Wall Cast Superalloy Specimen



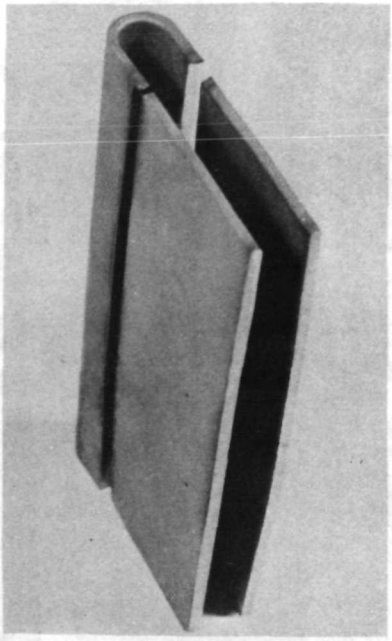
NOTES:

1. Radius & gage section to blend smoothly without undercuts.
2. Remove all burrs & sharp edges with .0481cm (.015") maximum radius.
3. Gage section to be concentric to center line of pin holes within .0051cm (.002").
4. Tolerence of gage section width to be ± .0025cm (.001").

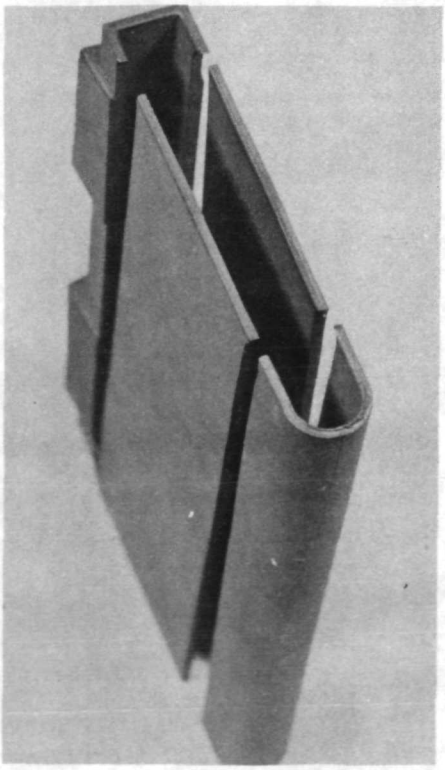
Figure 3 Mechanical Property Test Specimen



(A) 0.075 CM (0.030 INCH) WALL THICKNESS

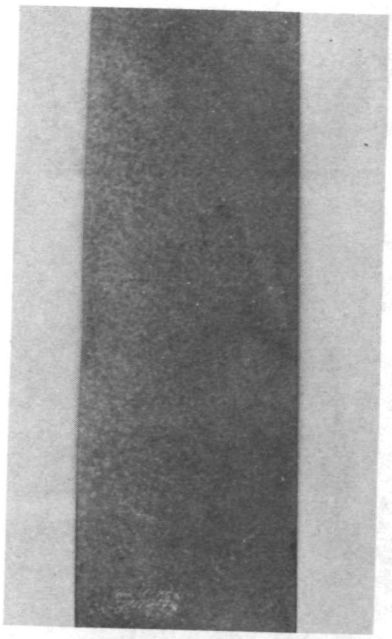


(B) 0.15 CM (0.060 INCH) WALL THICKNESS

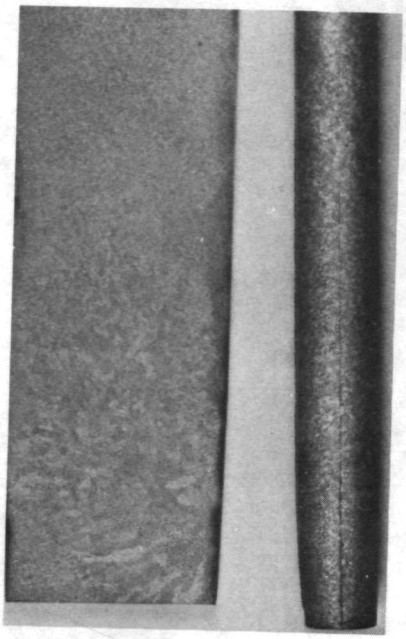


(C) 0.11 CM (0.045 INCH) WALL THICKNESS, WITH GATE SEGMENT

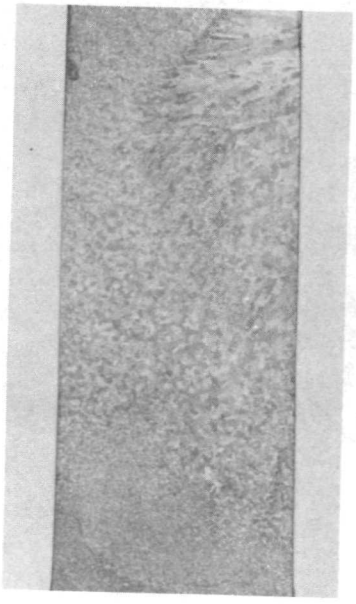
Figure 4 Sample Re-Constructed Castings



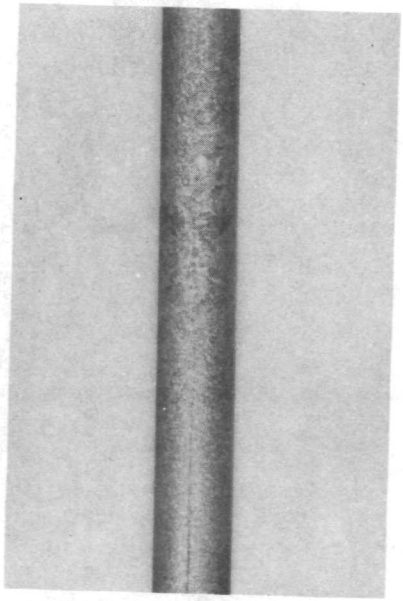
(A) 0.075 CM (0.030 INCH) WALL THICKNESS, FLAT SIDE



(B) 0.15 CM (0.060 INCH) WALL THICKNESS, FLAT SIDE & ROUNDED NOSE

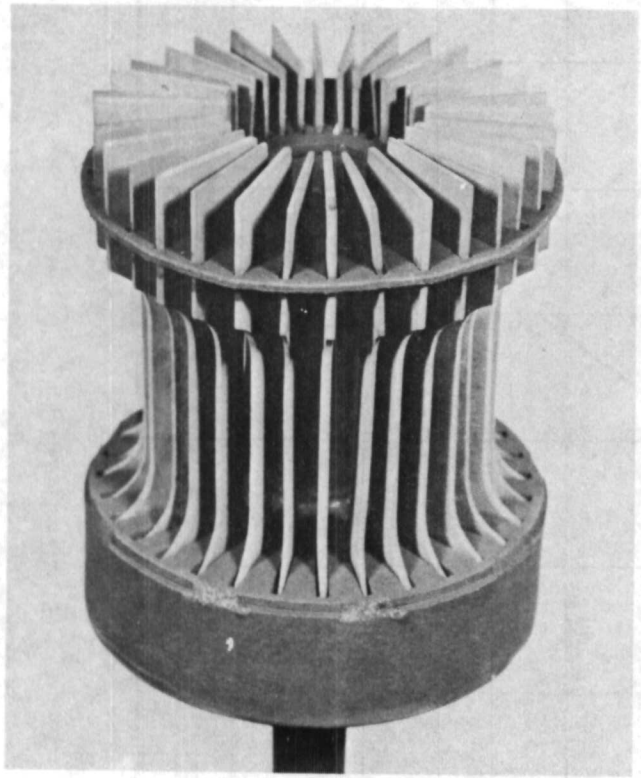


(C) 0.11 CM (0.045 INCH) WALL THICKNESS, FLAT SIDE

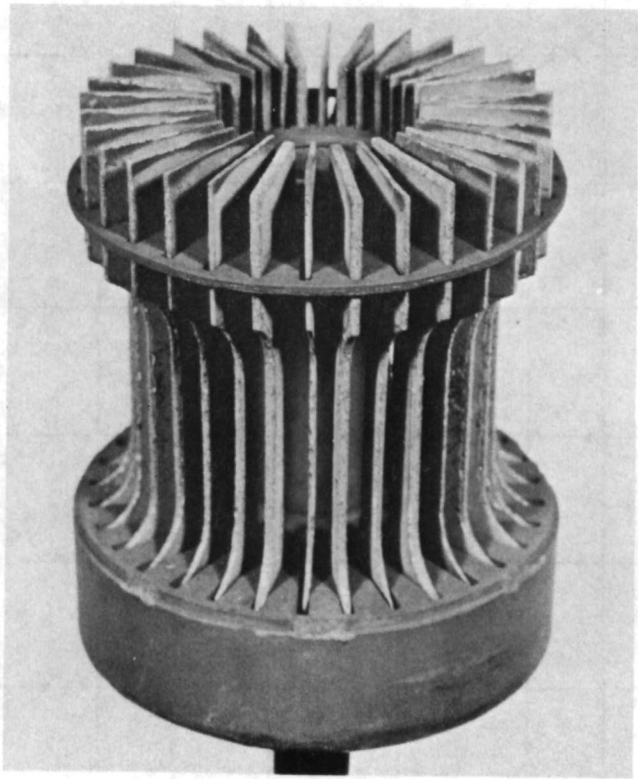


(D) 0.11 CM (0.045 INCH) WALL THICKNESS, ROUNDED NOSE

Figure 5 Macro-Etched Surfaces of Castings



(A) CODEP B-1 COATED SPECIMENS



(B) BARE SPECIMENS

Figure 6 Burner Rig Exposure Fixtures, 1093C (2000F) ~ 150 Hours

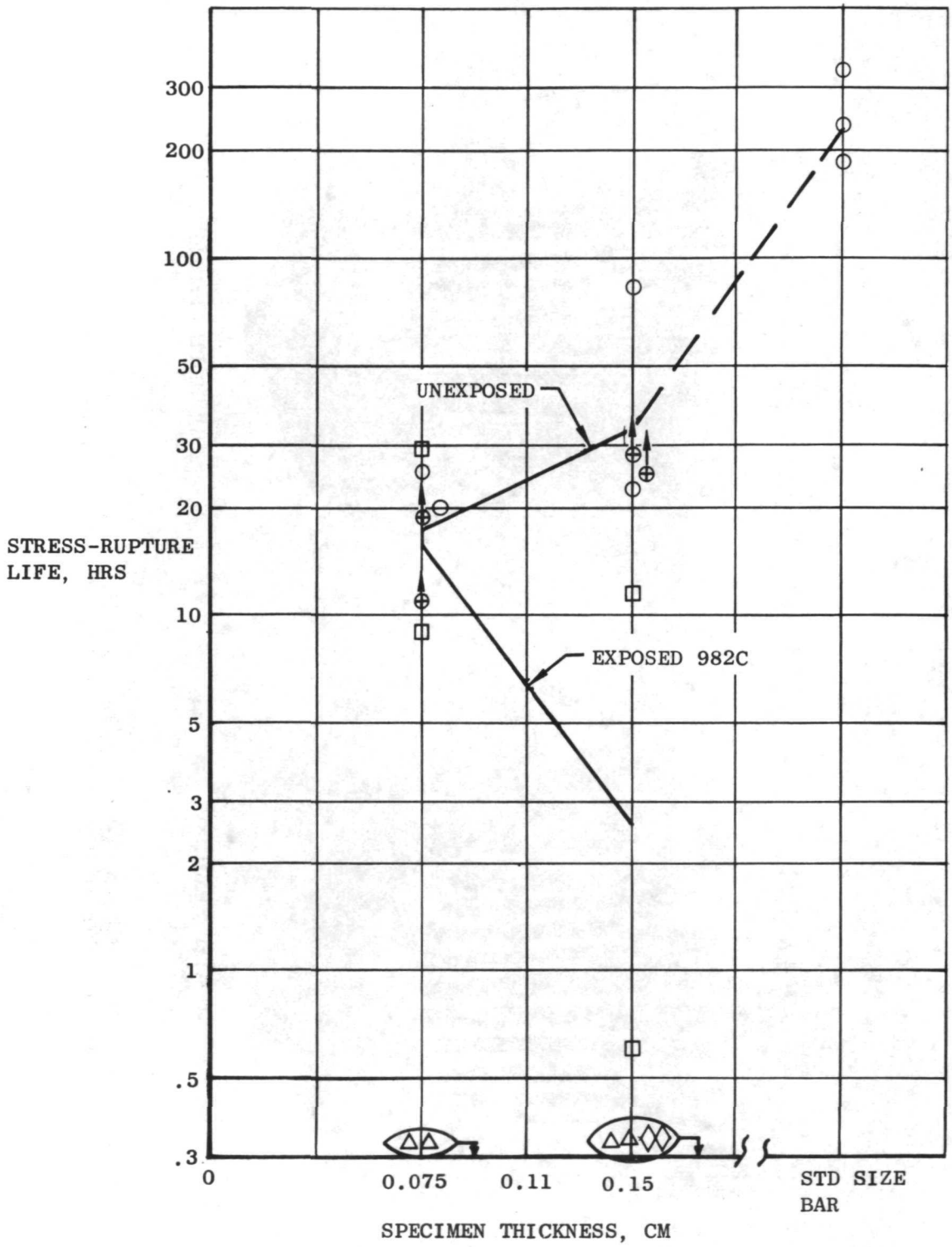


Figure 7 Effect of Size on Stress - Rupture Life of Bare Rene 80 at 760C (1400F), 565 MN/m^2 (82 KSI)

Legend for Figures 7 to 15

○ Unexposed

□ Exposed at 982C (1800F), 754 hours for Bare Rene 80
" " " " , 988 " " Codep B-1 Coated Rene 80
" " " " , 990 " " CoCrAlY " " "

◇ Exposed at 982C (1800F), stressed, 1000 to 1003.5 hours

△ Exposed at 1093C (2000F), 168 or 224 hours for Bare Rene 80
" " " " , 487 hours for Codep B-1 Coated Rene 80
" " " " , 375 " " CoCrAlY " " "

\+ Indicates life extrapolated from higher test stress

↑ Specimen poorly gripped in fixture, probably would have had greater life if properly gripped

↓ Specimen failed on loading

Note: All coated specimen lives extrapolated to stress based on before-coating metal thickness.

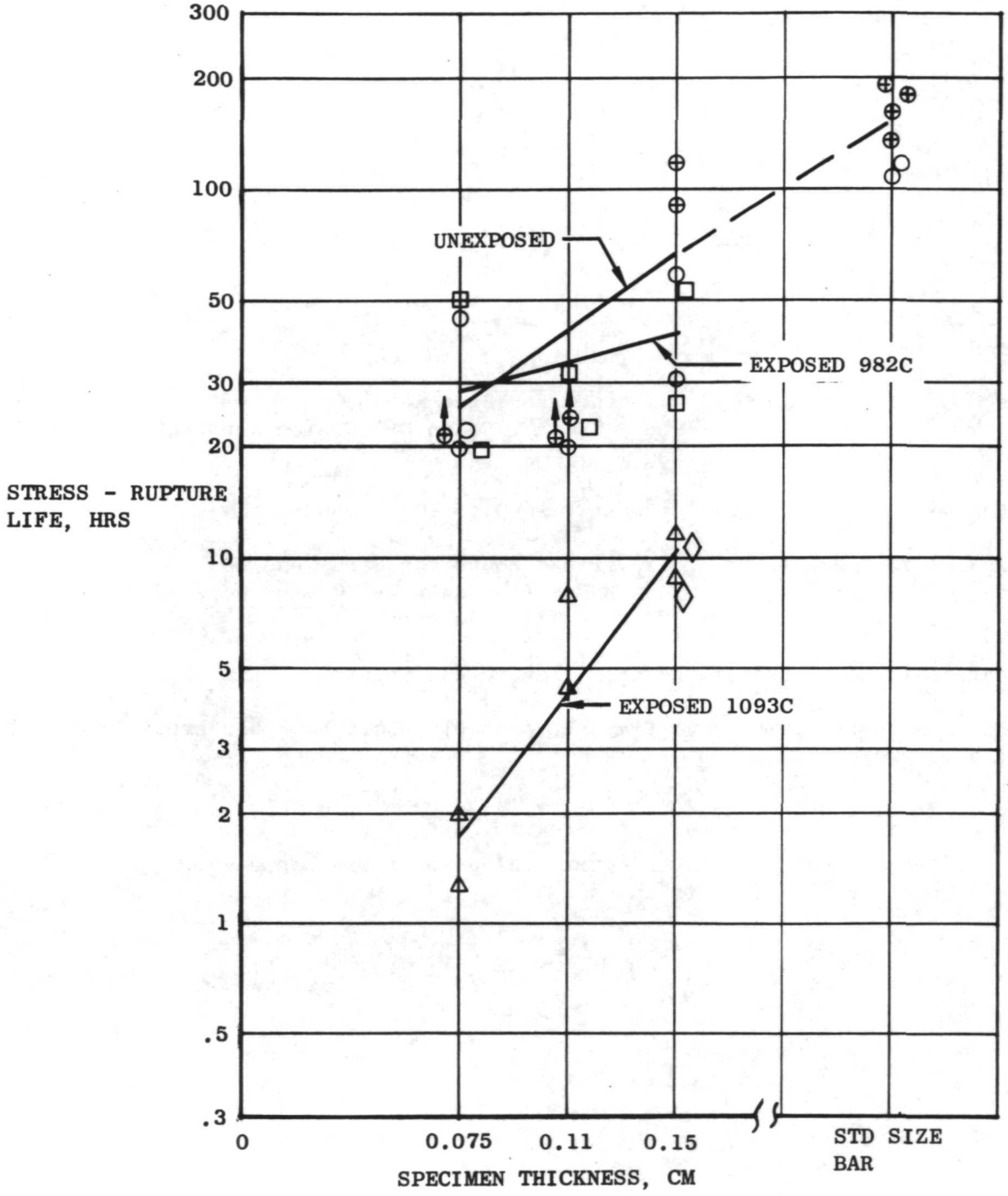


Figure 8 Effect of Size on Stress - Rupture Life of Bare Rene 80 at 982C (1800F), 144 MN/m^2 (21 KSI)

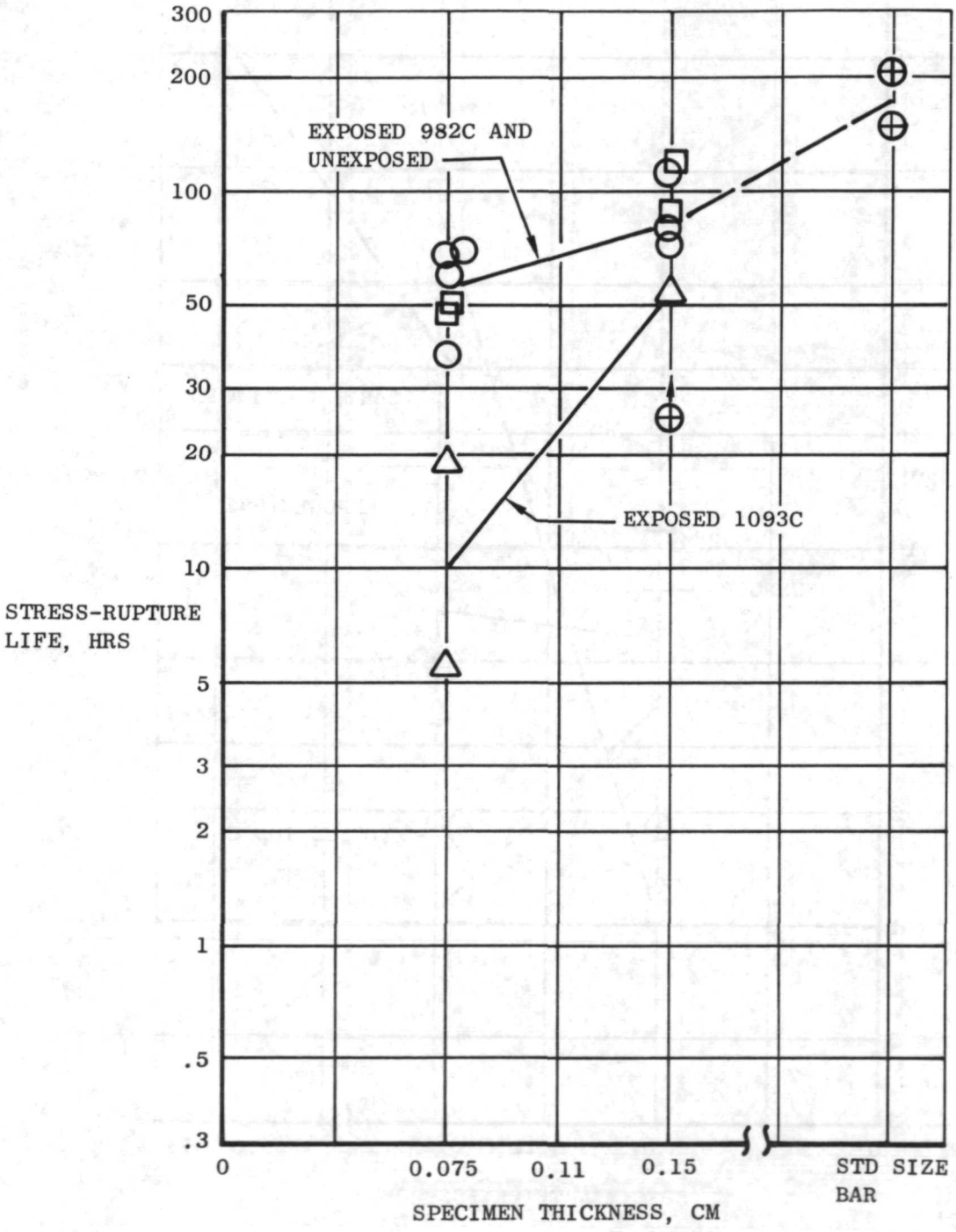


Figure 9 Effect of Size on Stress-Rupture Life of Bare Rene 80 at 1093C (2000F), 34.5 MN/m^2 (5KSI)

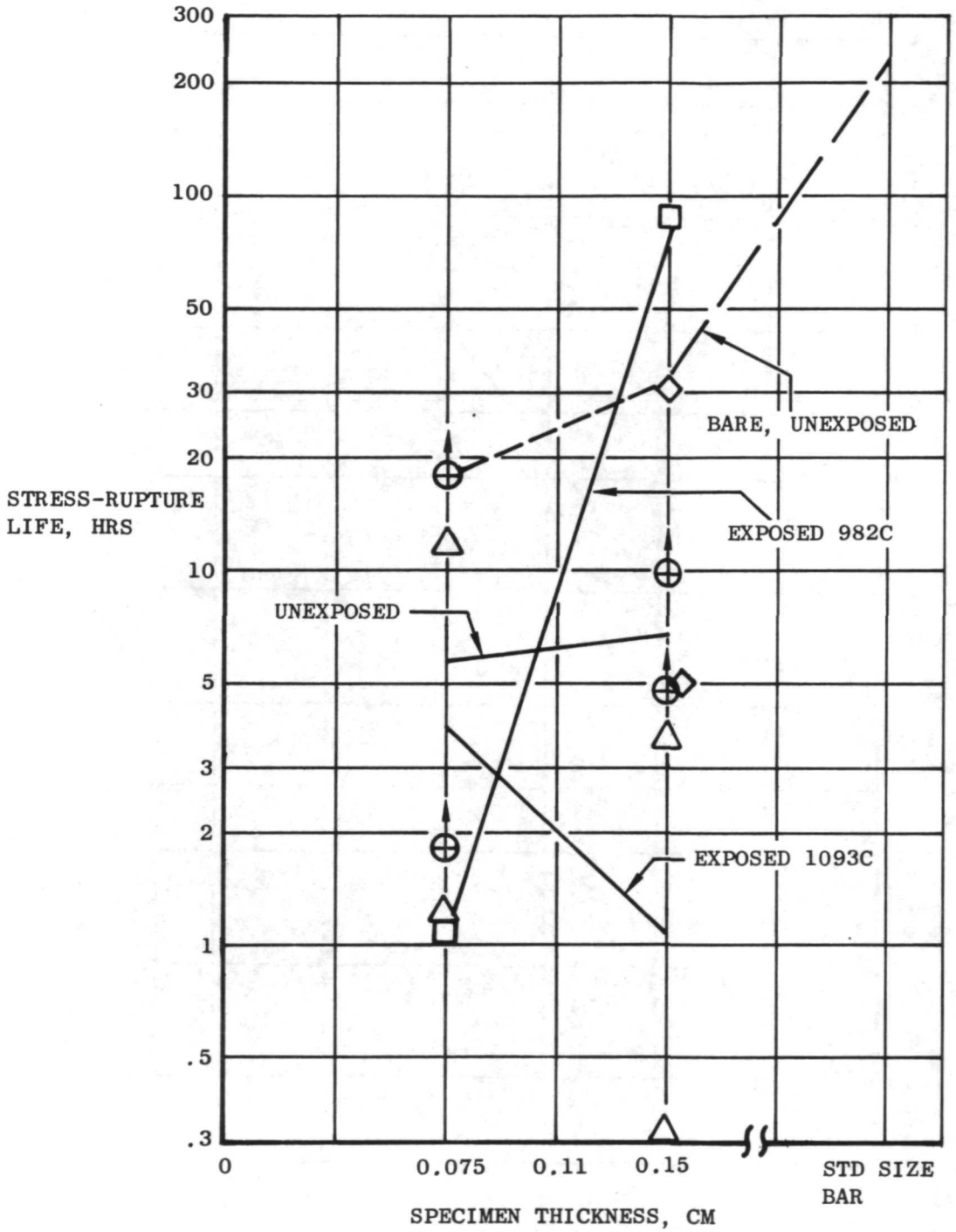


Figure 10 Effect of Size on Stress-Rupture Life of Codep B-1 Coated Rene 80 at 760C (1400F), Corrected to 565 MN/m^2 (82 KSI)

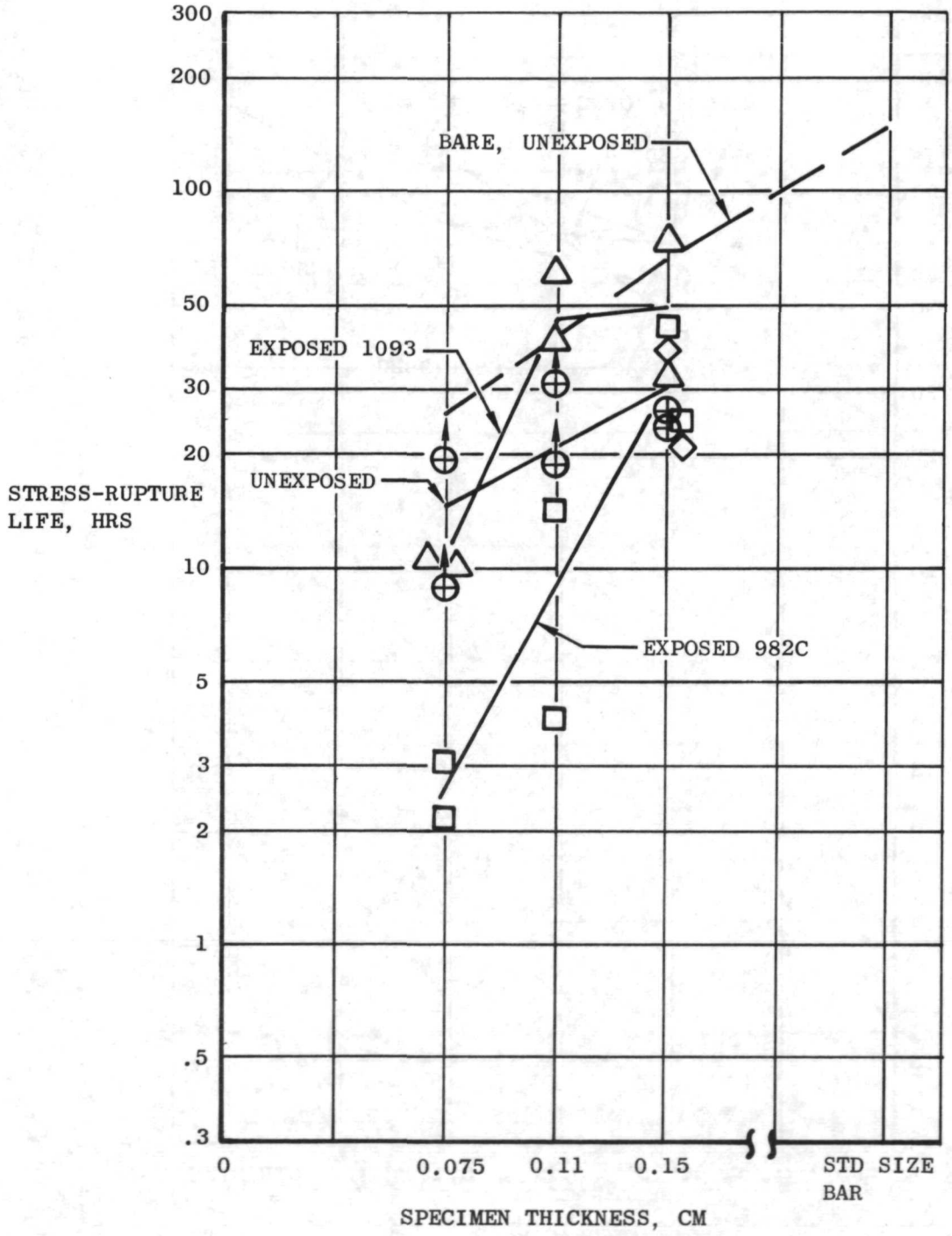


Figure 11 Effect of Size on Stress-Rupture Life of Codep B-1 Coated Rene 80 at 982C (1800F), Corrected to 144 MN/m^2 (21 KSI)

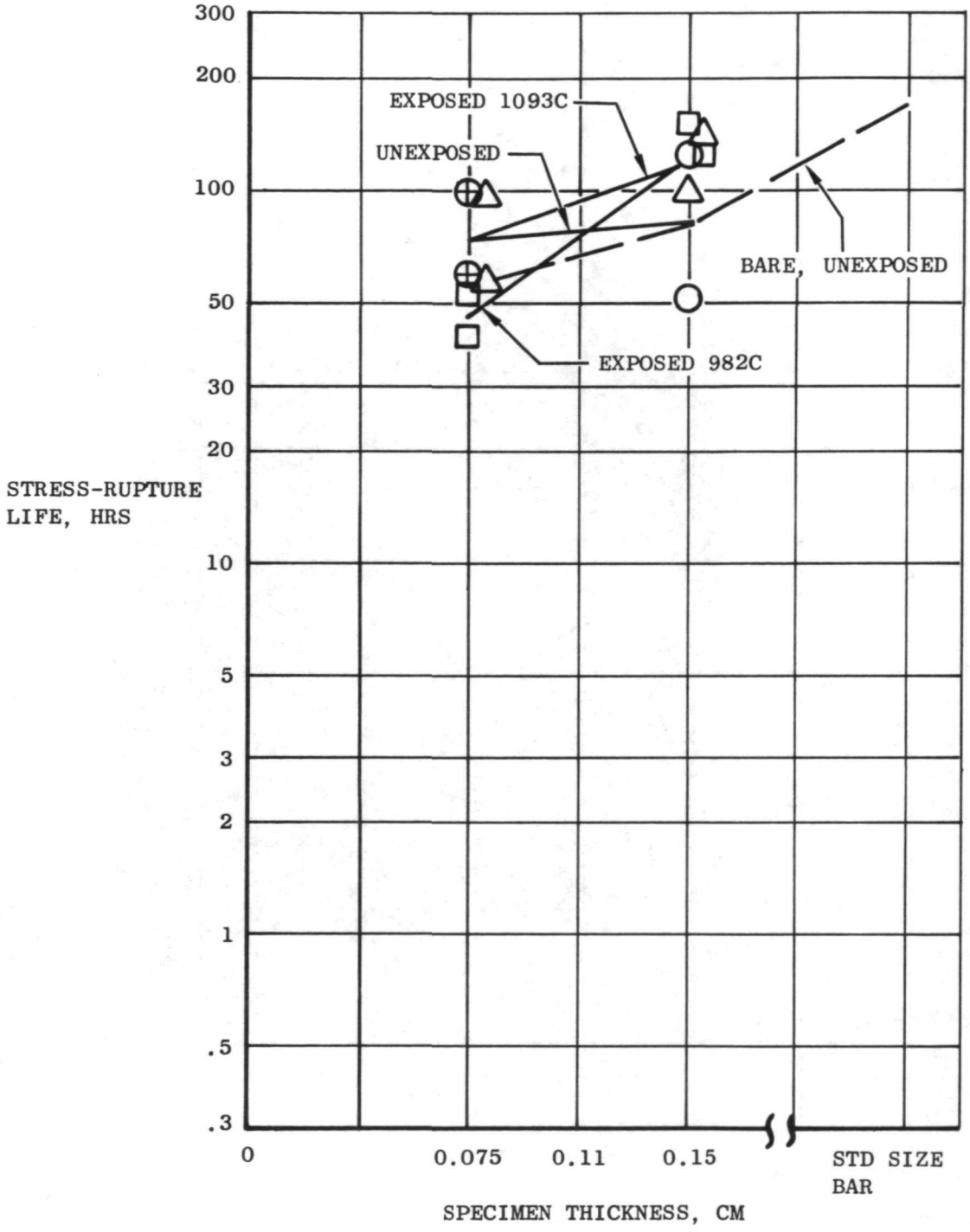


Figure 12 Effect of Size on Stress-Rupture Life of Codep B-1 Coated Rene 80 at 1093C (2000F), Corrected to 34.5 MN/m^2 (5 KSI)

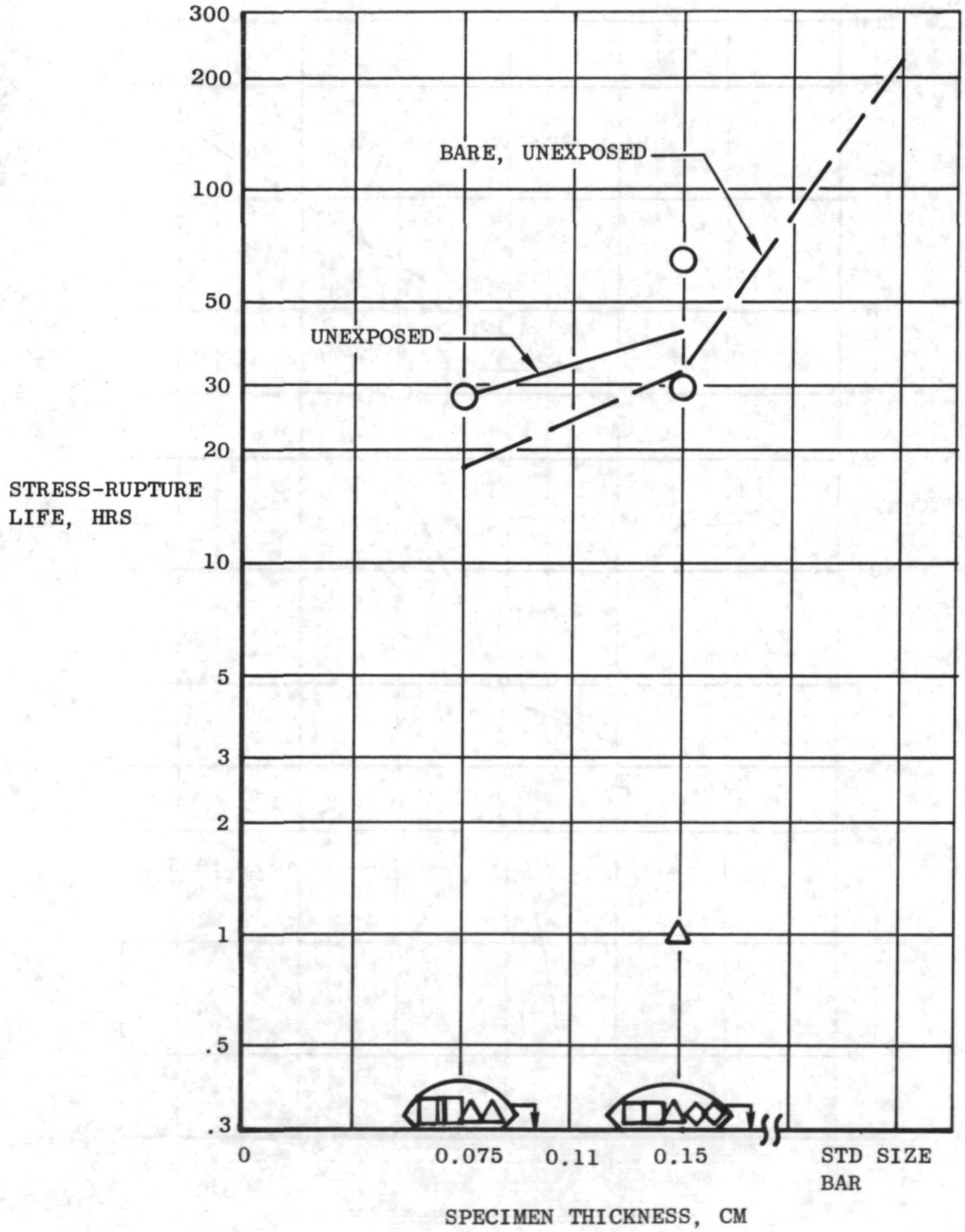


Figure 13 Effect of Size on Stress-Rupture Life of CoCrAlY Coated Rene 80 at 760C (1400), Corrected to 565 MN/m^2 (82 KSI)

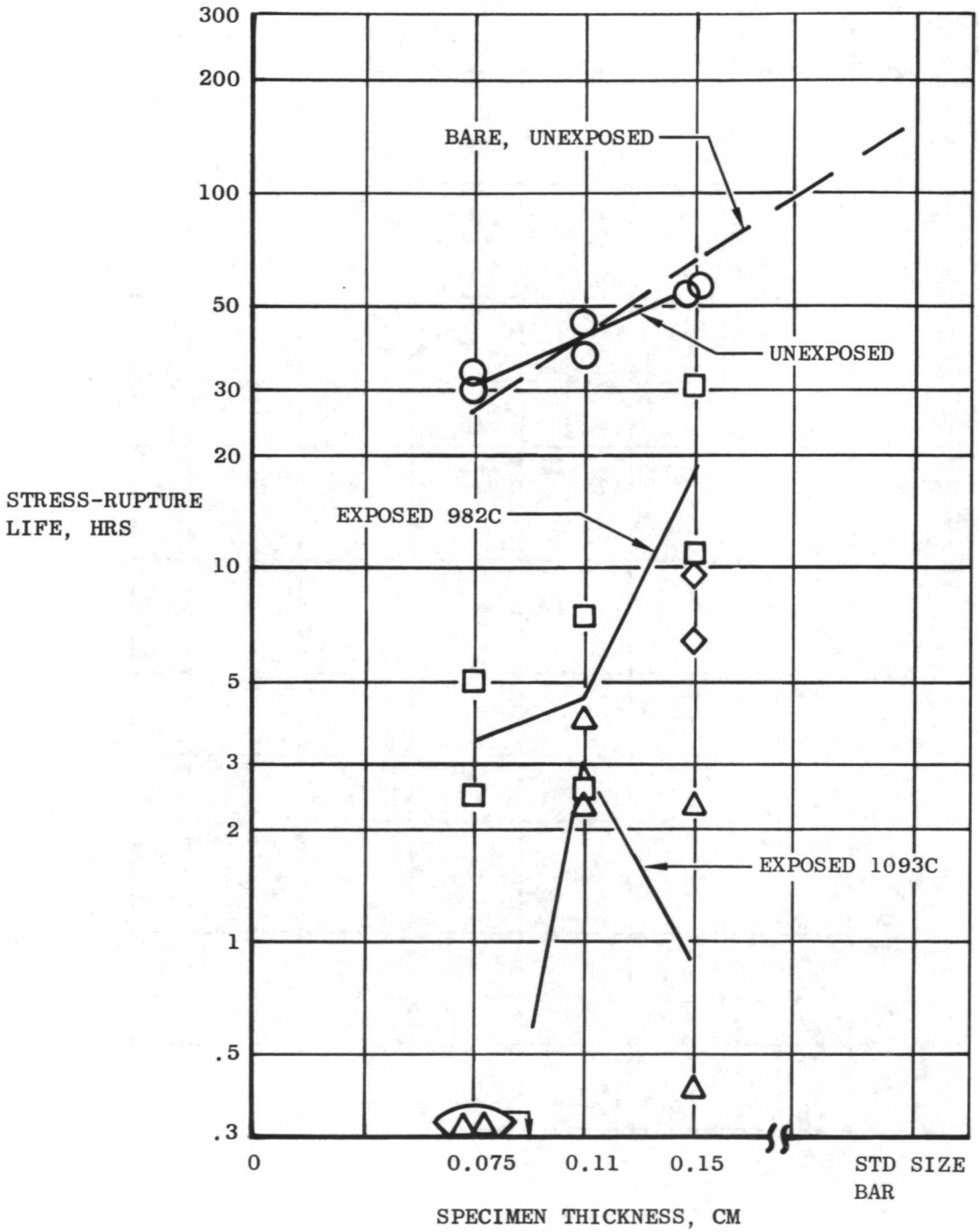


Figure 14 Effect of Size on Stress-Rupture Life of CoCrAlY Coated Rene 80 at 982C (1800F), Corrected to 144 MN/m^2 (21 KSI)

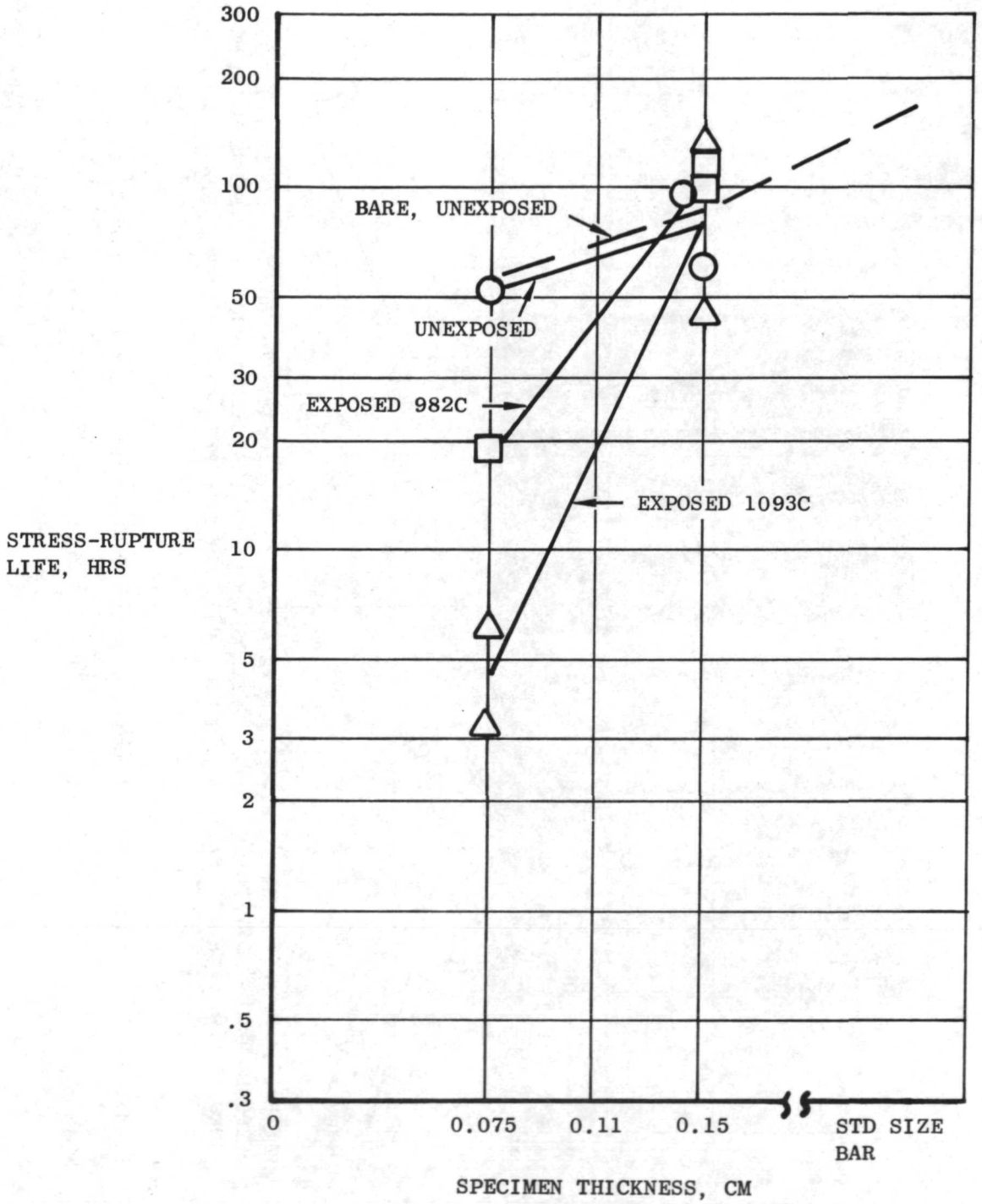
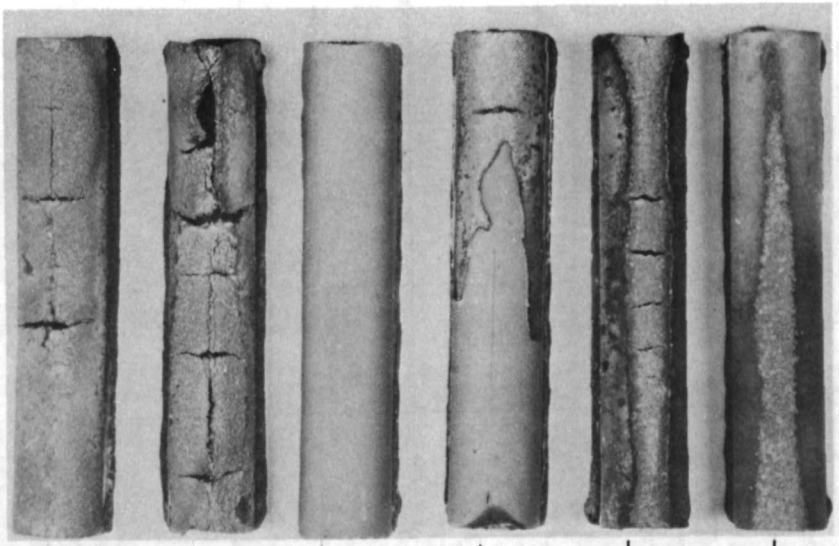


Figure 15 Effect of Size on Stress-Rupture Life of CoCrAlY Coated Rene 80 at 1093C (2000F), Corrected to 34.5 MN/m^2 (5 KSI)



BARE
UNEXPOSED
SPEC. #D

BARE
EXPOSED 982C
SPEC. #45

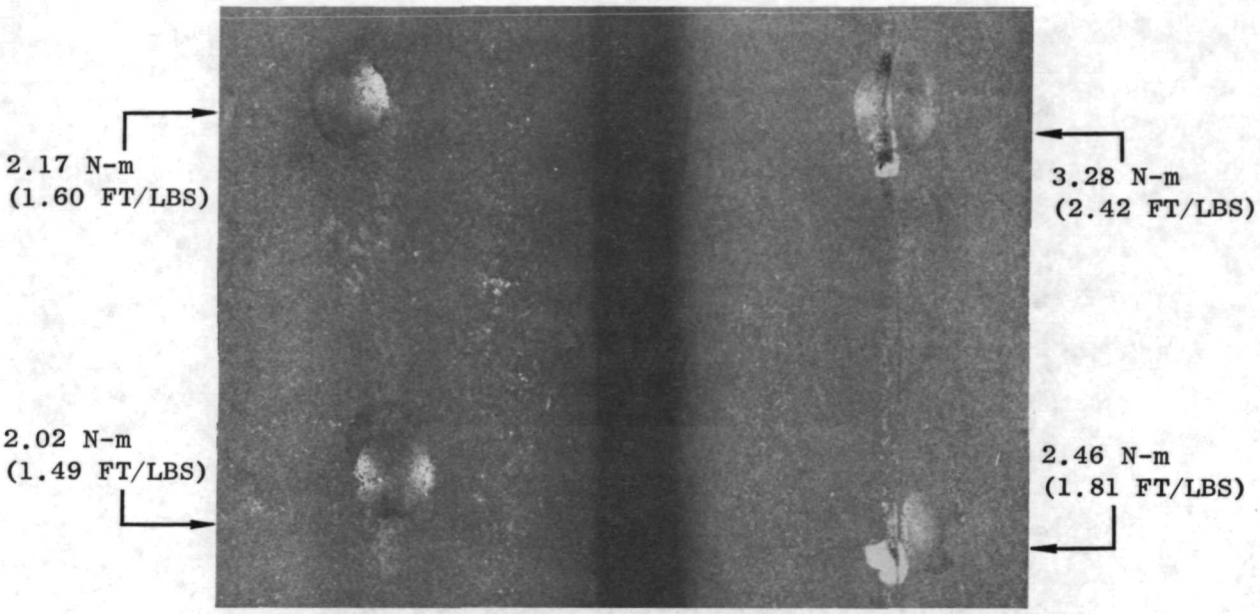
CoCrAlY Coated
UNEXPOSED
SPEC. #A

CoCrAlY COATED
UNEXPOSED
SPEC. #55

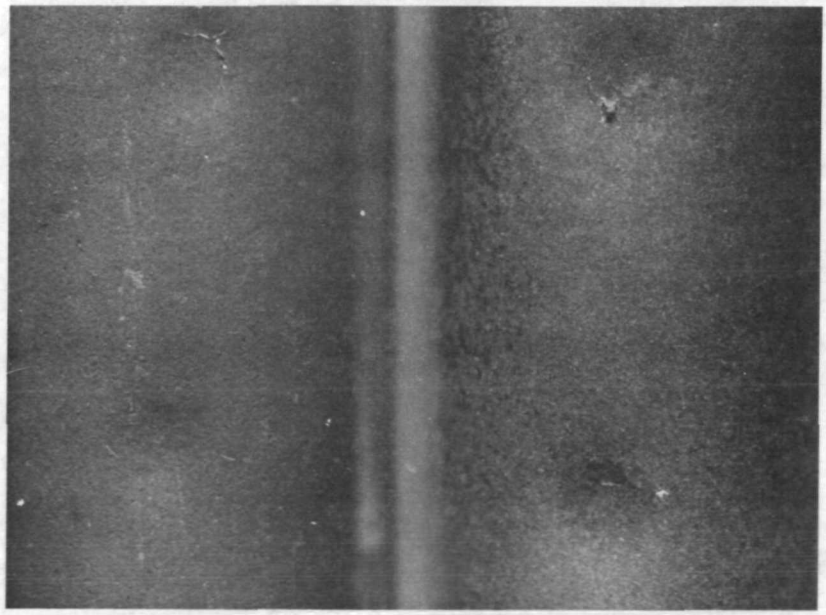
CoCrAlY COATED
EXPOSED 1093C
SPEC. #K

CODEP B-1 COATED
EXPOSED 1093C
SPEC. #M

Figure 16 Thermal Fatigue Specimens After 4000 Cycles, Magnification 1.25X

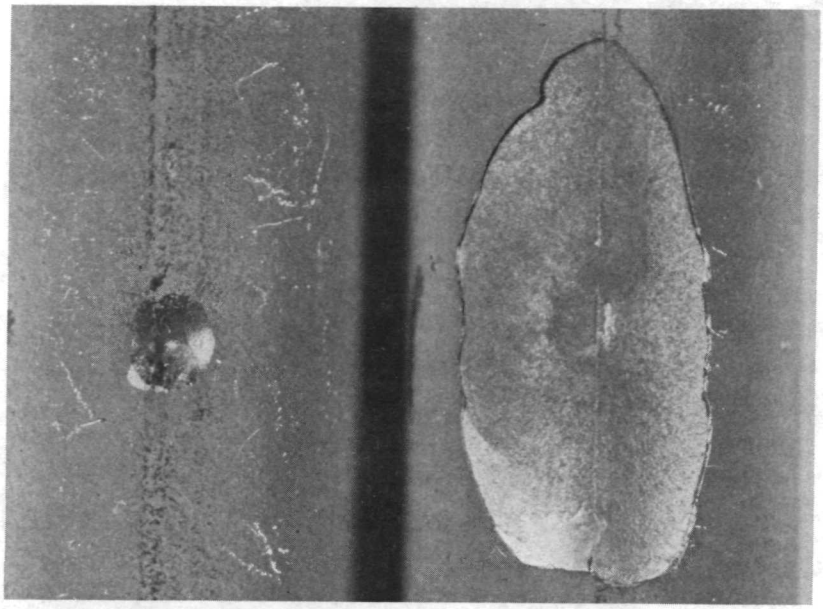


(A) BARE, SPEC #74 CODEP B-1, SPEC. #M
SPECIMEN FRONT



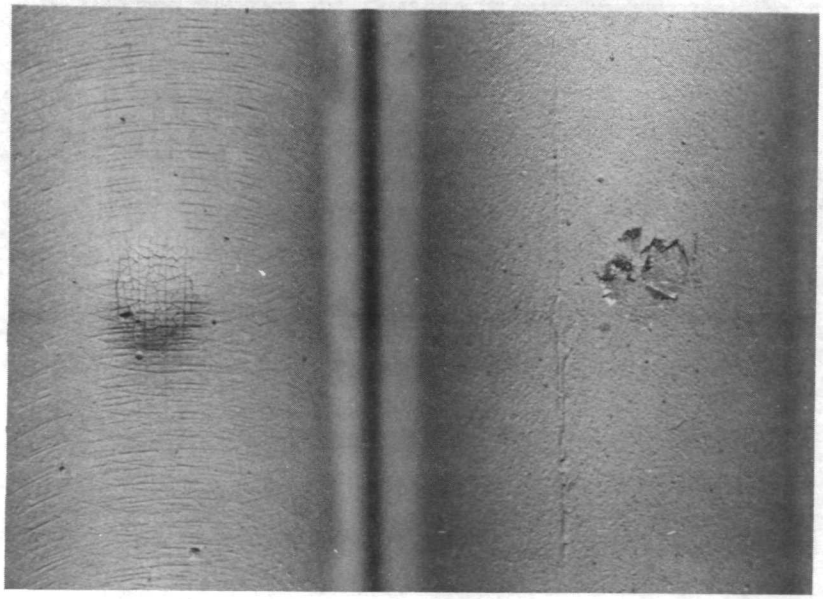
(B) SAME SPECIMENS
SPECIMEN BACK

Figure 17 Room Temperature Ballistic Impact Test, Unexposed, Mag. 5.5X



(A) SPEC. #8, 2.70 N-m (1.98 FT/LBS) SPEC. #3, 0.65 N-m (0.48 FT/LBS)

SPECIMEN FRONT



(B) SAME SPECIMENS

SPECIMEN BACK

Figure 18 Room Temperature Ballistic Impact Test CoCrAlY Coated Specimens, Unexposed, Mag. 5.5X

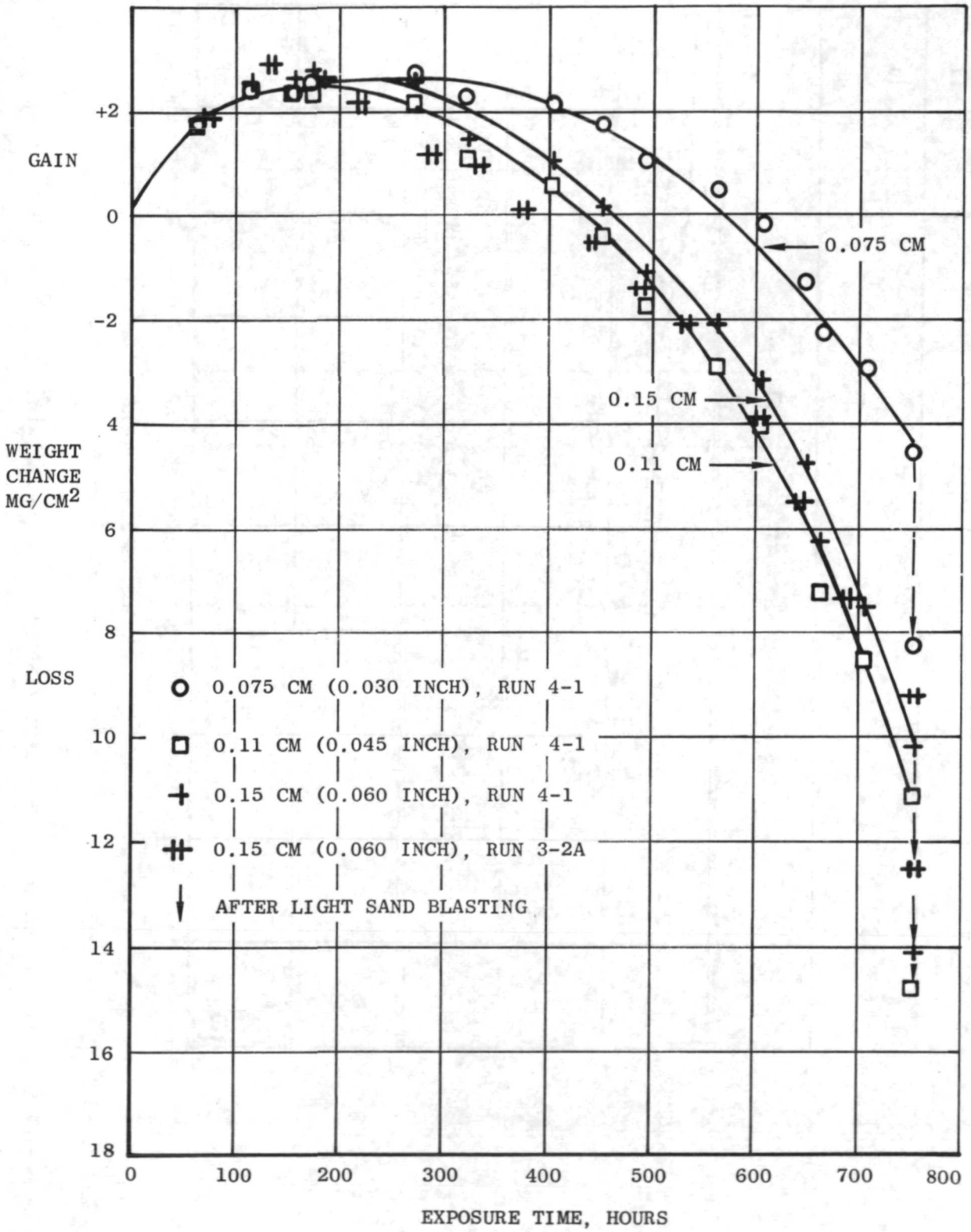


Figure 19 Weight Changes During 982C (1800F) Exposure in Burner Rig (Bare)

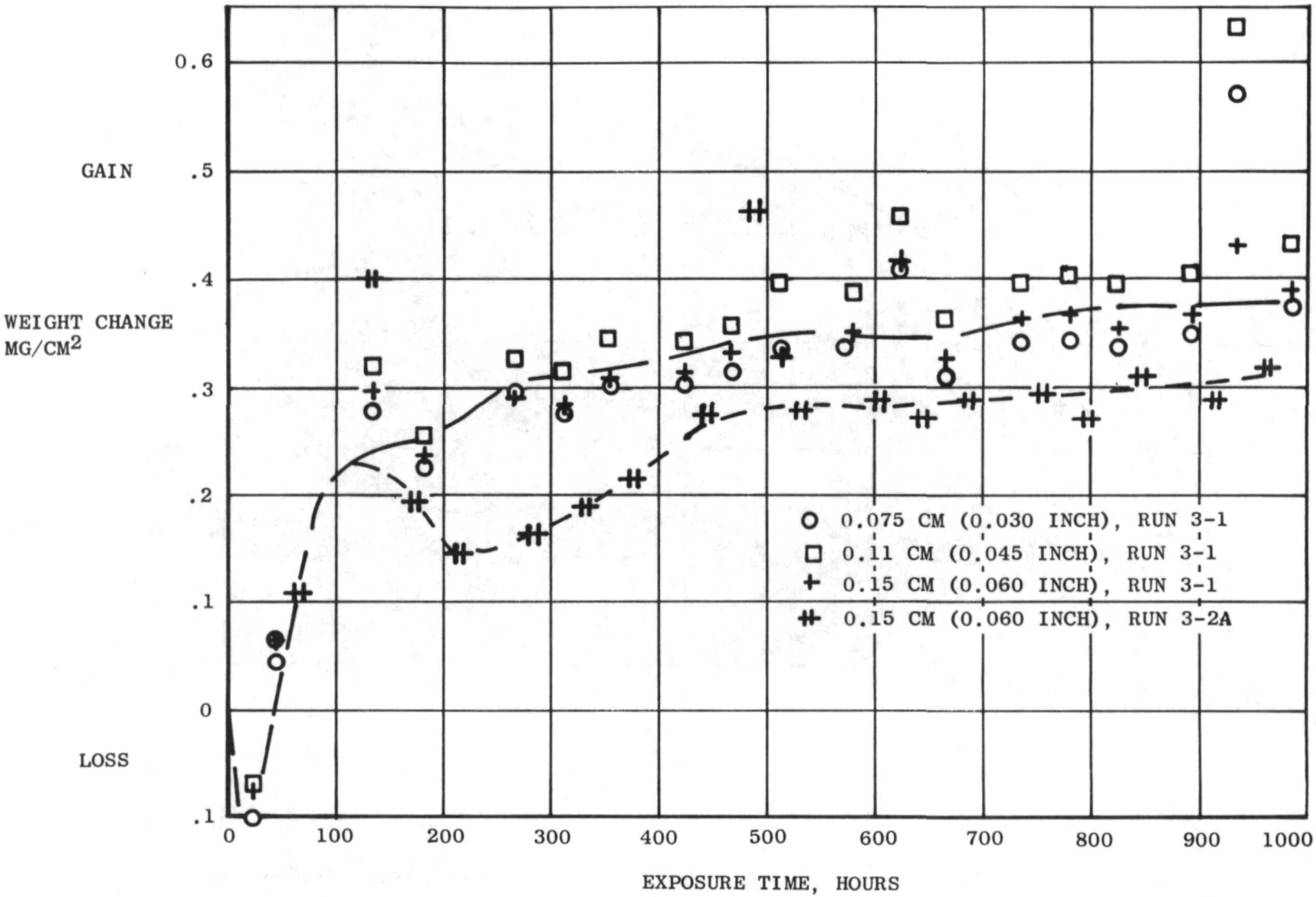


Figure 20 Weight Changes During 982C (1800F) Exposure in Burner Rig (Codep B-1 Coated)

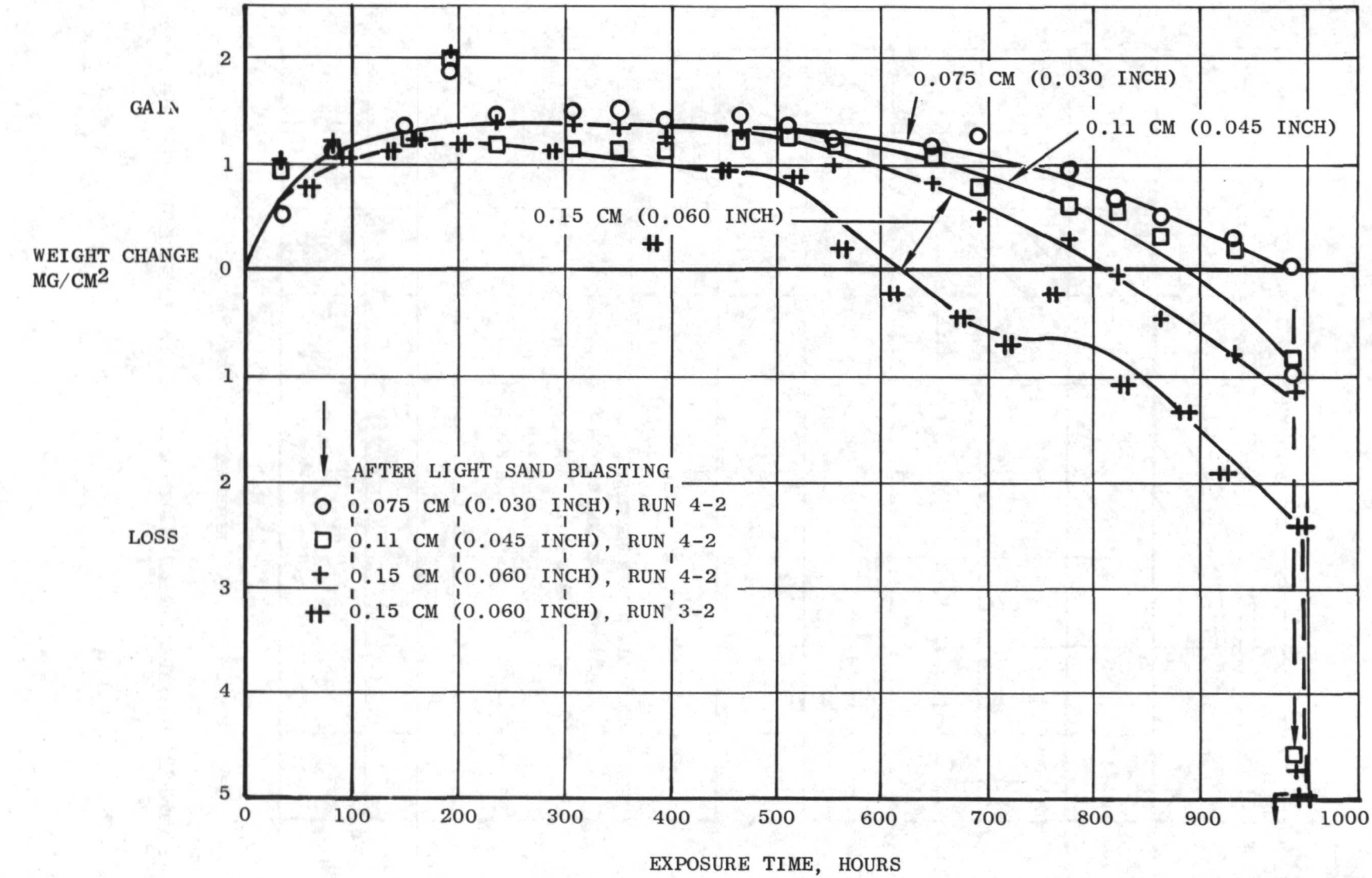


Figure 21 Weight Changes During 982C (1800F) Exposure in Burner Rig (CoCrAlY)

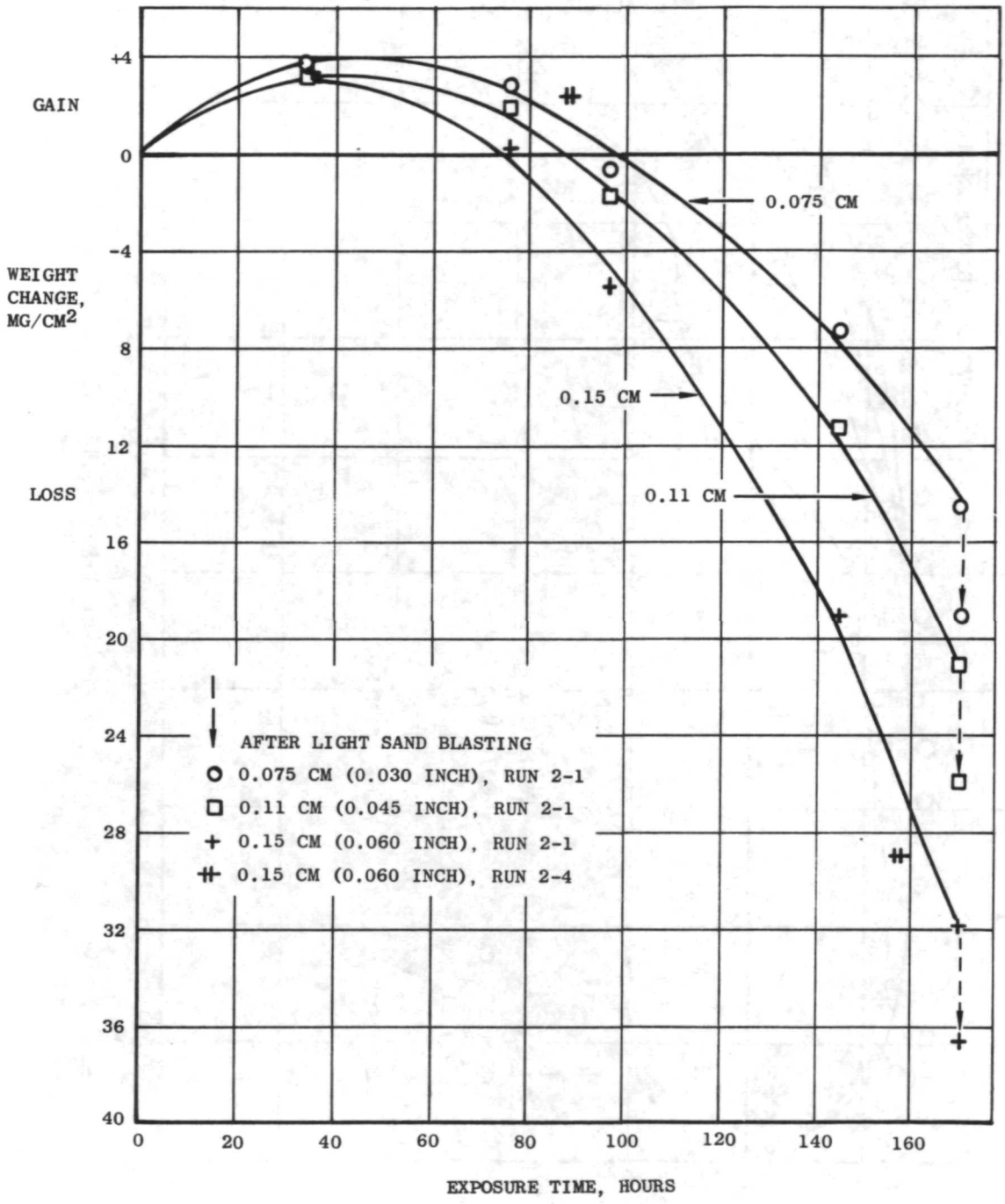


Figure 22 Weight Changes During 1093C (2000F) Exposure in Burner Rig (Bare)

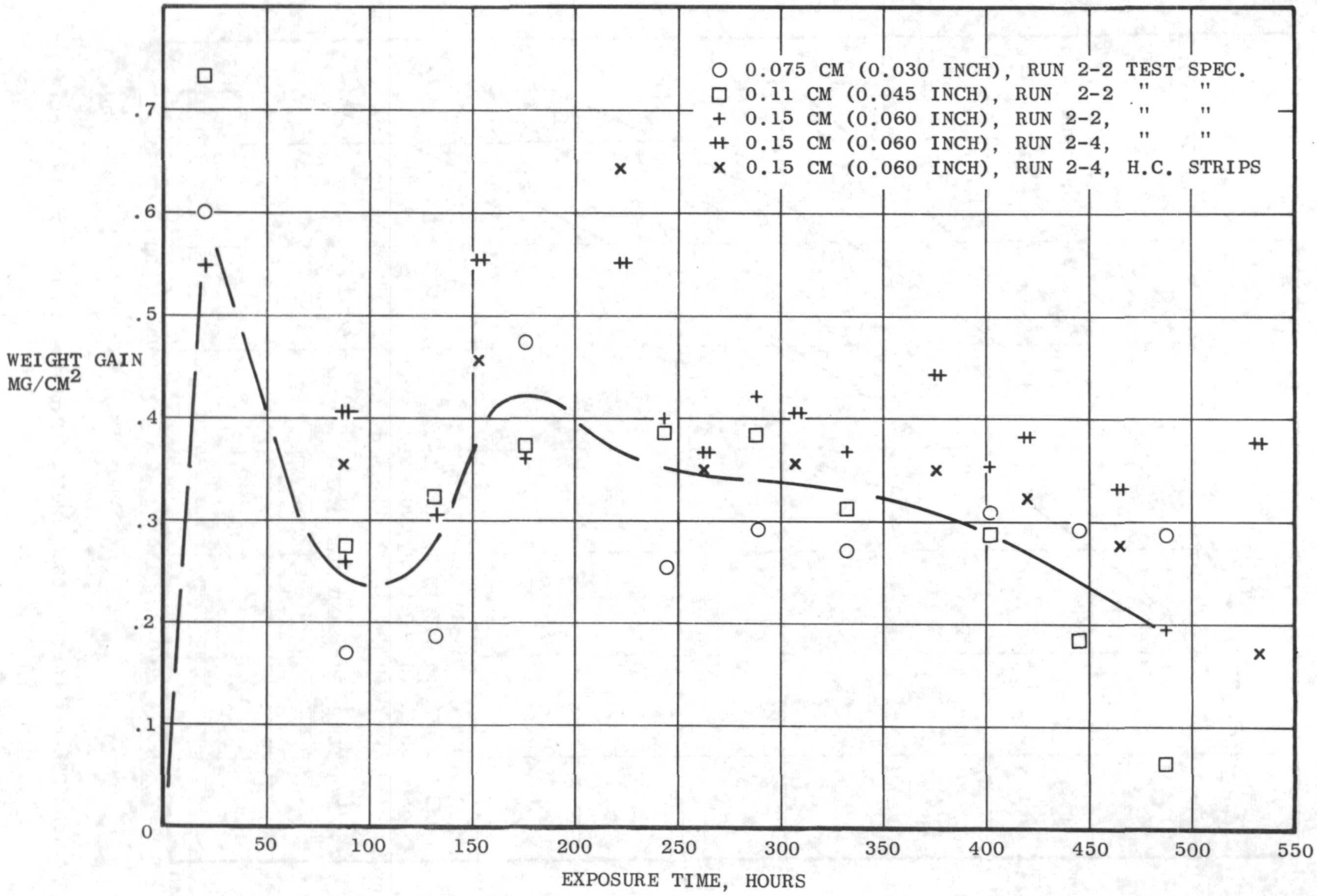


Figure 23 Weight Changes During 1093C (2000F) Exposure in Burner Rig (Codep B-1 Coated)

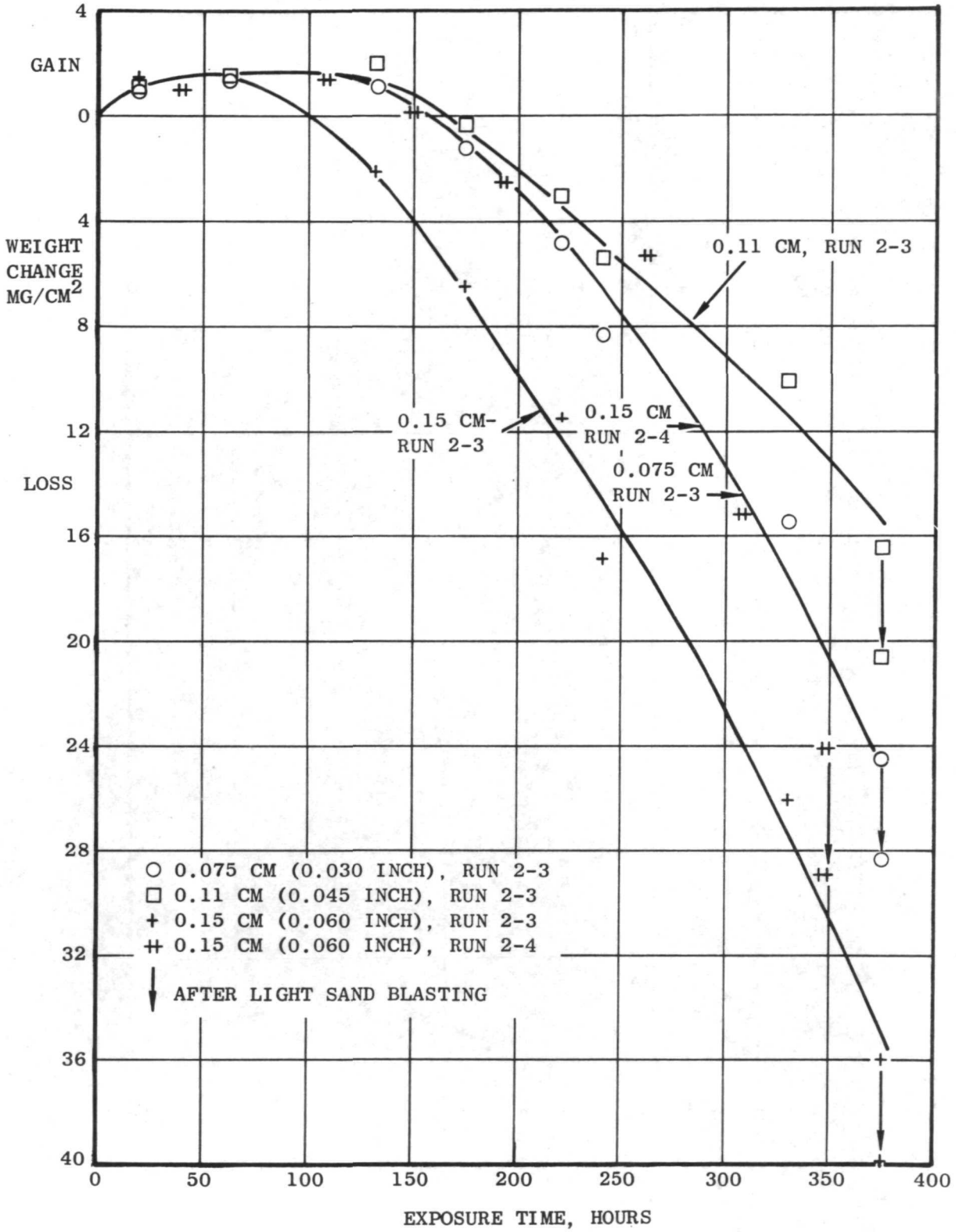
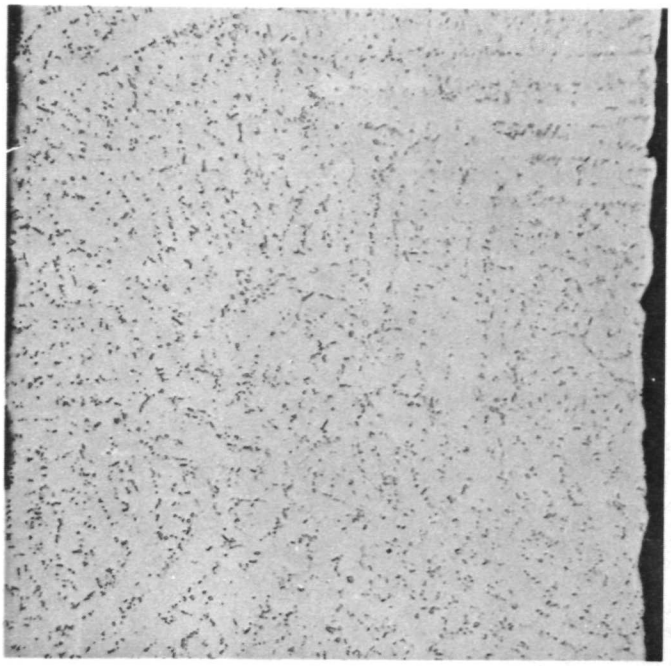
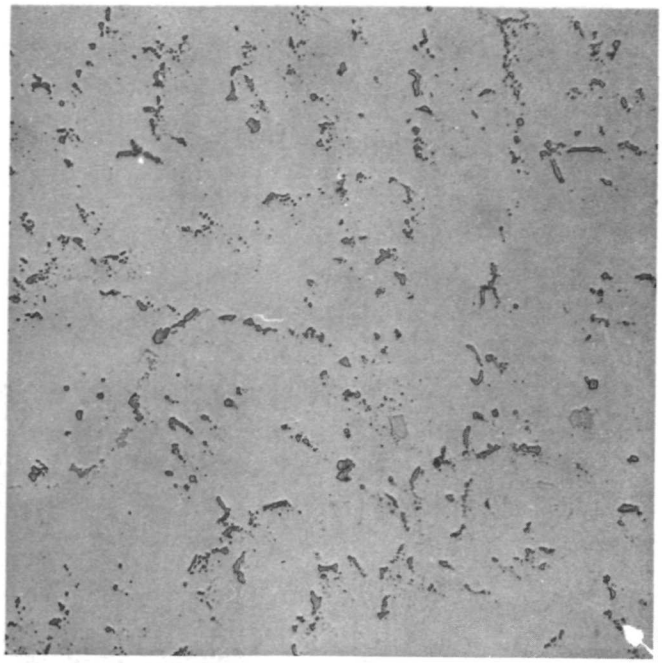


Figure 24 Weight Changes During 1093C (2000F) Exposure in Burner Rig (CoCrAlY Coated)

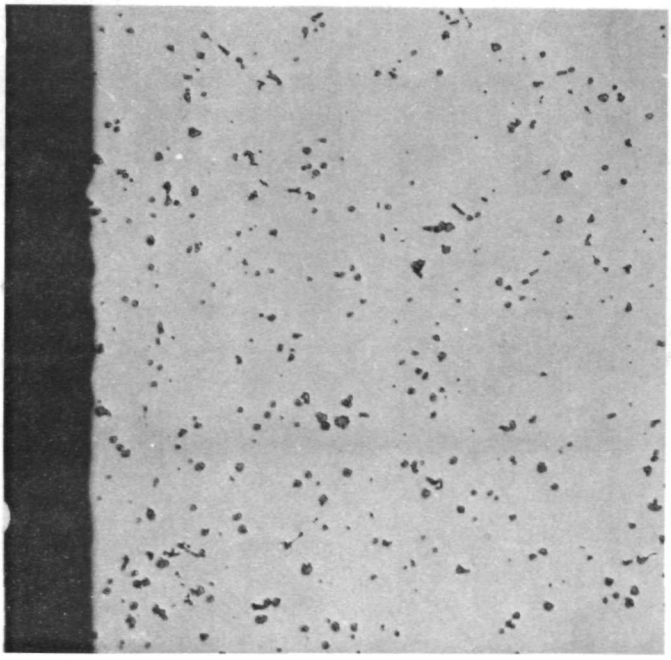
Figure 25 CoCrAlY Coated Specimen #39 After 150 Hours Exposure at 1093C (2000F) 14X



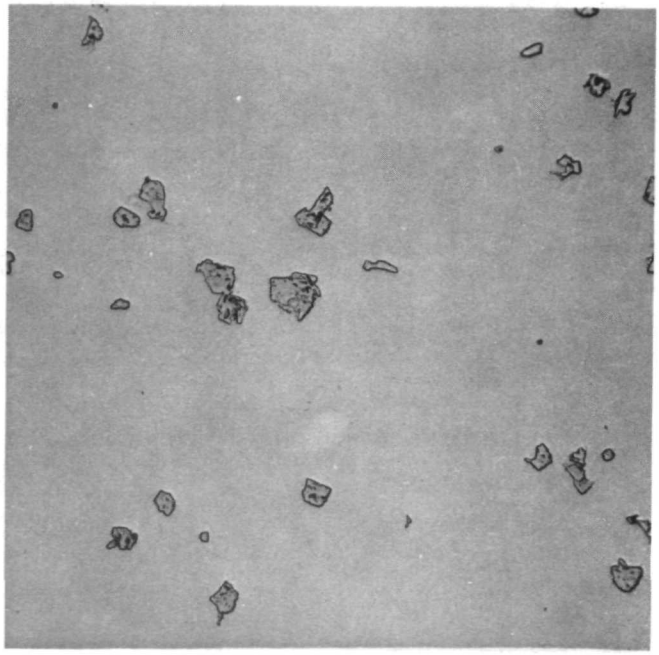
(A) 0.075 CM (0.030 INCH) WALL THICKNESS, TRANSVERSE CENTER, 100X



(B) SAME AS (A) AT 400X

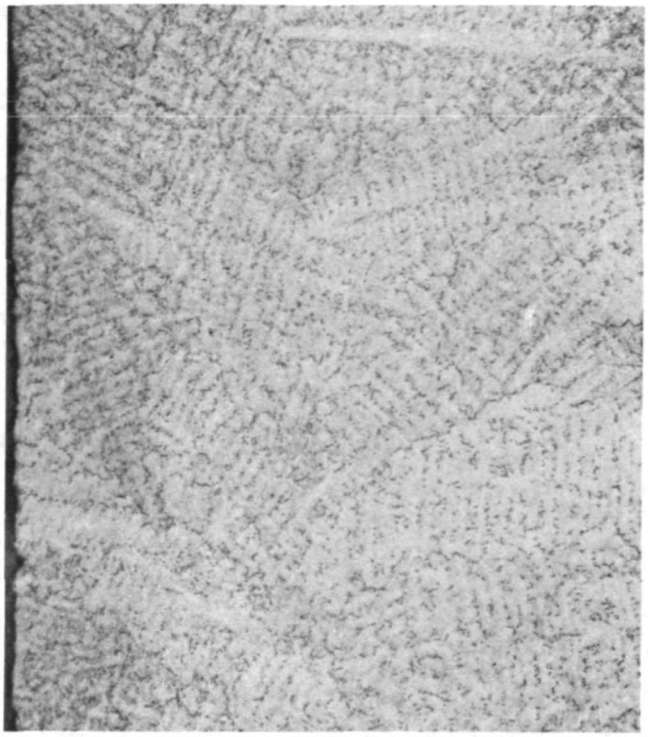


(C) 0.11 CM (0.045 INCH) WALL THICKNESS, TRANSVERSE CENTER, 100X



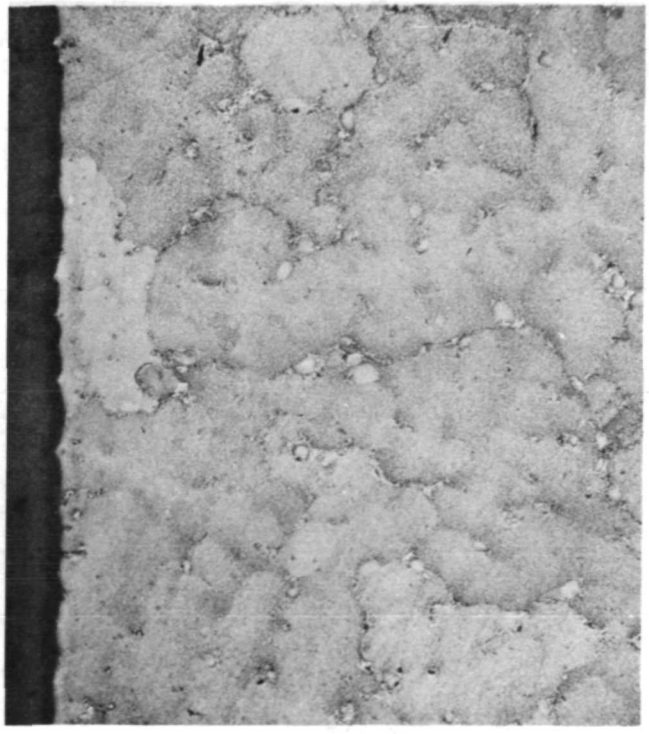
(D) SAME AS (C) AT 400X

Figure 26 Representative Cross-Sections of Castings, Unetched

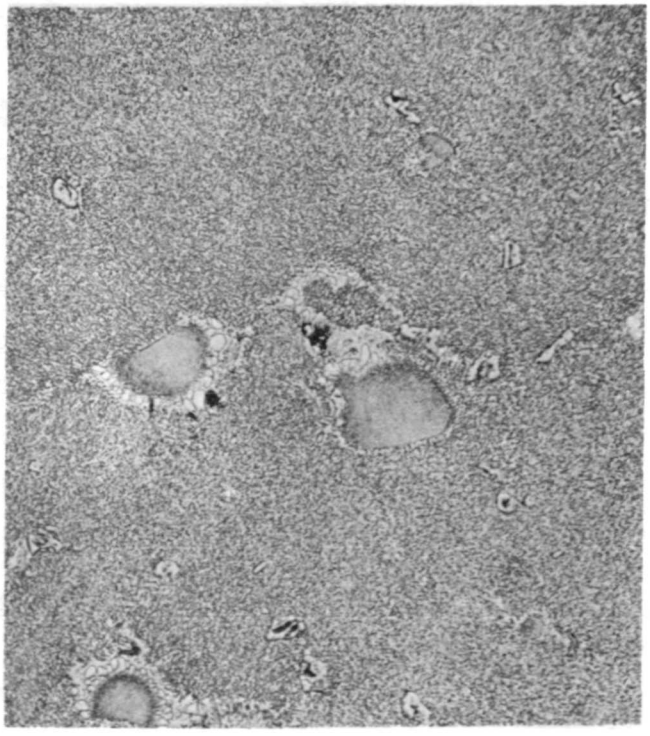


(A) 0.075 CM (0.030 INCH) WALL THICKNESS, TRANSVERSE CENTER, 100X

(B) SAME AS (A) AT 400X

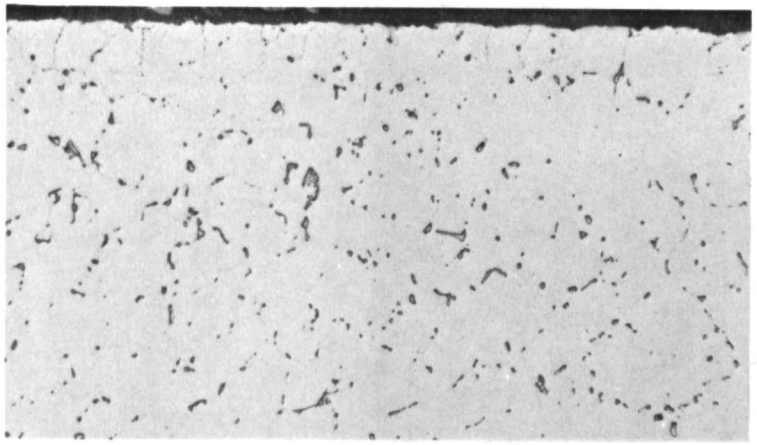


(C) 0.15 CM (0.060 INCH) WALL THICKNESS, TRANSVERSE CENTER, 100X

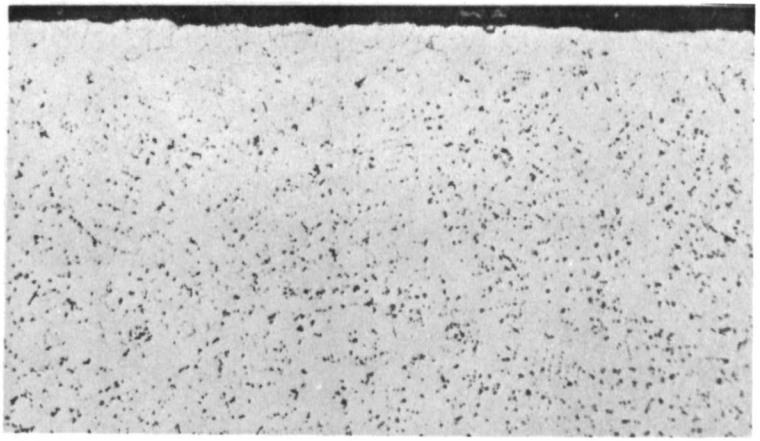


(D) SAME AS (C) AT 400X

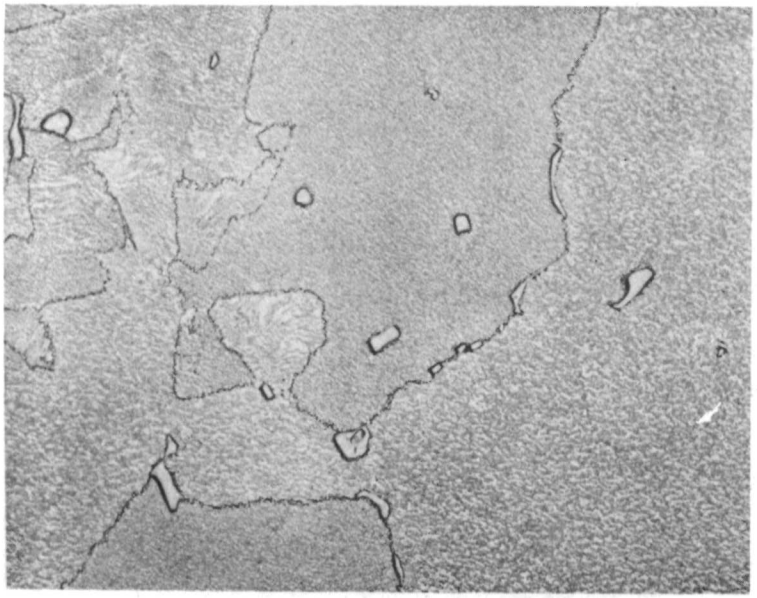
Figure 27 Representative Cross Sections of Castings, Etched



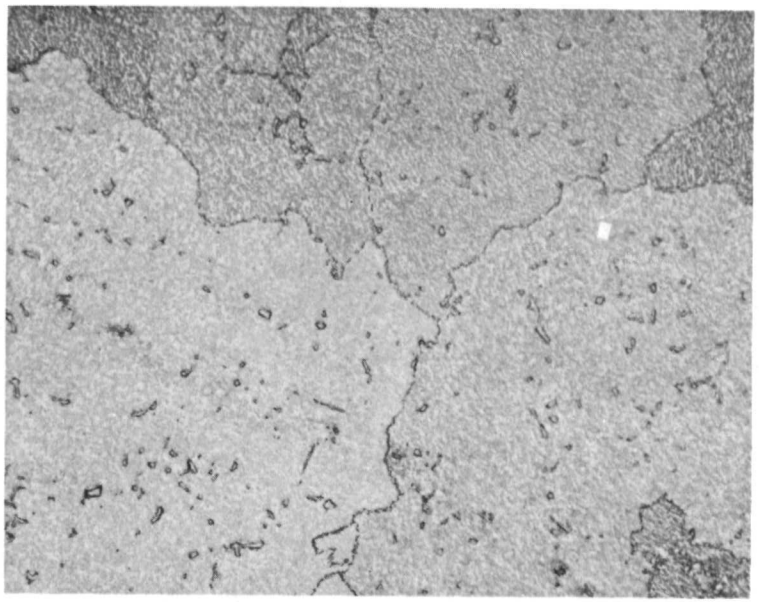
(A) 0.15 CM (0.060 INCH) SPECIMEN.
UNETCHED, 100X



(B) 0.075 CM (0.030 INCH) SPECIMEN.
UNETCHED, 100X

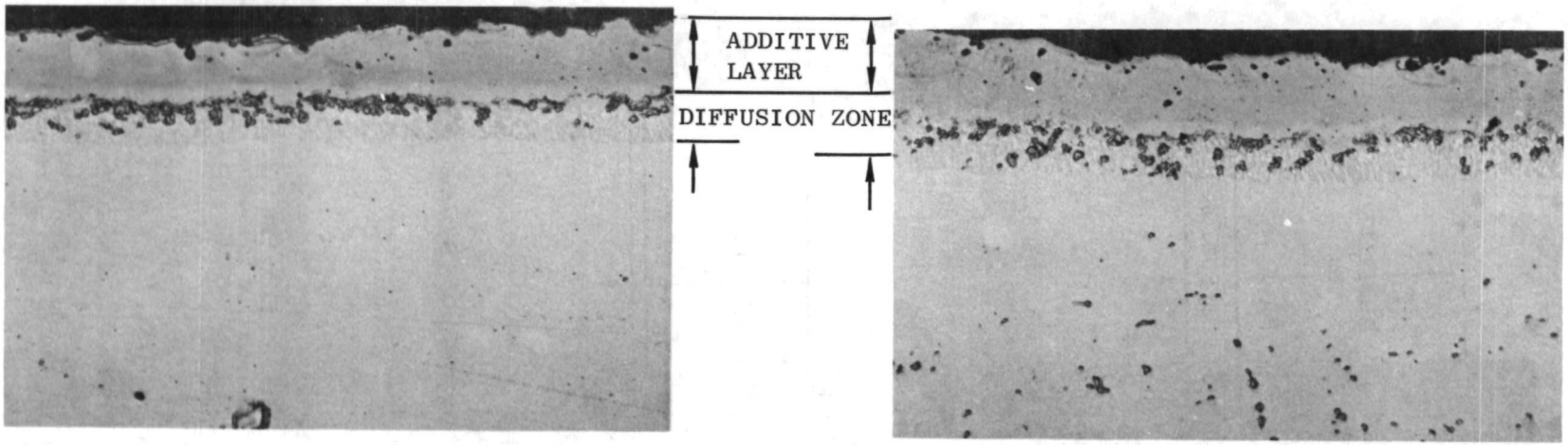


(C) 0.15 CM (0.060 INCH) SPECIMEN.
ETCHED, 400X



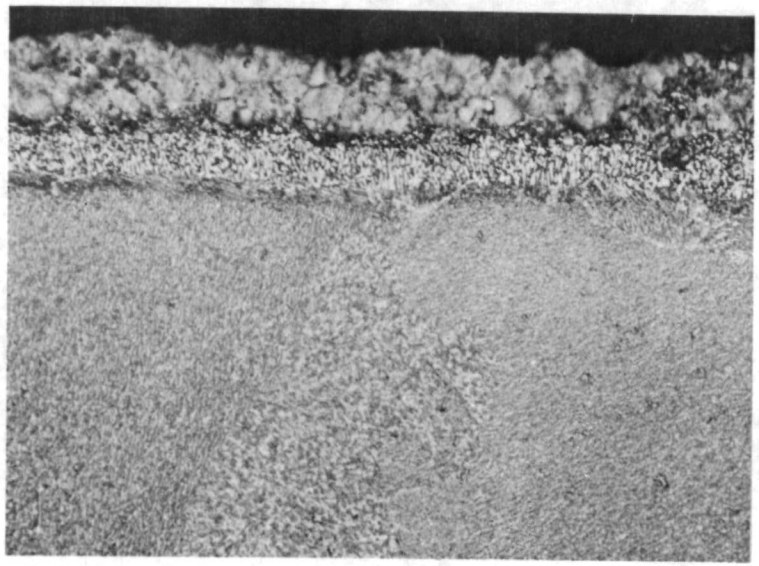
(D) 0.075 CM (0.030 INCH) SPECIMEN.
ETCHED, 400X

Figure 28 Rene'80 Fully Heat Treated Structures



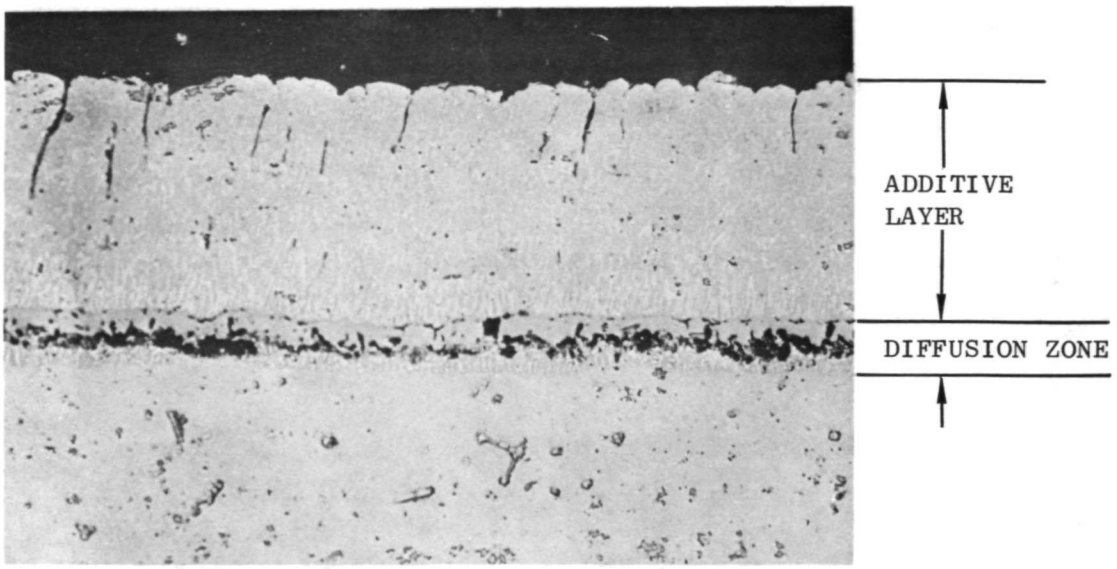
(A) 0.15 CM (0.060 INCH) SPECIMEN COATING. UNETCHED, 400X

(B) 0.075 CM (0.030 INCH) SPECIMEN COATING. UNETCHED, 400X

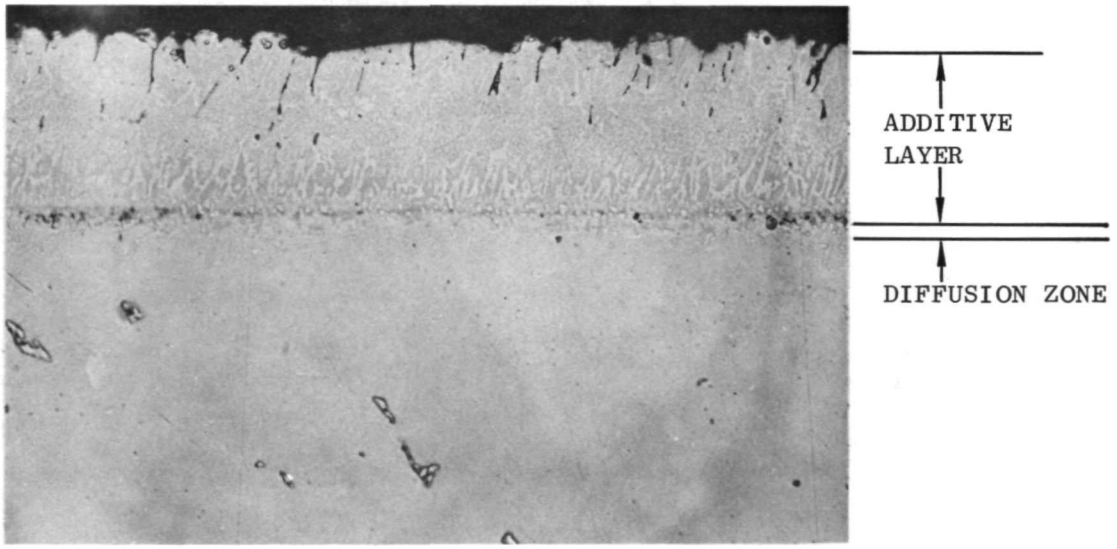


(C) 0.075 CM (0.030 INCH) SPECIMEN COATING. ETCHED, 400X

Figure 29 Rene'80 Fully Heat Treated, Codep B-1 Coated Structures



(A) SPECIMEN NO. 17, 0.11 CM (0.045 INCH) THICK, COATING RUN V85



(B) SPECIMEN NO. 29, 0.15 CM (0.060 INCH) THICK, COATING RUN V88

Figure 30 CoCrAlY Coating Structures, Unetched, 400X

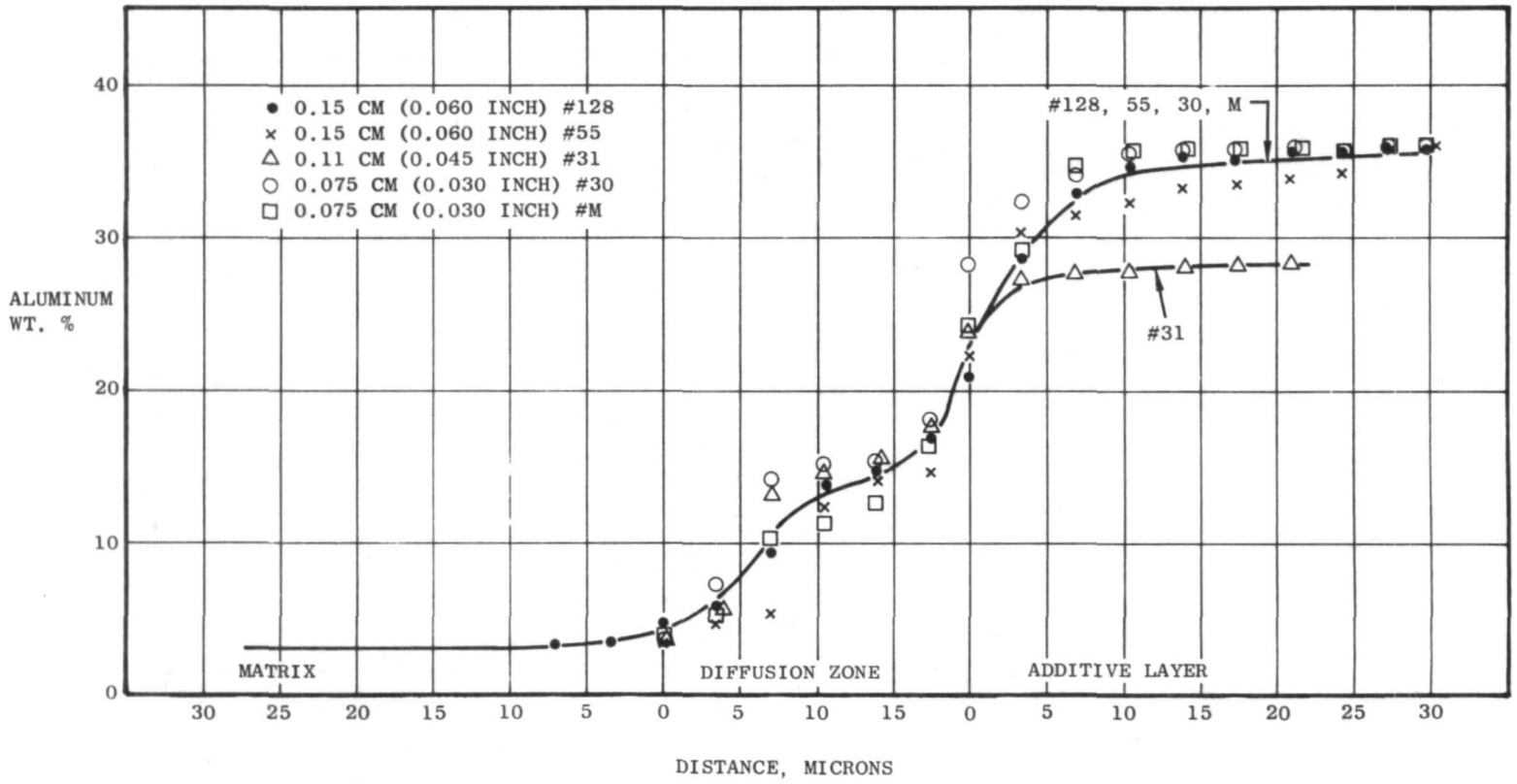


Figure 31 Codep B-1 Coating, Aluminum Content, Weight Percent

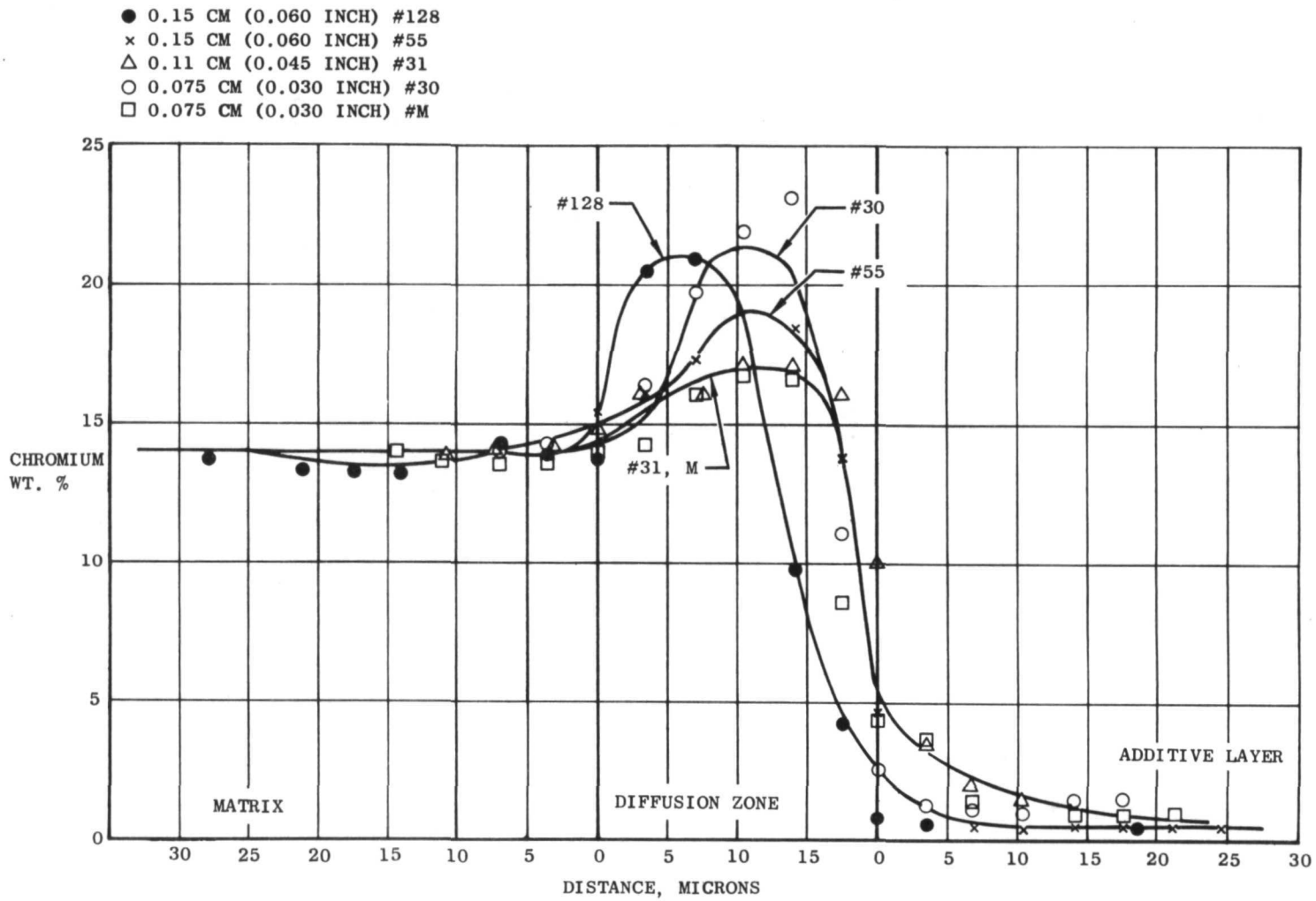


Figure 32 Codep B-1 Coating, Chromium Content, Weight Percent

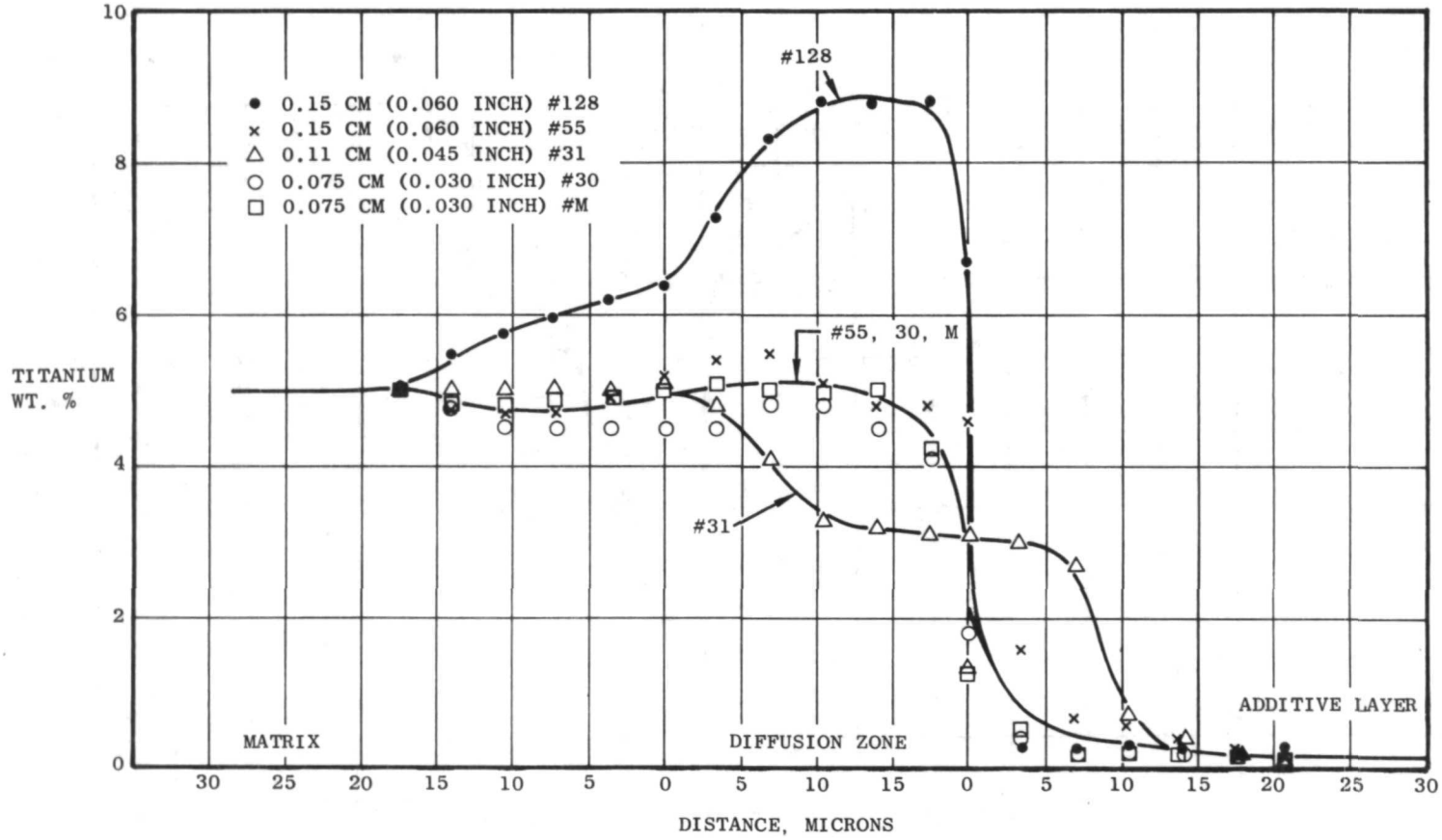


Figure 33 Codep B-1 Coating, Titanium Content, Weight Percent

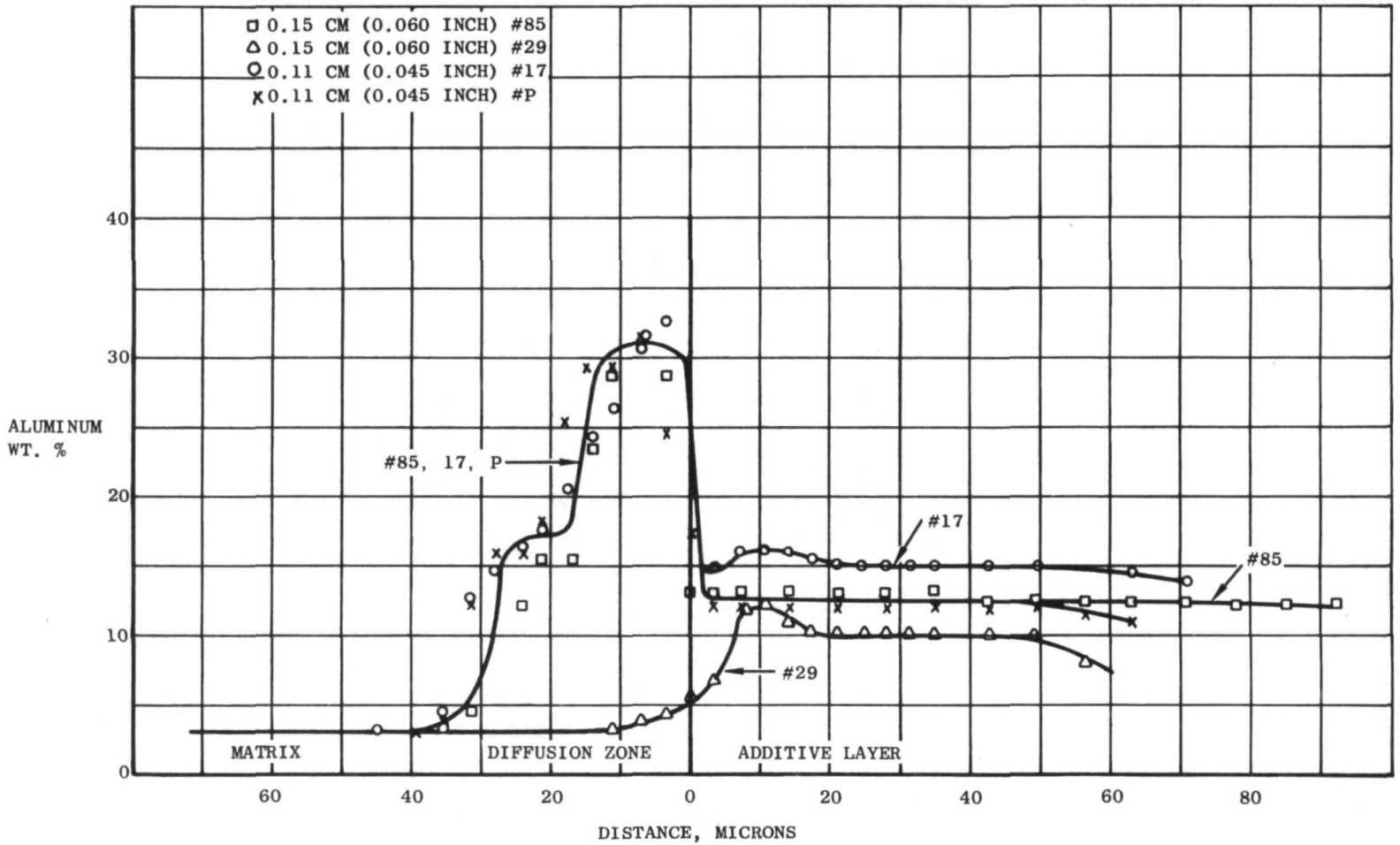


Figure 34 CoCrAlY Coating, Aluminum Content, Weight Percent

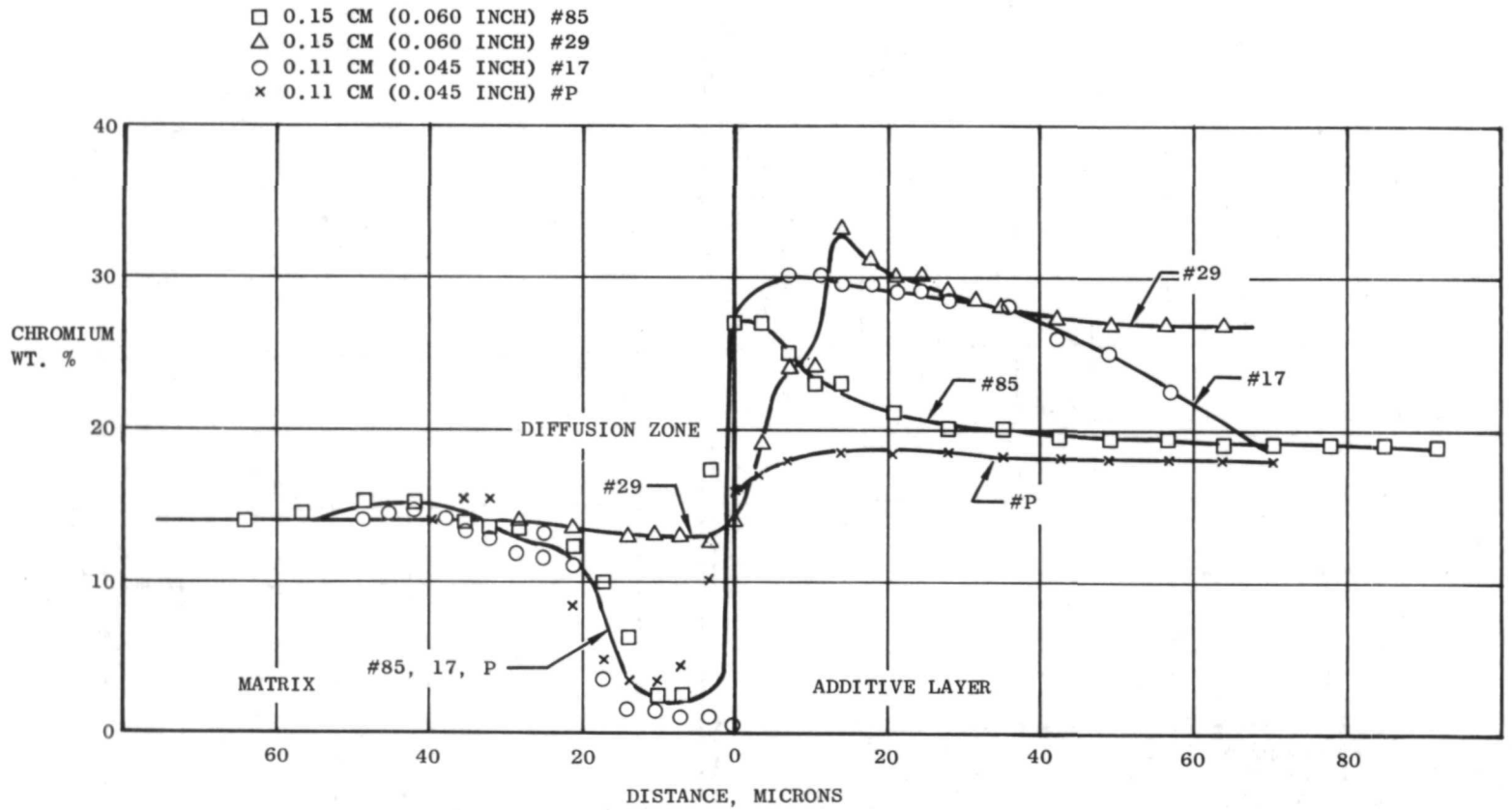


Figure 35 CoCrAlY Coating, Chromium Content, Weight Percent

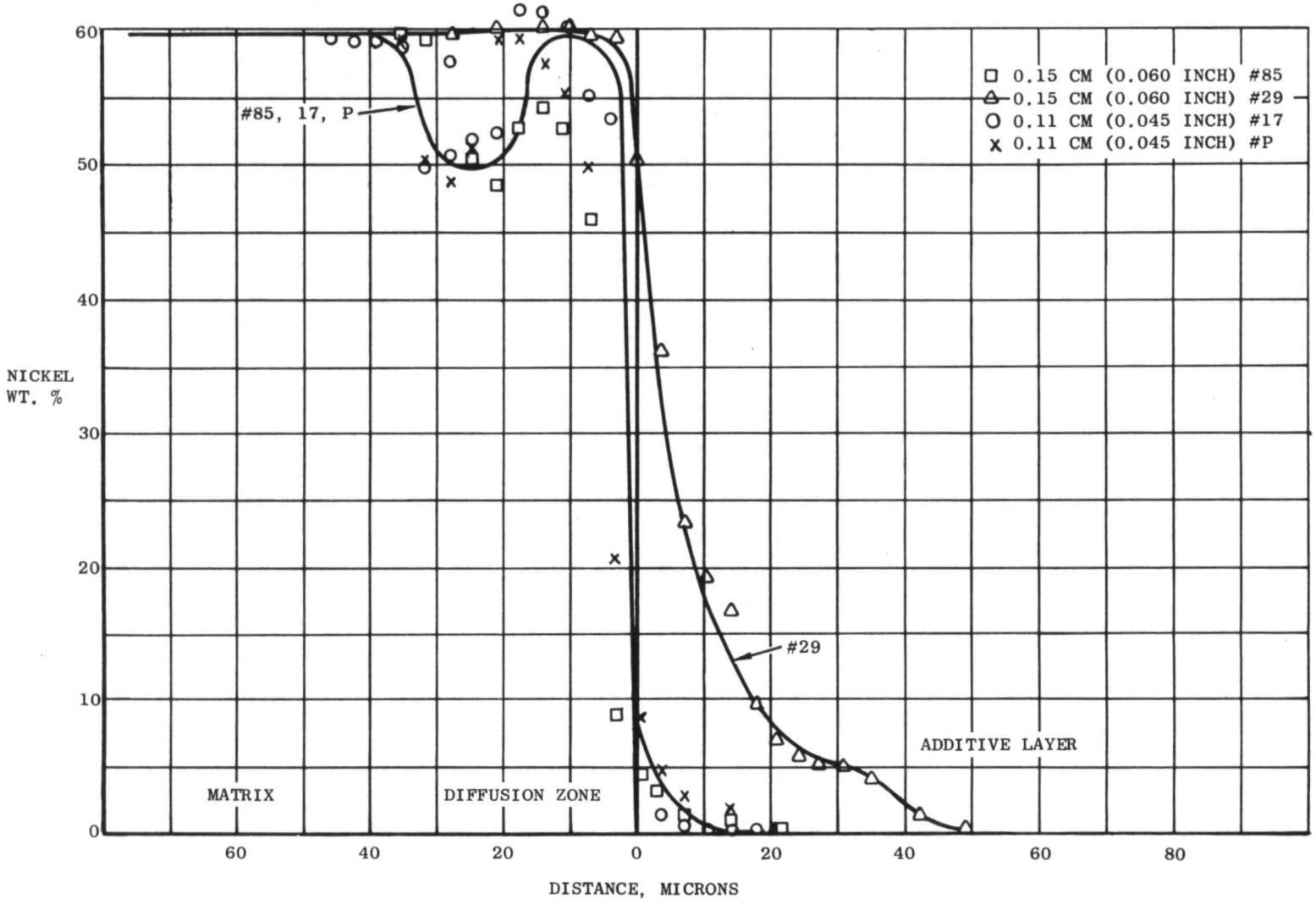
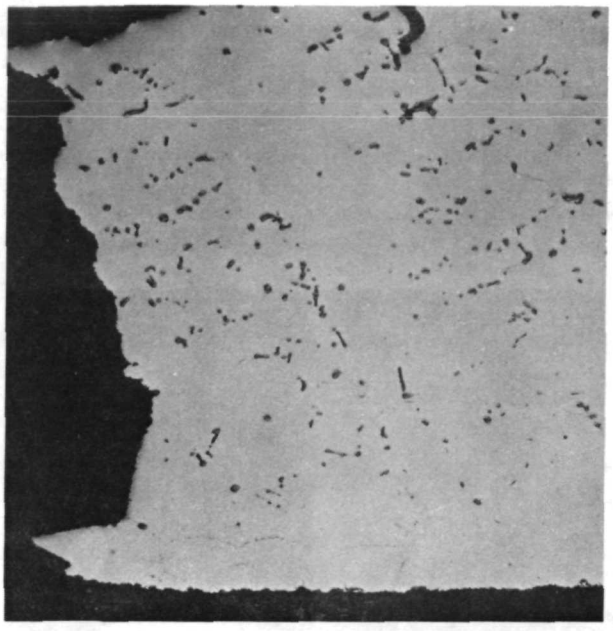
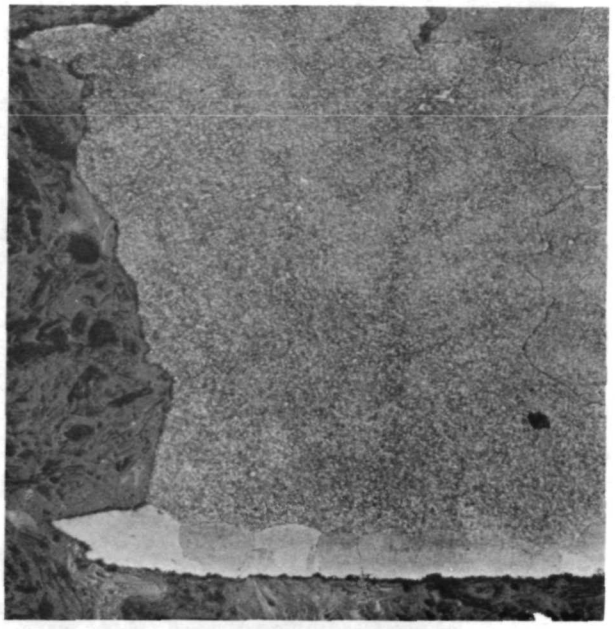


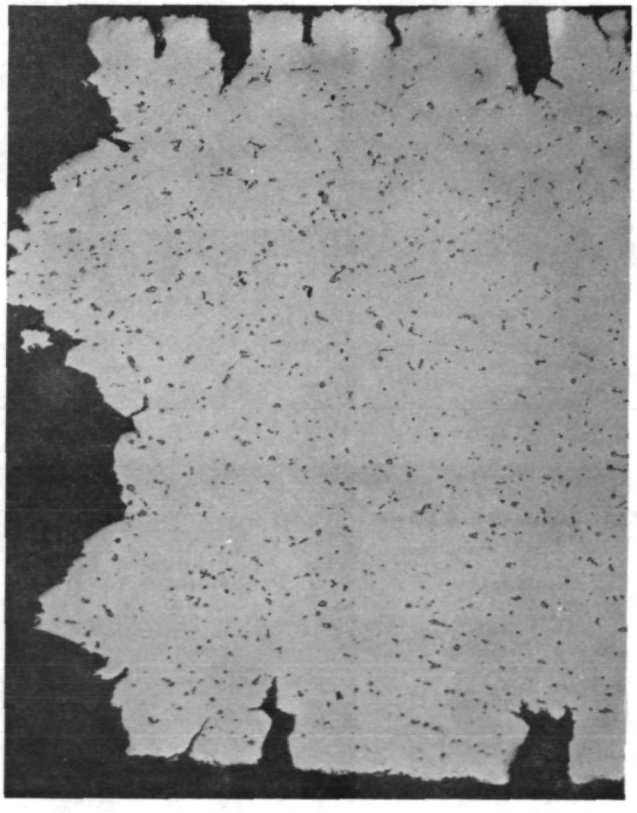
Figure 36 CoCrA1Y Coating , Nickel Content, Weight Percent



(A) STANDARD SIZE BAR, ROOM TEMPERATURE TEST, UNETCHED

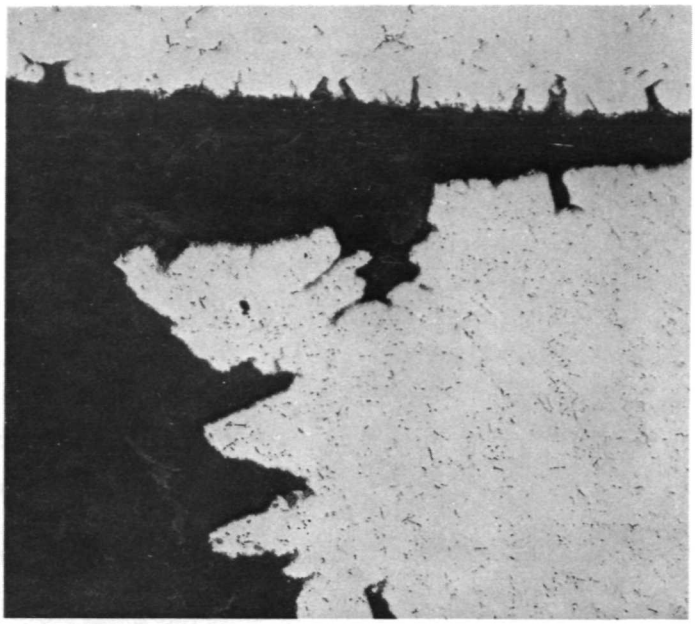


(B) SAME AS (A), ETCHED

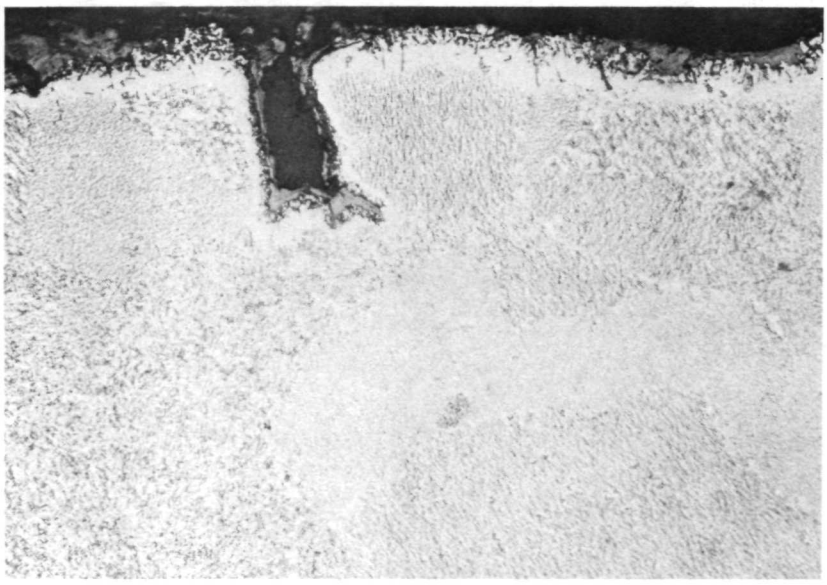


(C) 0.11 CM (0.045 INCH) SPECIMEN #AA, 982C (1800F) TEST, UNETCHED

Figure 37 Rene' 80 Uncoated, Tensile Test Fractures, 100X (Fractures on Left Side)

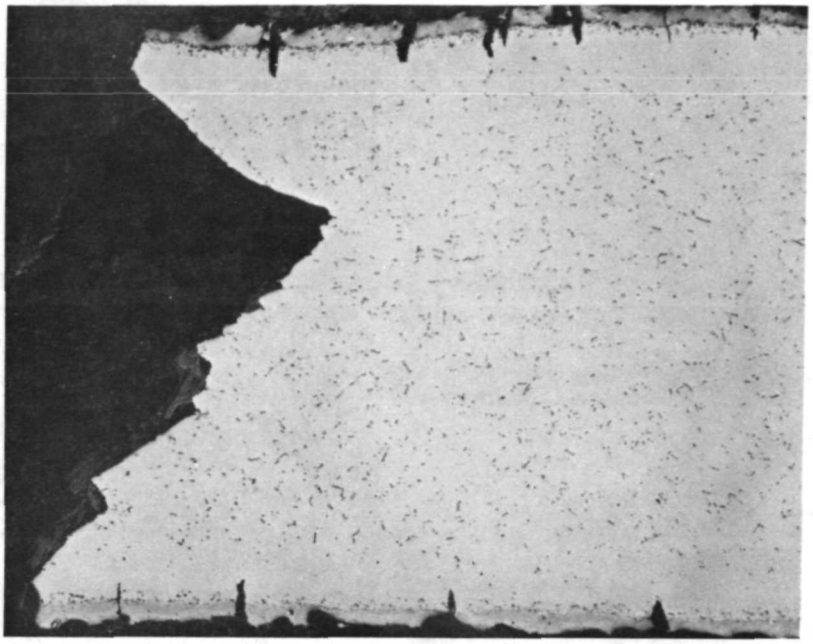


(A) 0.075 CM (0.030 INCH) SPEC. #-5, BELOW; 0.15 CM (0.060 INCH) SPEC. #21 ABOVE, UNETCHED, 100X

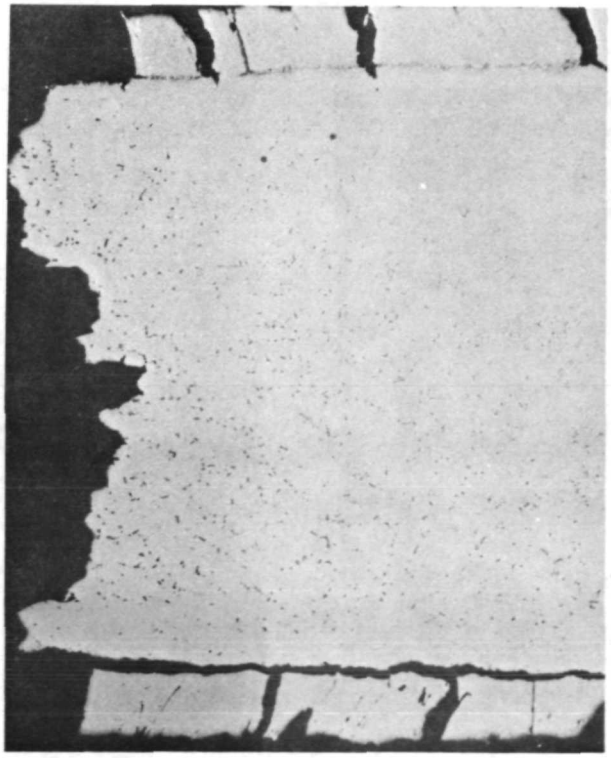


(B) 0.075 CM (0.030 INCH) SPEC. #-5, ETCHED, 400X

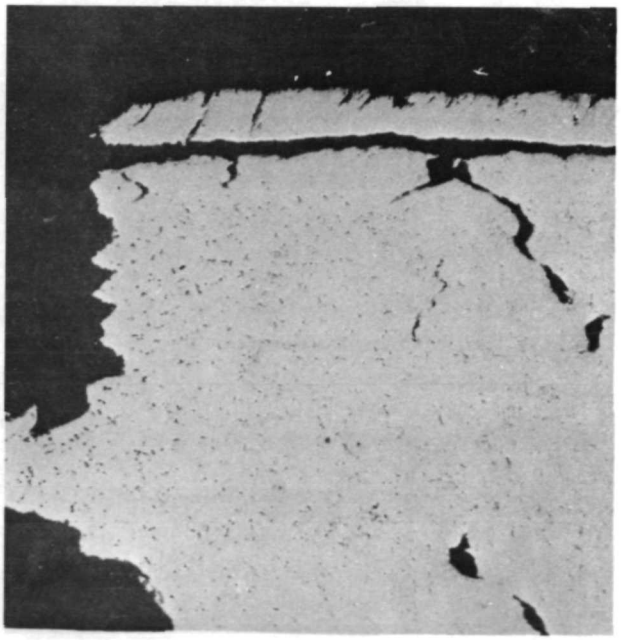
Figure 38 Rene' 80, Uncoated, 1093C (2000F) Tensile Test Fracture



(A) CODEP B-1, 0.075 CM (0.030 INCH) SPEC. #4, 760C (1400F) TEST

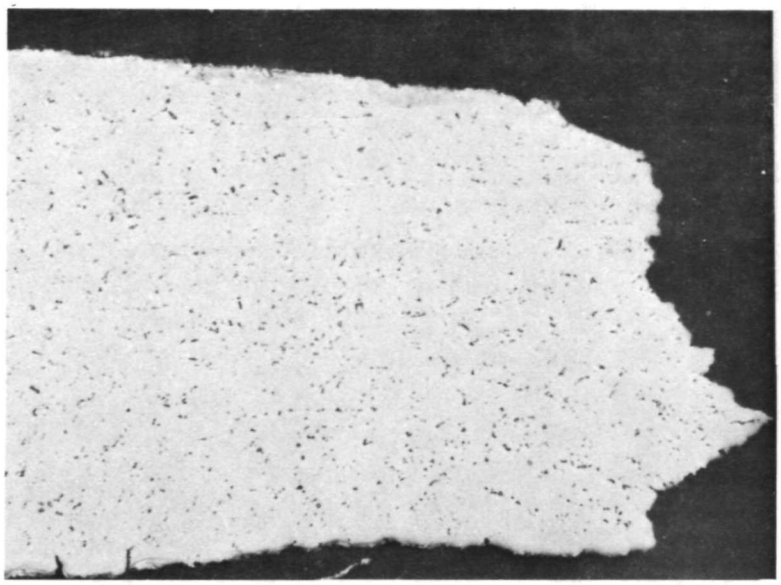


(B) CoCrAlY, 0.075 CM (0.030 INCH)
SPEC. #-12, ROOM TEMPERATURE TEST

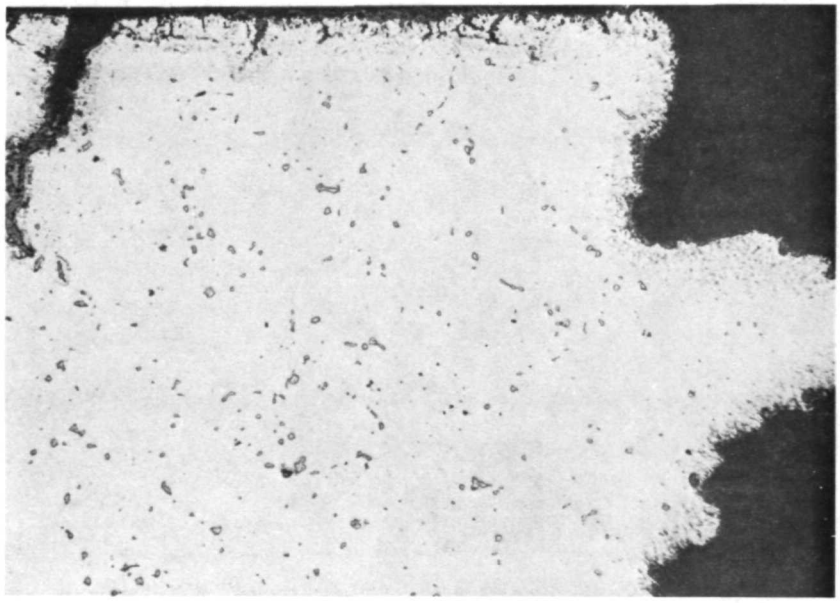


(C) CoCrAlY, 0.075 CM (0.030 INCH)
SPEC. #6, 1093C (2000F) TEST

Figure 39 Rene' 80 Coated Tensile Test Fractures, Unetched, 100X
(Fractures on Left Side)

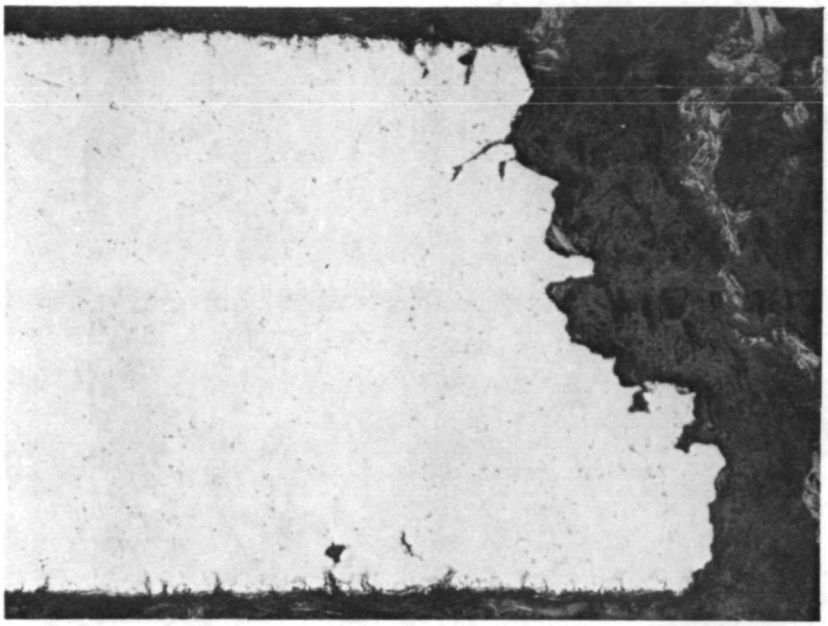


(A) 0.075 CM (0.030 INCH) SPECIMEN, TESTED AT 760C (1400F), 6.0 HOURS

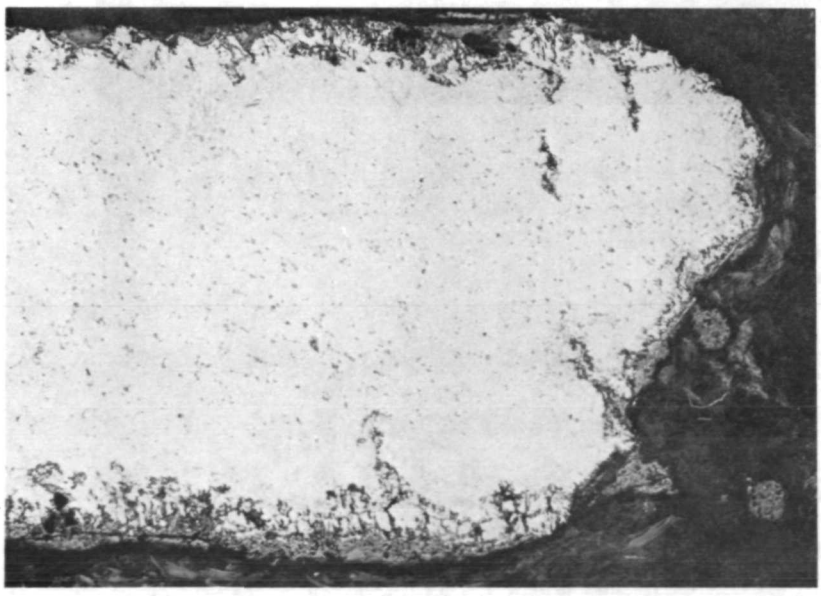


(B) 0.15 CM (0.060 INCH) SPECIMEN, TESTED AT 982C (1800F), 52.9 HOURS

Figure 40 Stress Rupture Test Fractures (Bare Specimens), Unetched, 100X

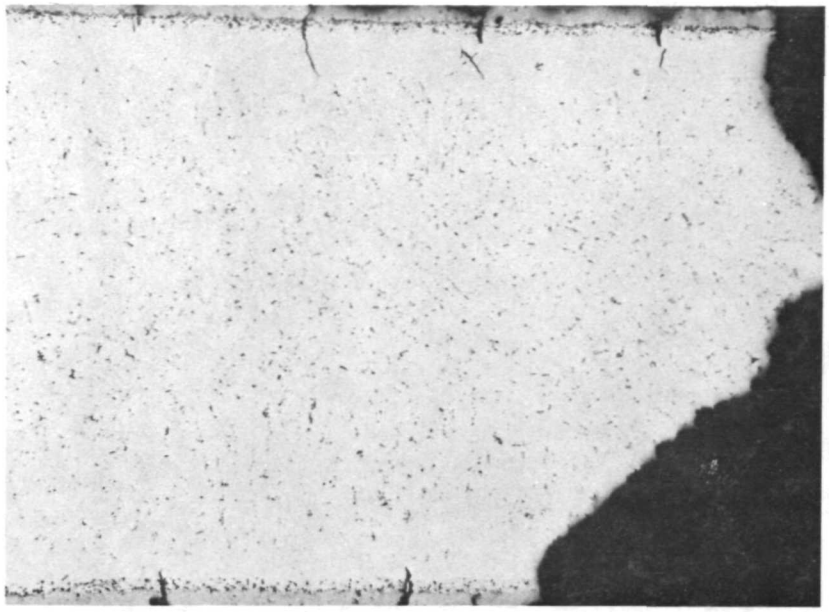


(A) TESTED AT 982C (1800F), 22.7 HOURS

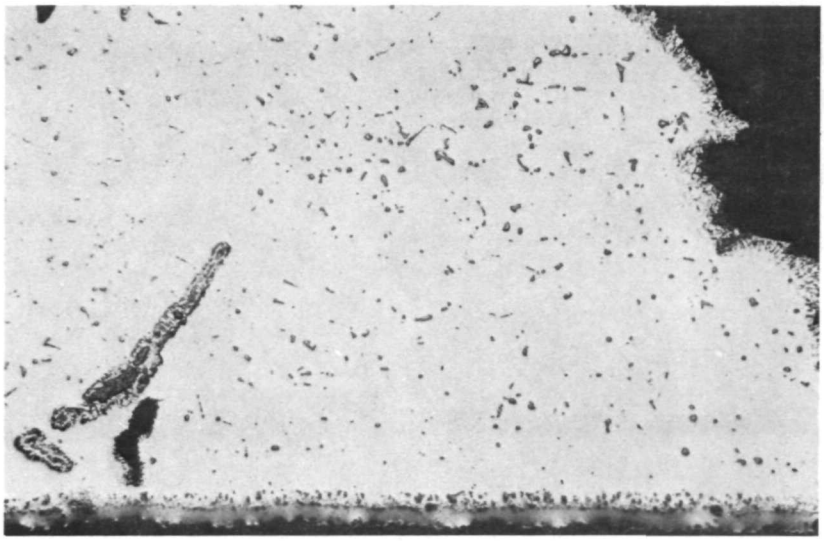


(B) TESTED AT 1093C (2000F), 36. 8 HOURS

Figure 41 Stress Rupture Test Fractures, Bare Specimens, 0.075 CM (0.030 inch) Thick, Unetched, 100X

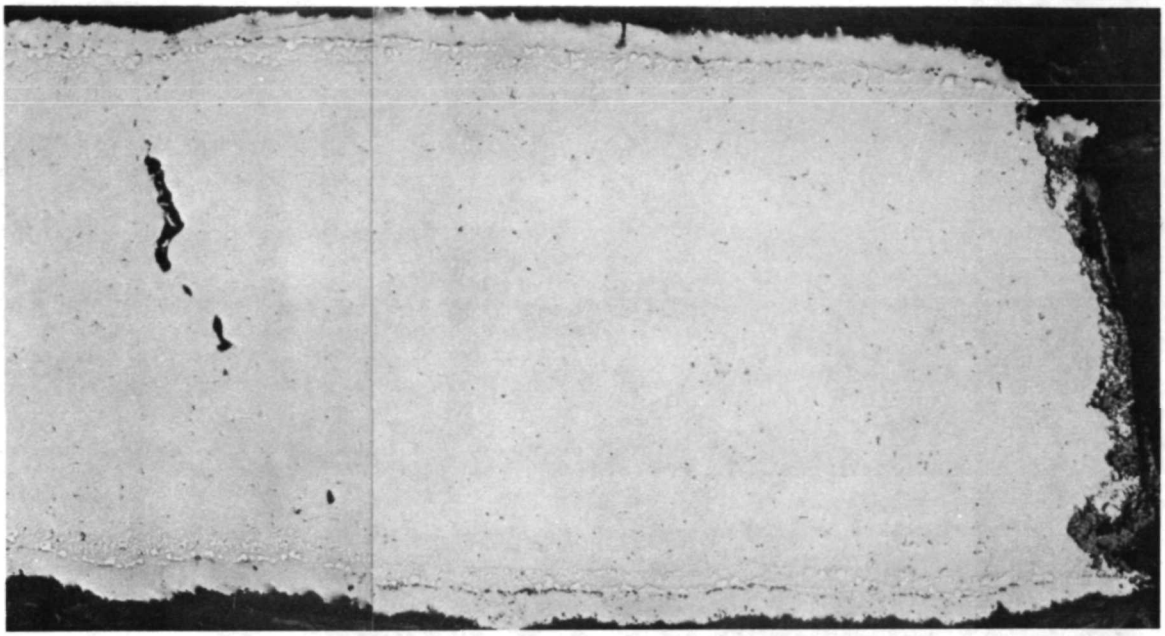


(A) 0.075 CM (0.030 INCH) SPECIMEN, TESTED AT 760C (1400F), 0.2 HOURS

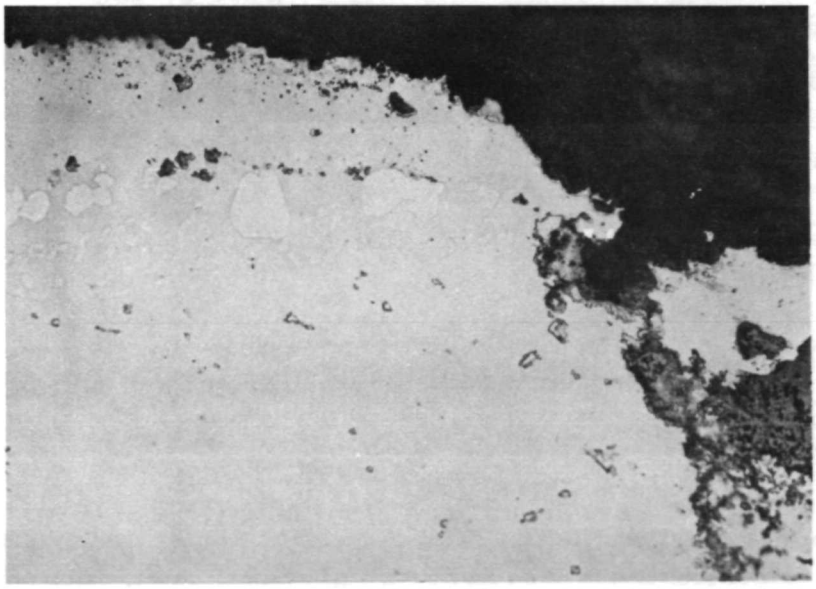


(B) 0.15 CM (0.060 INCH) SPECIMEN, TESTED AT 982C (1800F), 9.7 HOURS

Figure 42 Stress Rupture Test Fractures (Codep B-1 Coated Specimens), Unetched, 100X

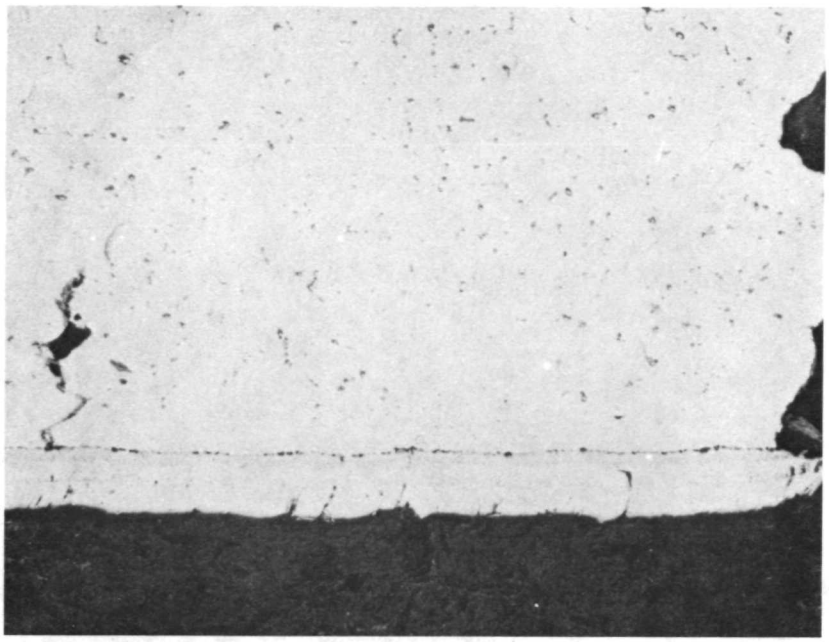


(A) MAGNIFICATION 100X

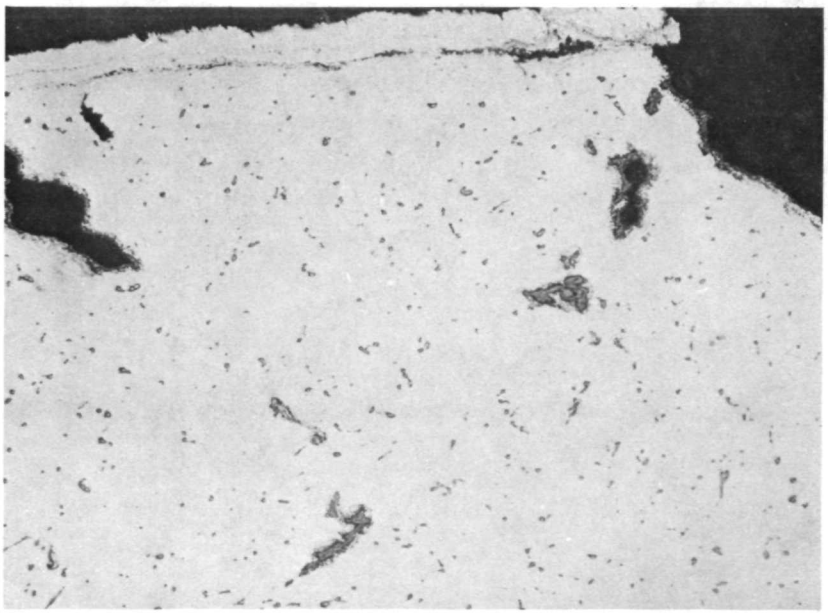


(B) MAGNIFICATION 400X

Figure 43 Stress Rupture Test Fracture, Codep B-1 Coated 0.075 cm (0.030 inch) Thick Specimen, Tested at 1093C (2000F), 51.5 Hours, Unetched

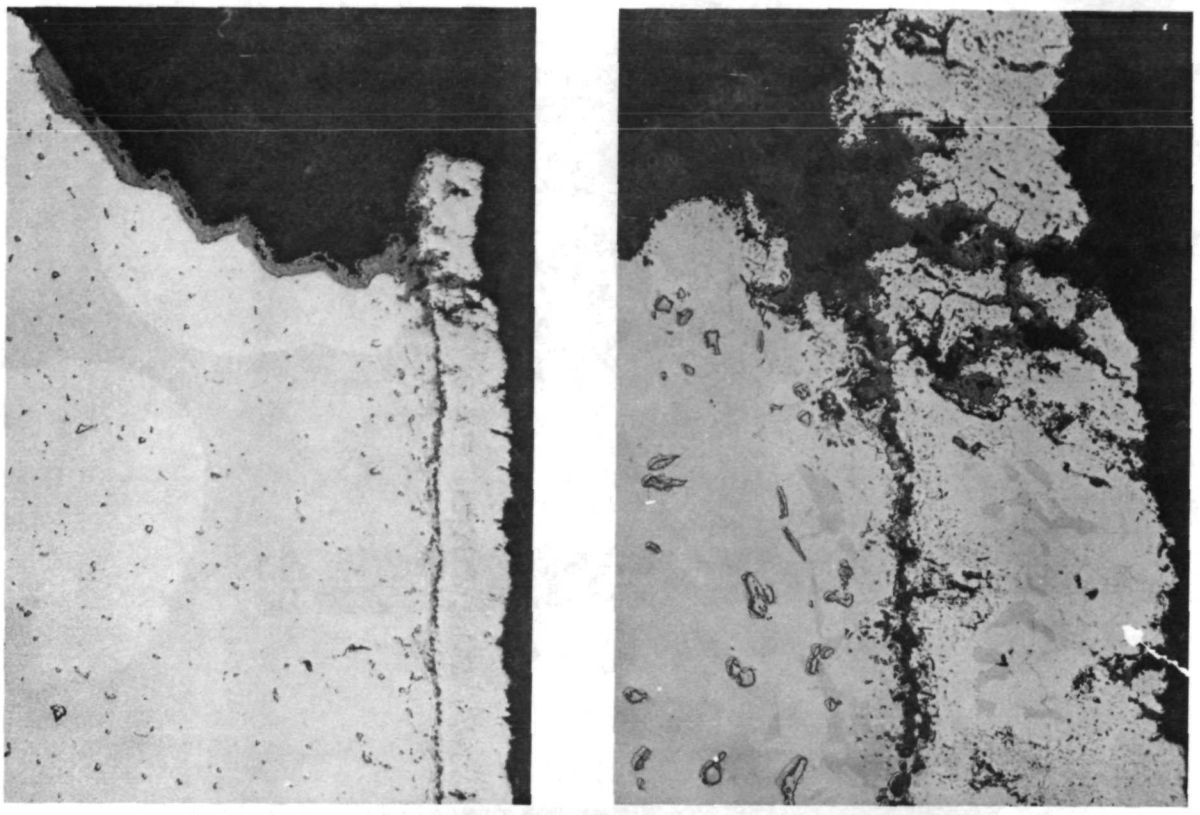


(A) TESTED AT 760C (1400F), 27.0 HOURS



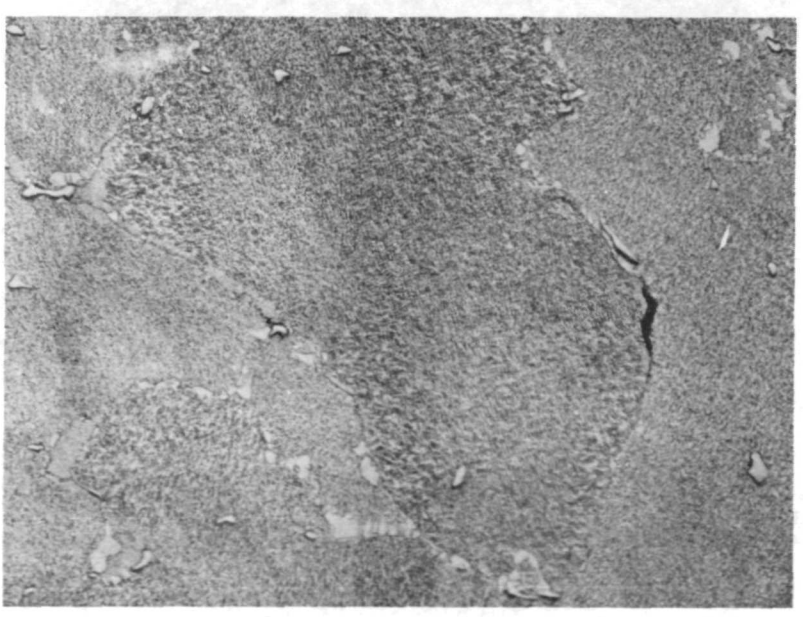
(B) TESTED AT 982C (1800F), 34.1 HOURS

Figure 44 Stress Rupture Test Fractures, CoCrAlY Coated 0.015 cm (0.060 inch) Thick Specimens, Unetched, 100X



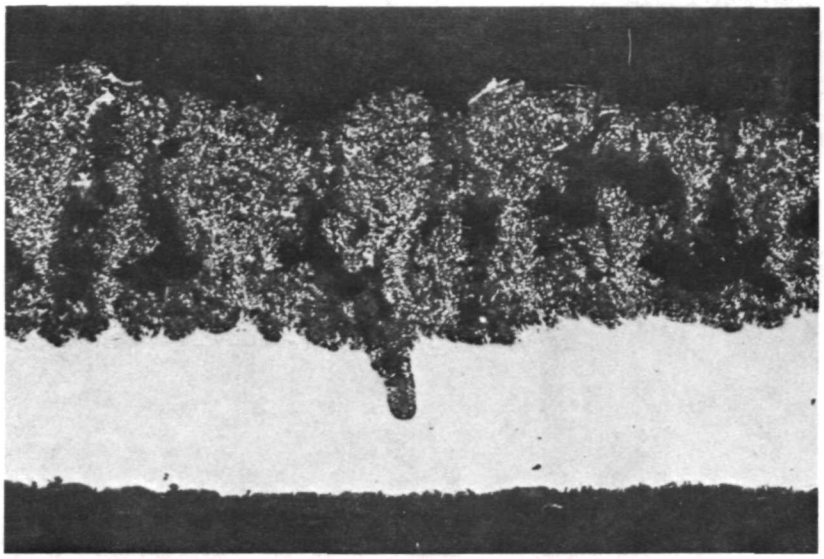
(A) UNETCHED, 100X

(B) UNETCHED, 400X

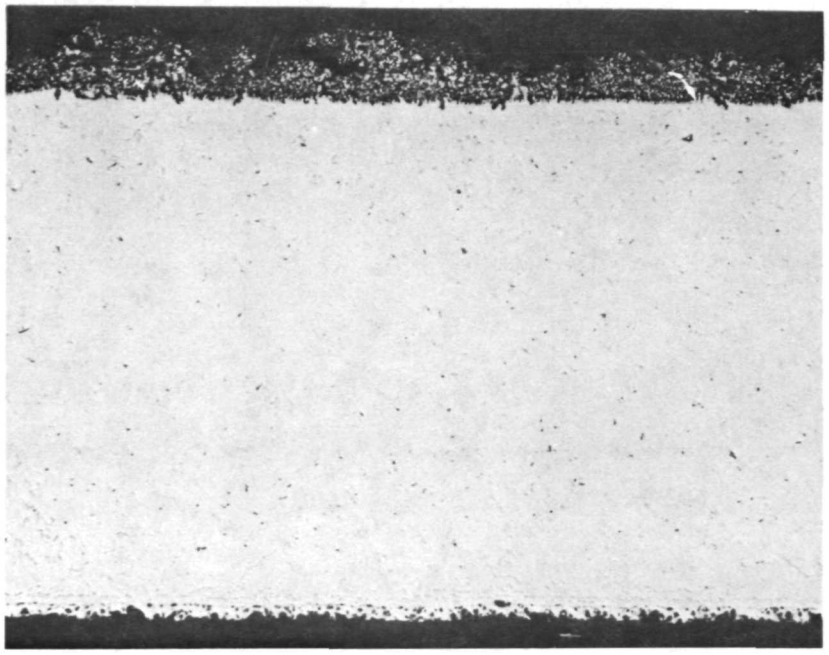


(C) ETCHED, 400X

Figure 45 Stress Rupture Test Fracture, CoCrAlY Coated 0.015 cm (0.060 inch) Thick Specimen. Tested at 1093C (2000F), 82.0 Hours

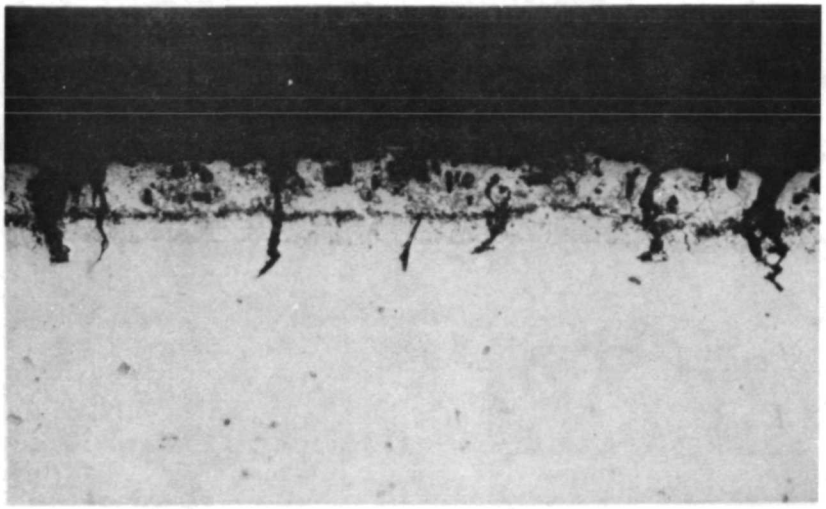


(A) BARE SPEC. #P, UNEXPOSED

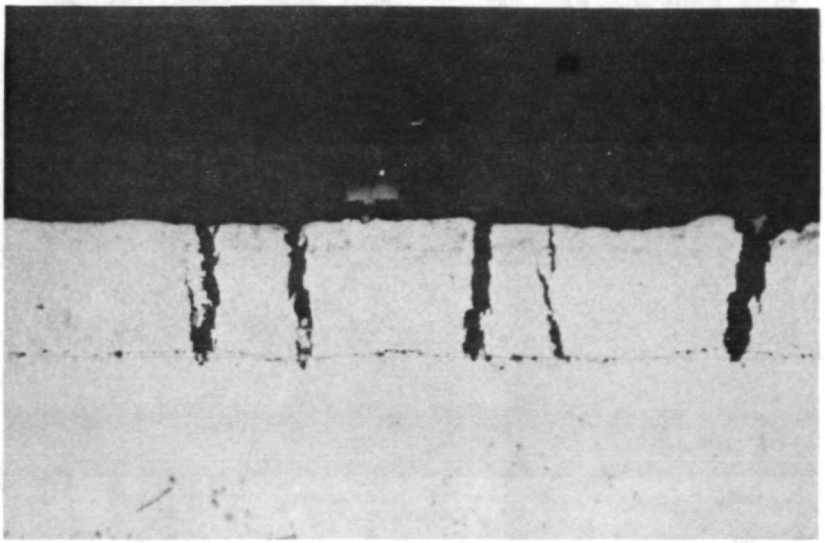


(B) CODEP B-1 SPEC. #3, EXPOSED 1093C (2000F), 483 HRS.

Figure 46 Thermal Fatigue Test, 1093C (2000F) Peak Temperature, 4000 Cycles Unetched, 100X, Thermal Fatigue Surface at Top

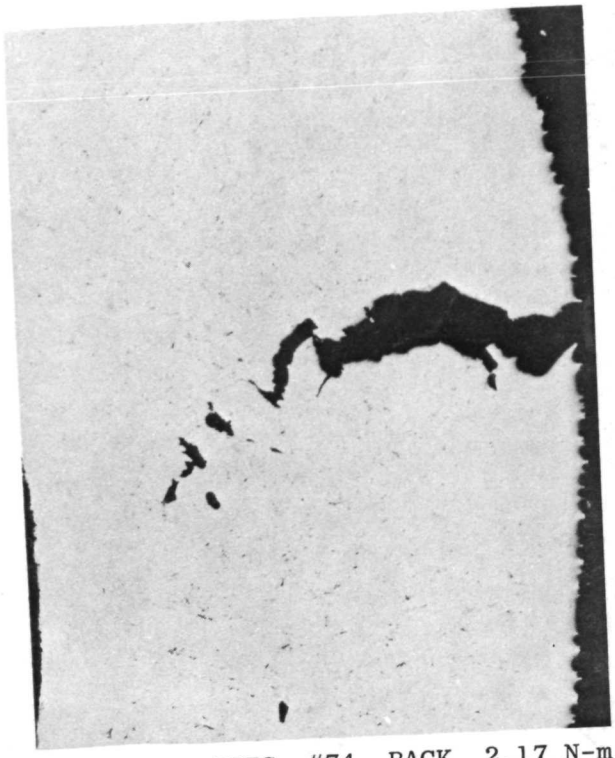


(A) CODEP B-1, SPECIMEN #-3, BACK, 2.44 N-m (1.80 FT-LBS) UNETCHED, 400X

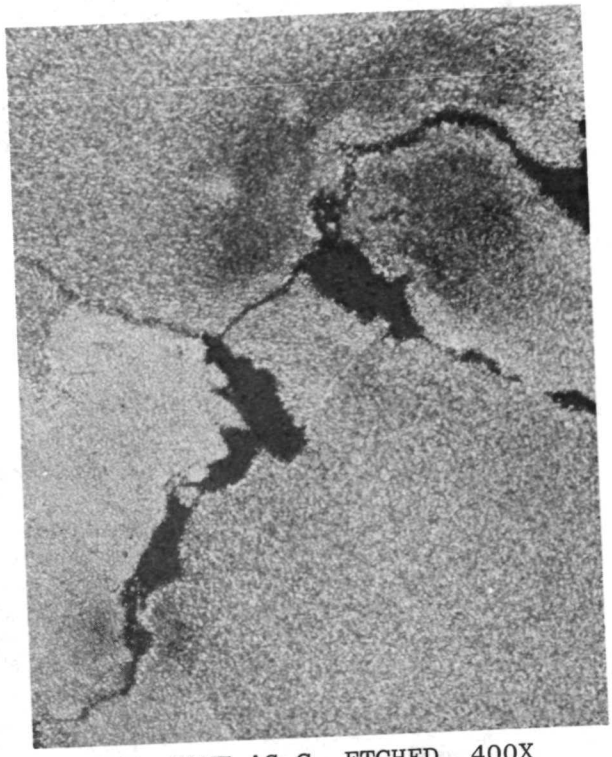


(B) CoCrAlY, SPECIMEN #8, BACK, 2.03 N-m (1.50 FT-LBS) UNETCHED, 400X

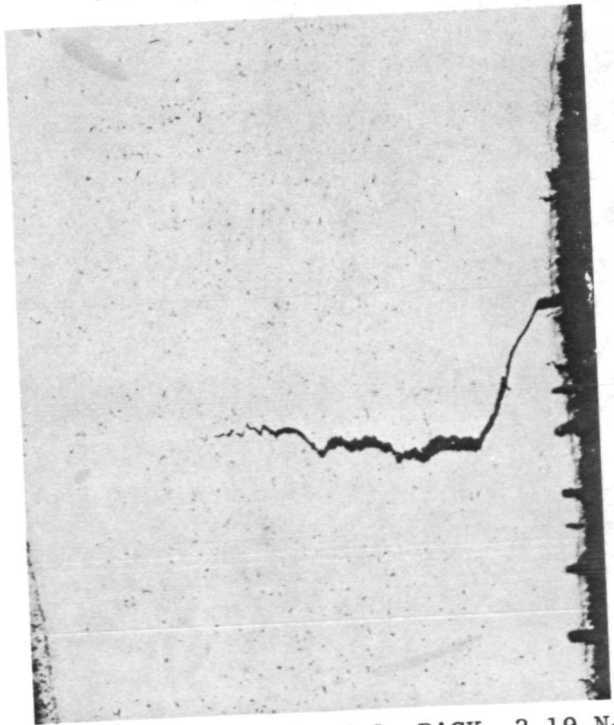
Figure 47 Ballistic Impact Tests at Room Termperature, Bare and Coated Rene' 80



(C) BARE, SPEC. #74, BACK, 2.17 N-m (1.60 FT-LBS) UNETCHED, 100X



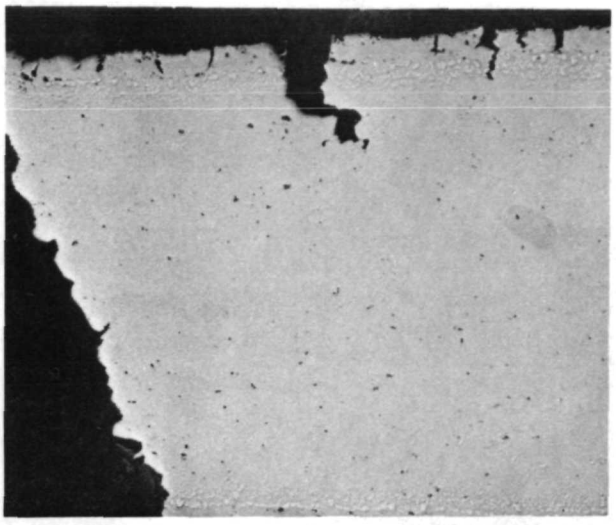
(D) SAME AS C, ETCHED, 400X



(E) CODEP B-1 SPEC. #-3, BACK, 3.19 N-m (2.35 FT-LBS) UNETCHED, 100X

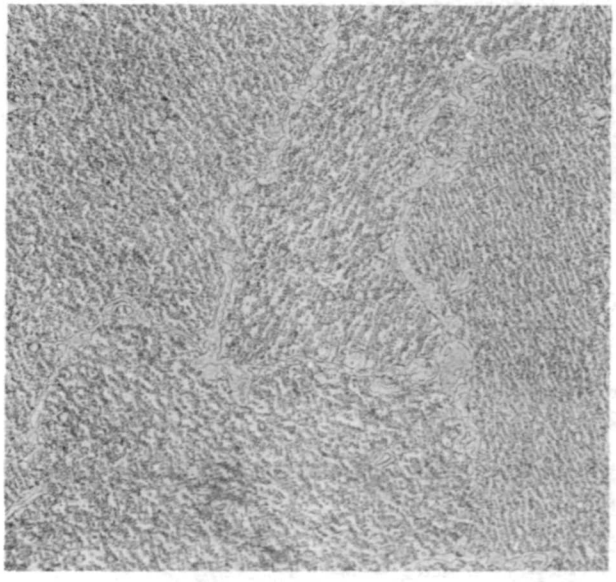
(F) SAME AS E, ETCHED, 400X

Figure 47 (cont.) Ballistic Impact Tests at Room Temperature, Bare and Coated Rene'80

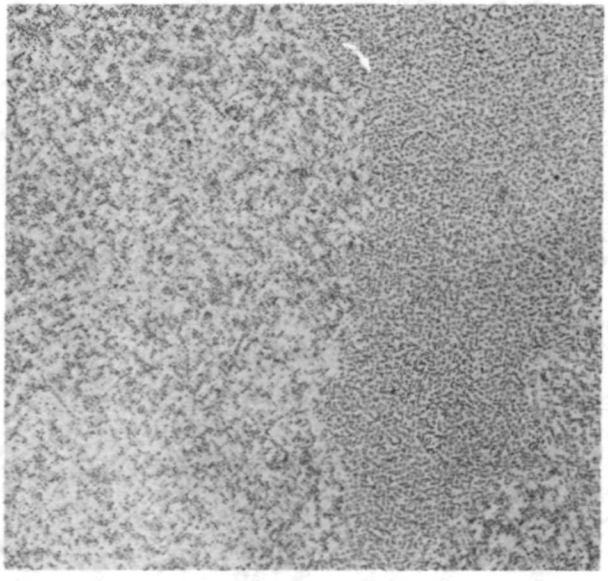


(A) CODEP B-1 SPEC. #-9, 0.075 CM (0.030 INCH), EXPOSED 1093C (2000F), 487 HRS., TENSILE TEST AT R.T., UNETCHED, 100X

(B) BARE SPEC. #-8, 0.075 CM (0.030 INCH), EXPOSED 982C (1800F), 754 HRS., TENSILE TEST AT R.T., ETCHED, 400X

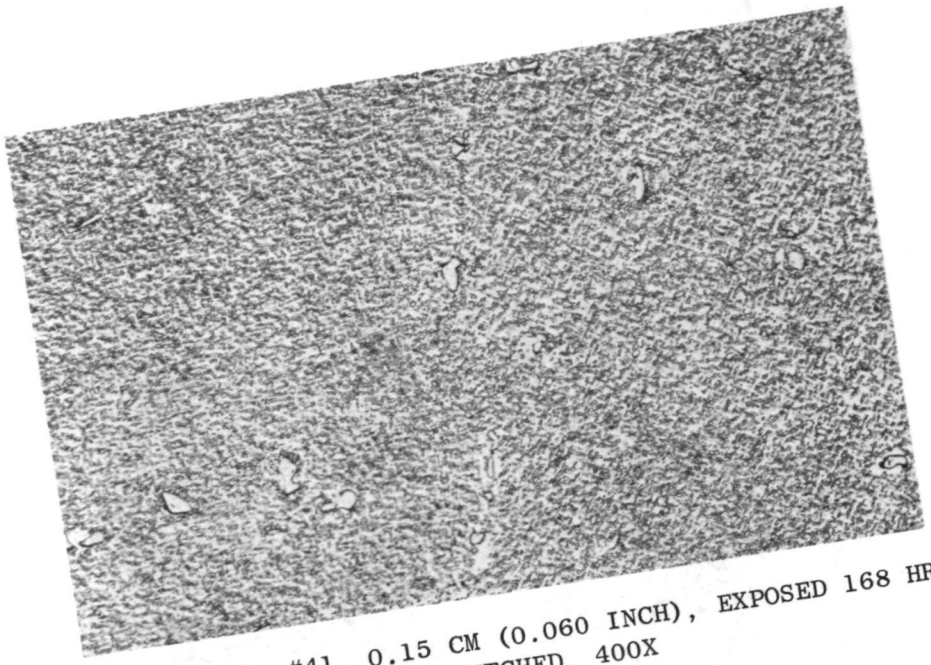


(C) CODEP B-1 SPEC. #73, 0.15 CM (0.060 INCH), EXPOSED 982C (1800F), 989 HRS., TENSILE TEST AT R.T., ETCHED, 400X

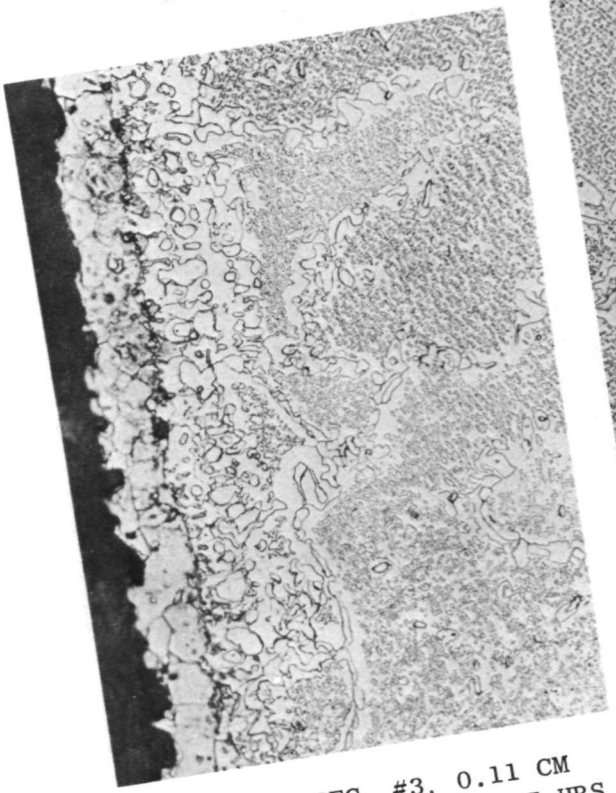


(D) CODEP B-1 SPEC. #-3, 0.075 CM (0.030 INCH), EXPOSED 982C (1800F), 989 HRS., TENSILE TEST AT 1093C (2000F), ETCHED, 400X

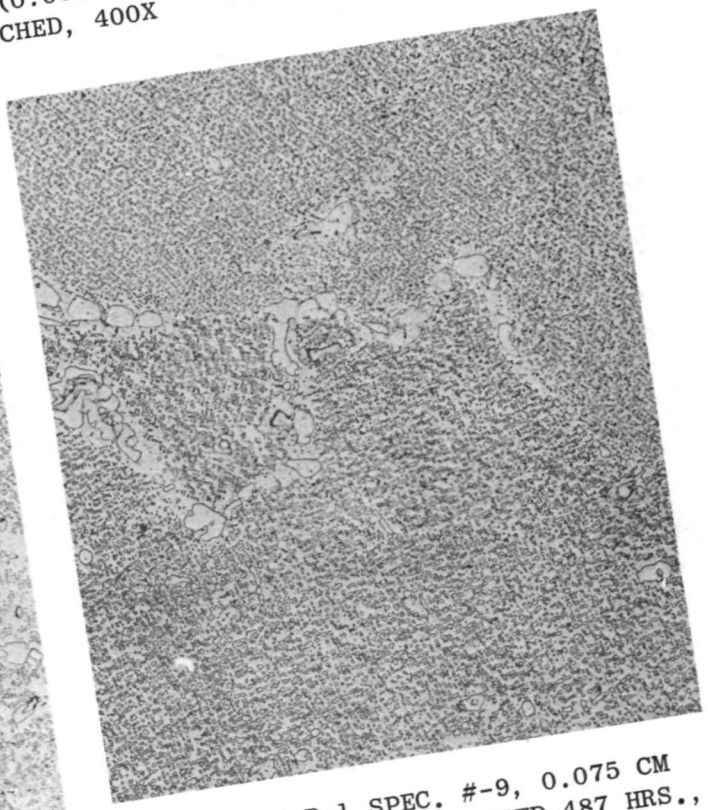
Figure 48 Microstructure of Exposed Rene'80



(A) BARE SPEC. #41, 0.15 CM (0.060 INCH), EXPOSED 168 HRS. TENSILE TEST AT R.T., ETCHED, 400X

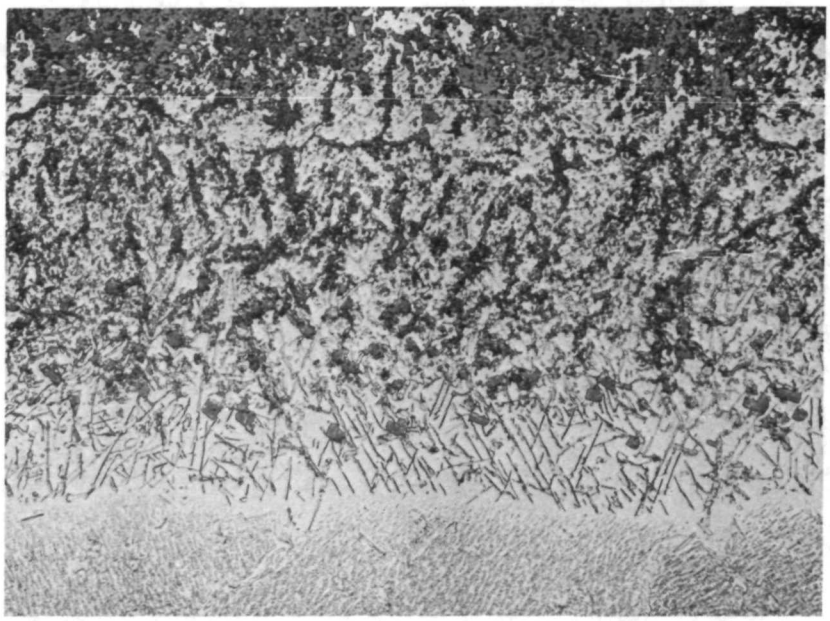


(B) CODEP B-1 SPEC. #3, 0.11 CM (0.045 INCH), EXPOSED 487 HRS., TENSILE TEST AT R.T., ETCHED 400X

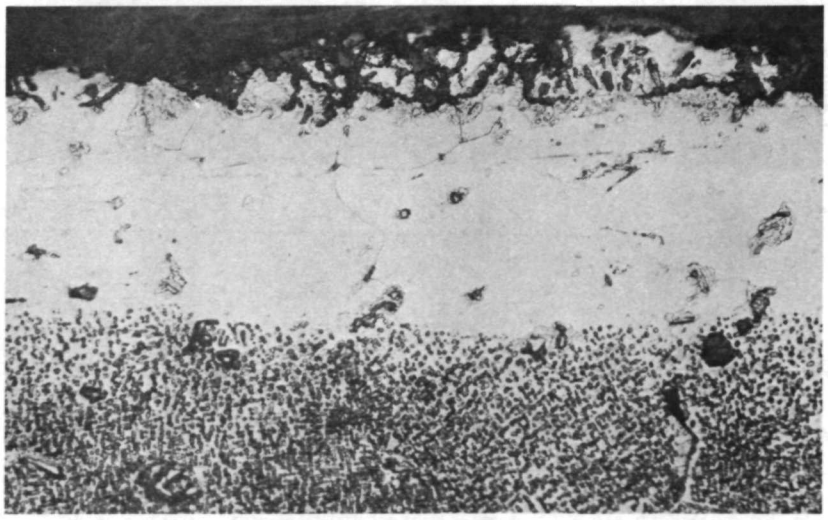


(C) CODEP B-1 SPEC. #-9, 0.075 CM (0.030 INCH), EXPOSED 487 HRS., TENSILE TEST AT R.T., ETCHED, 400X

Figure 49 Microstructure of Rene' 80 Exposed at 1093C (2000F)

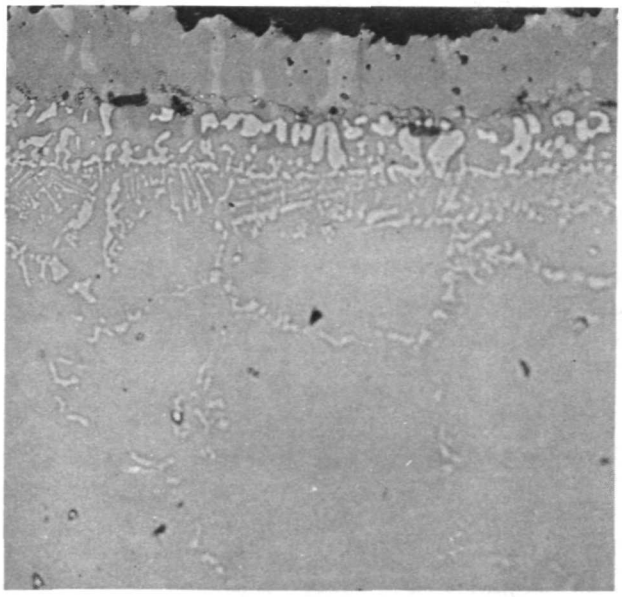


(A) 0.075 CM (0.030 INCH) SPEC. #-8, 982C (1800F), 754 HRS., TENSILE TEST AT R.T.

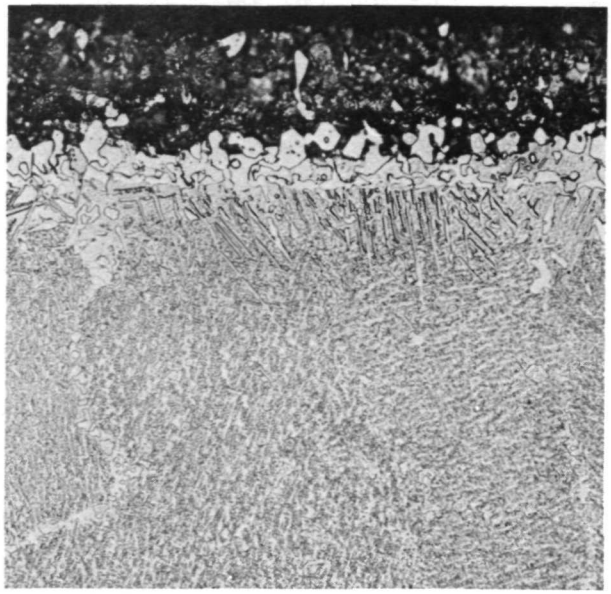


(B) 0.11 CM (0.045 INCH) SPEC. #1, 1093C (2000F), 168 HRS., TENSILE TEST AT R.T.

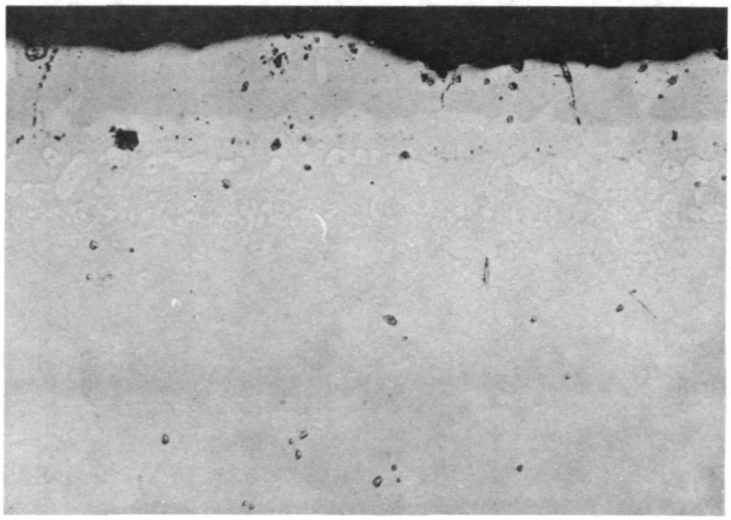
Figure 50 Typical Surface Structures After Exposure, Bare Rene'80 Etched, 400X



(A) SPEC. #73, 0.15 CM (0.060 INCH), EXPOSED 982C (1800F), 989 HRS., UNETCHED

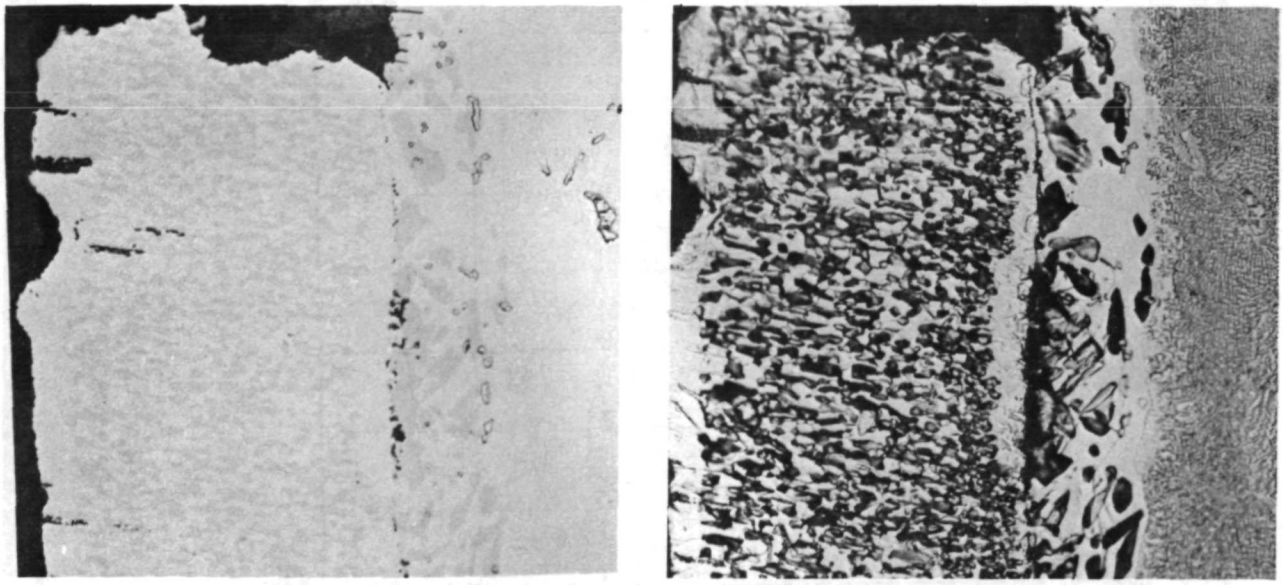


(B) SPEC. #15 0.075 CM (0.030 INCH), EXPOSED 982C (1800F), 989 HRS., ETCHED



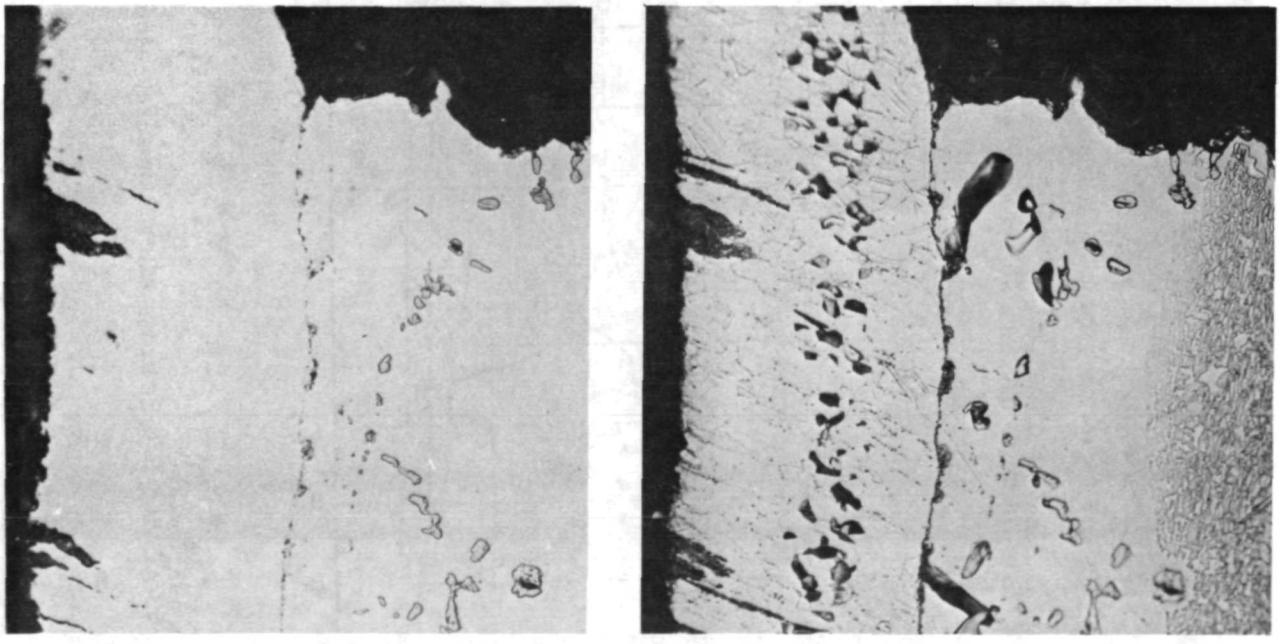
(C) SPEC. #-9, 0.075 CM (0.030 INCH), EXPOSED 1093C (2000F), 487 HRS., UNETCHED

Figure 51 Microstructure of Exposed Codep B-1 Coatings on Rene' 80 Tensile Tested at Room Temperature, 400X



(A) SPEC. #22, 0.075 CM (0.030 INCH), UNETCHED

EXPOSED 982C (1800F), 990 HRS. ETCHED



(B) SPEC. #72, 0.15 CM (0.060 INCH), UNETCHED

EXPOSED 1093C (2000F), 349 HRS. ETCHED

Figure 52 Microstructure of Exposed CoCrAlY Coatings on Rene'80 Tensile Tested at Room Temperature, 400X

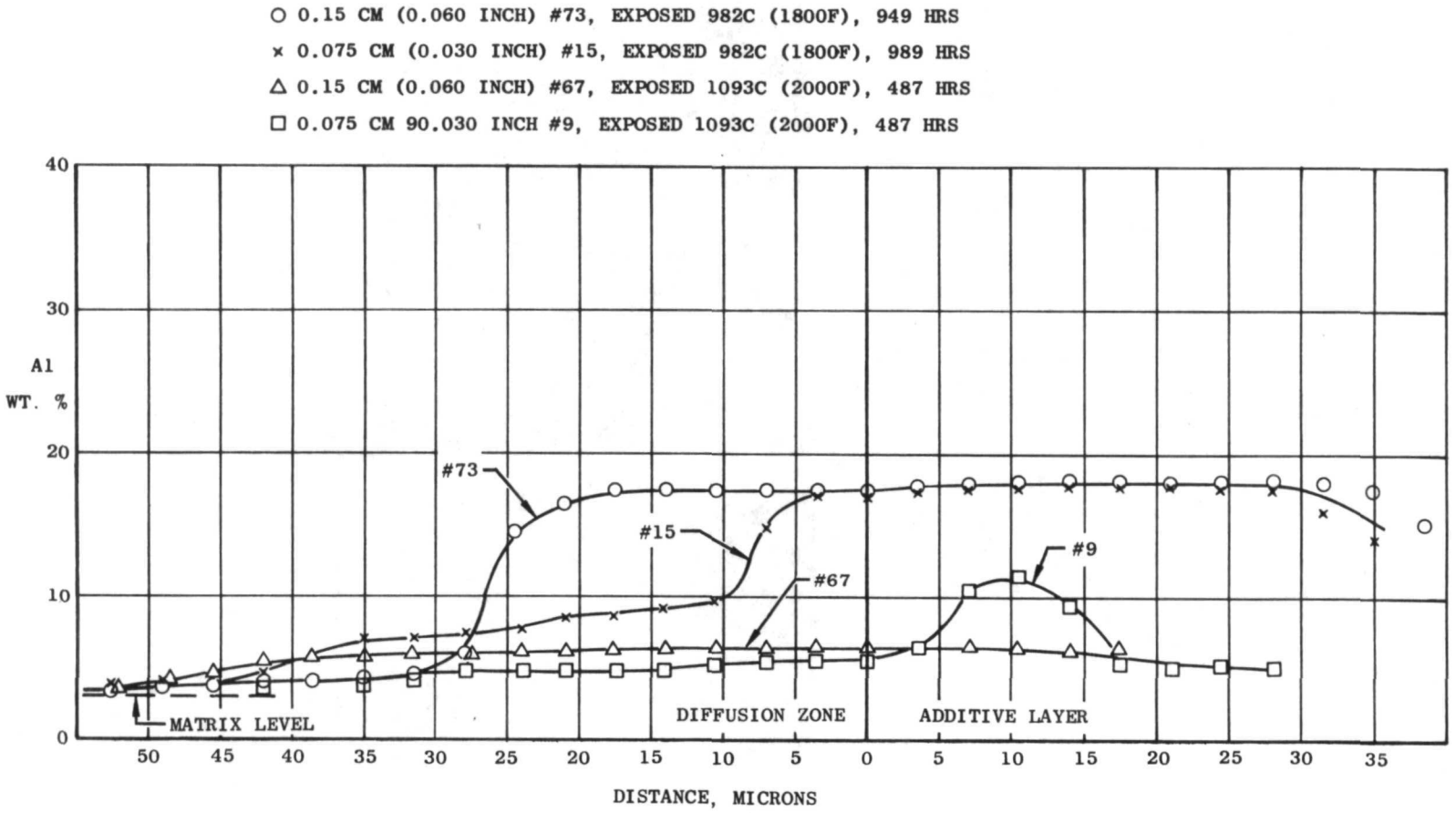


Figure 53 Codep B-1 Coating, After Exposure, Aluminum Content, Weight Percent

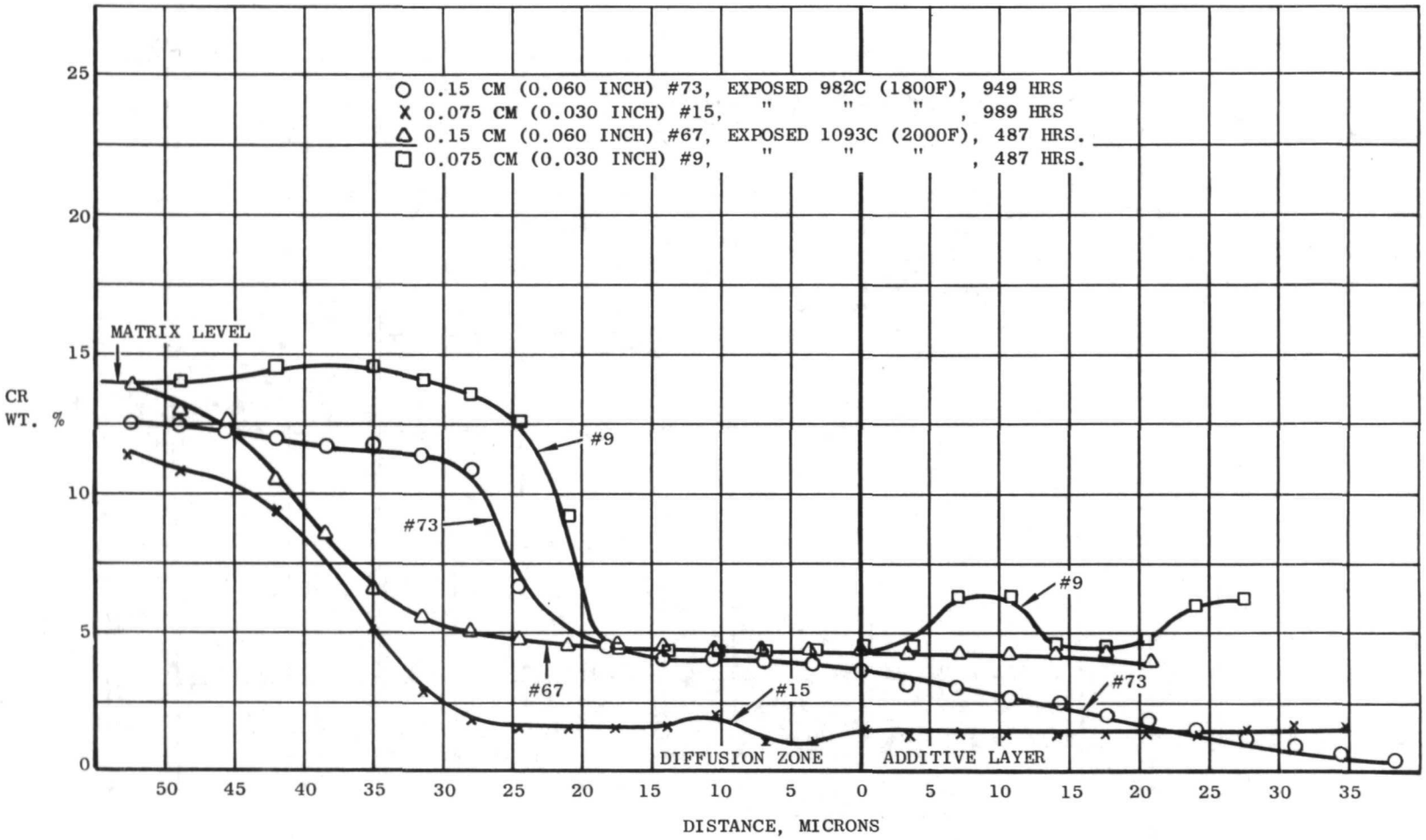


Figure 54 Codep B-1 Coating, After Exposure, Chromium Content, Weight Percent

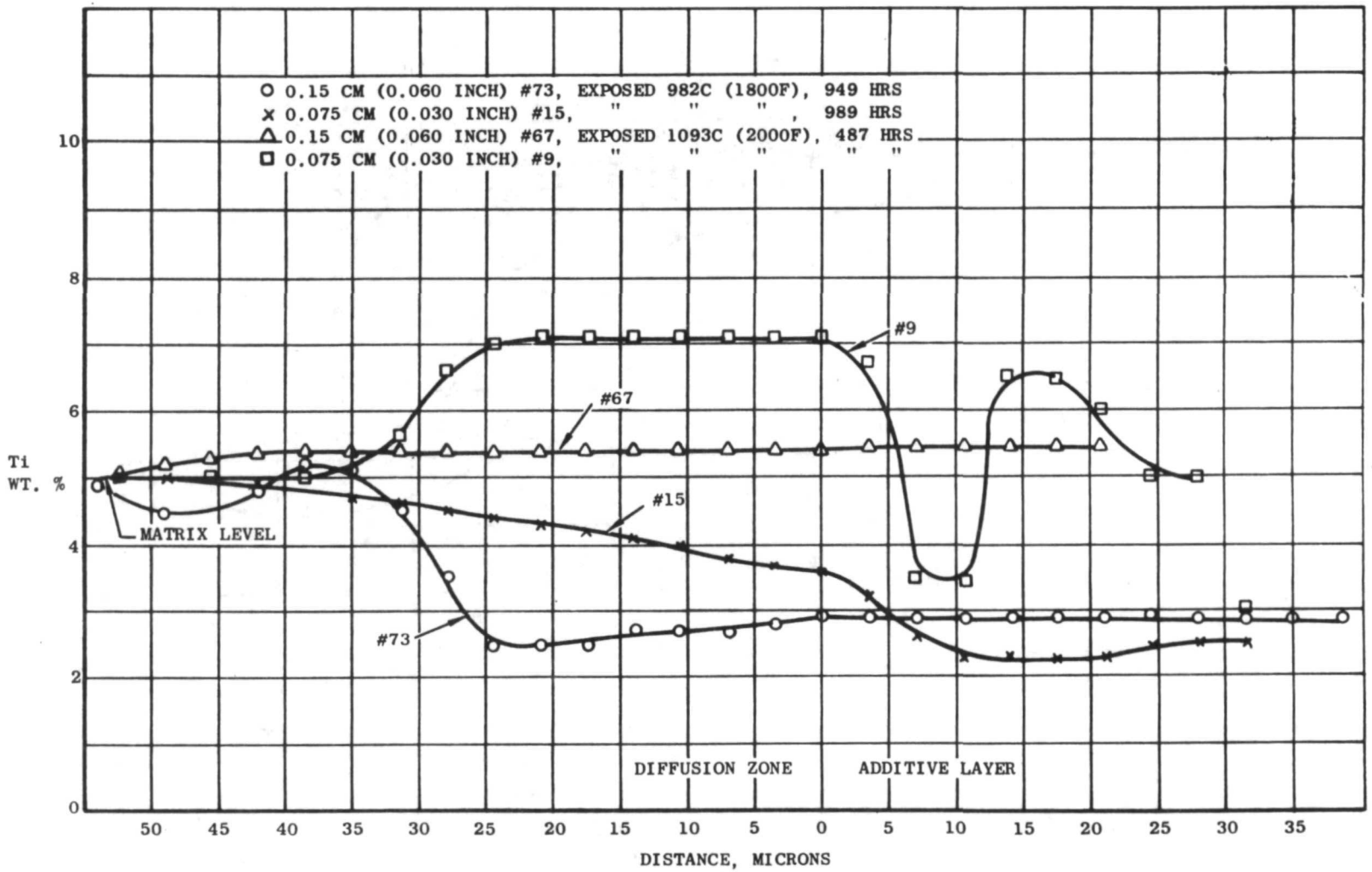


Figure 55 Codep B-1 Coating, After Exposure, Titanium Content, Weight Percent

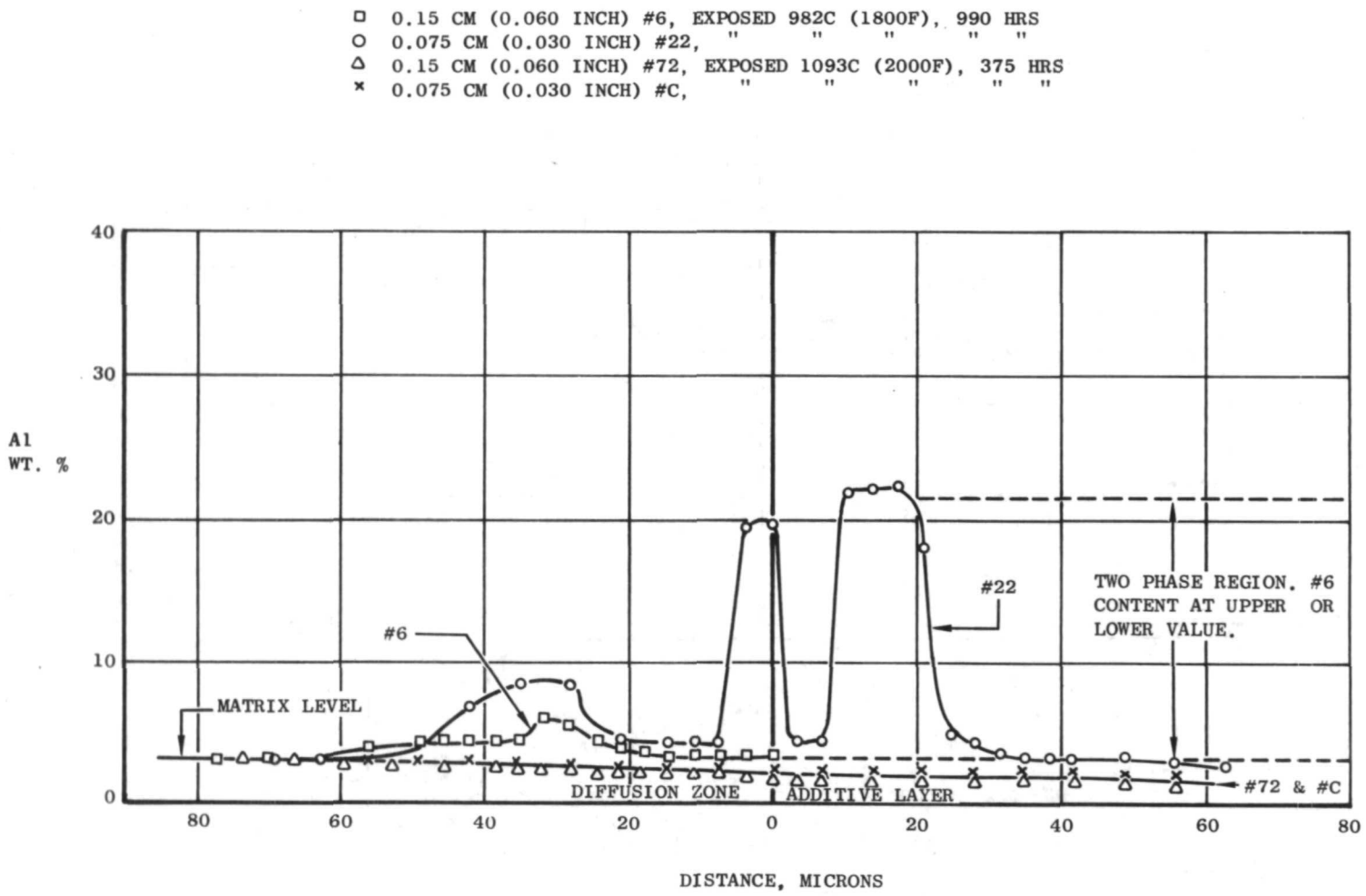


Figure 56 CoCrAlY Coating, After Exposure, Aluminum Content, Weight Percent

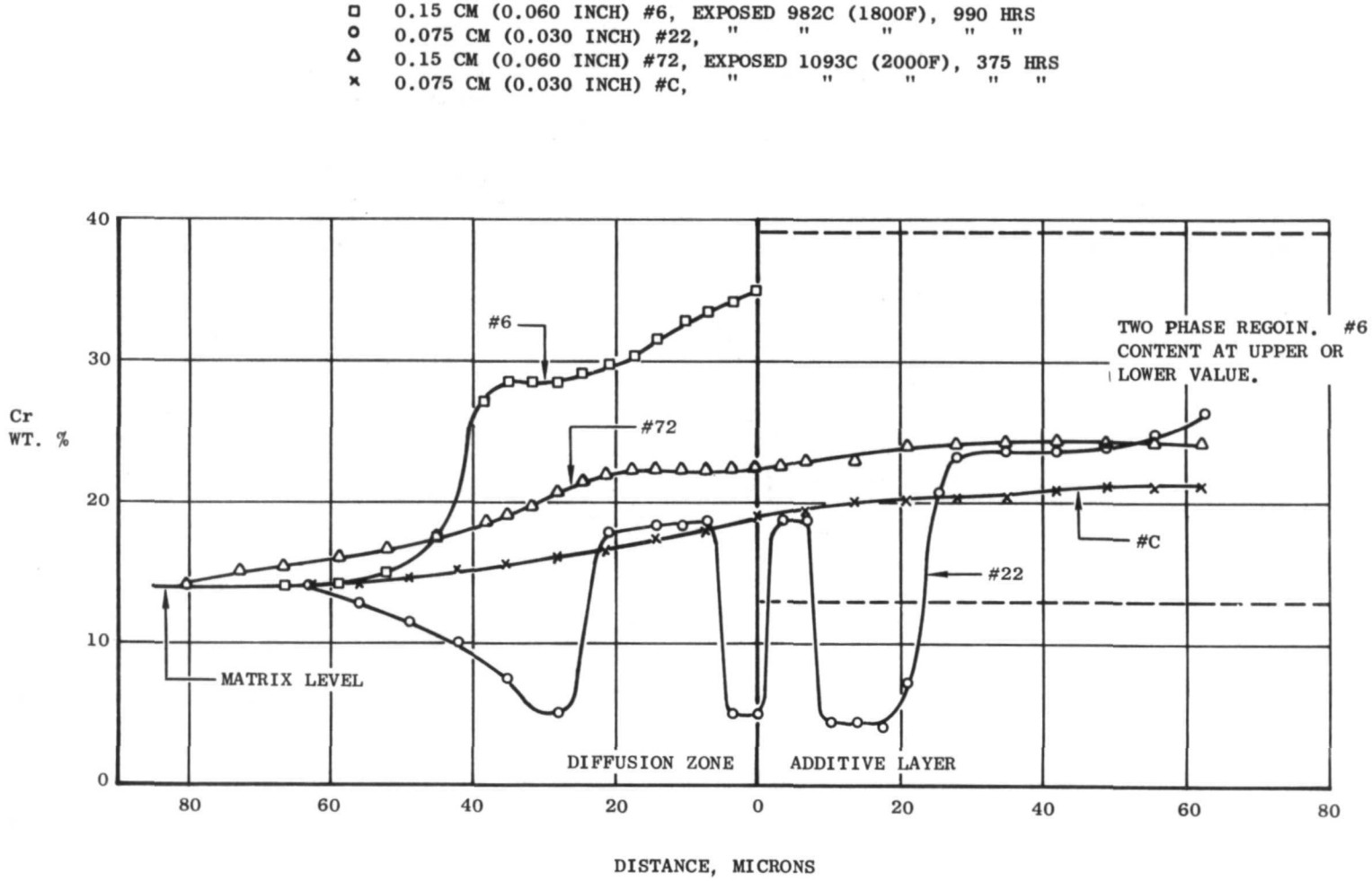


Figure 57 CoCrAlY Coating, After Exposure, Chromium Content, Weight Percent

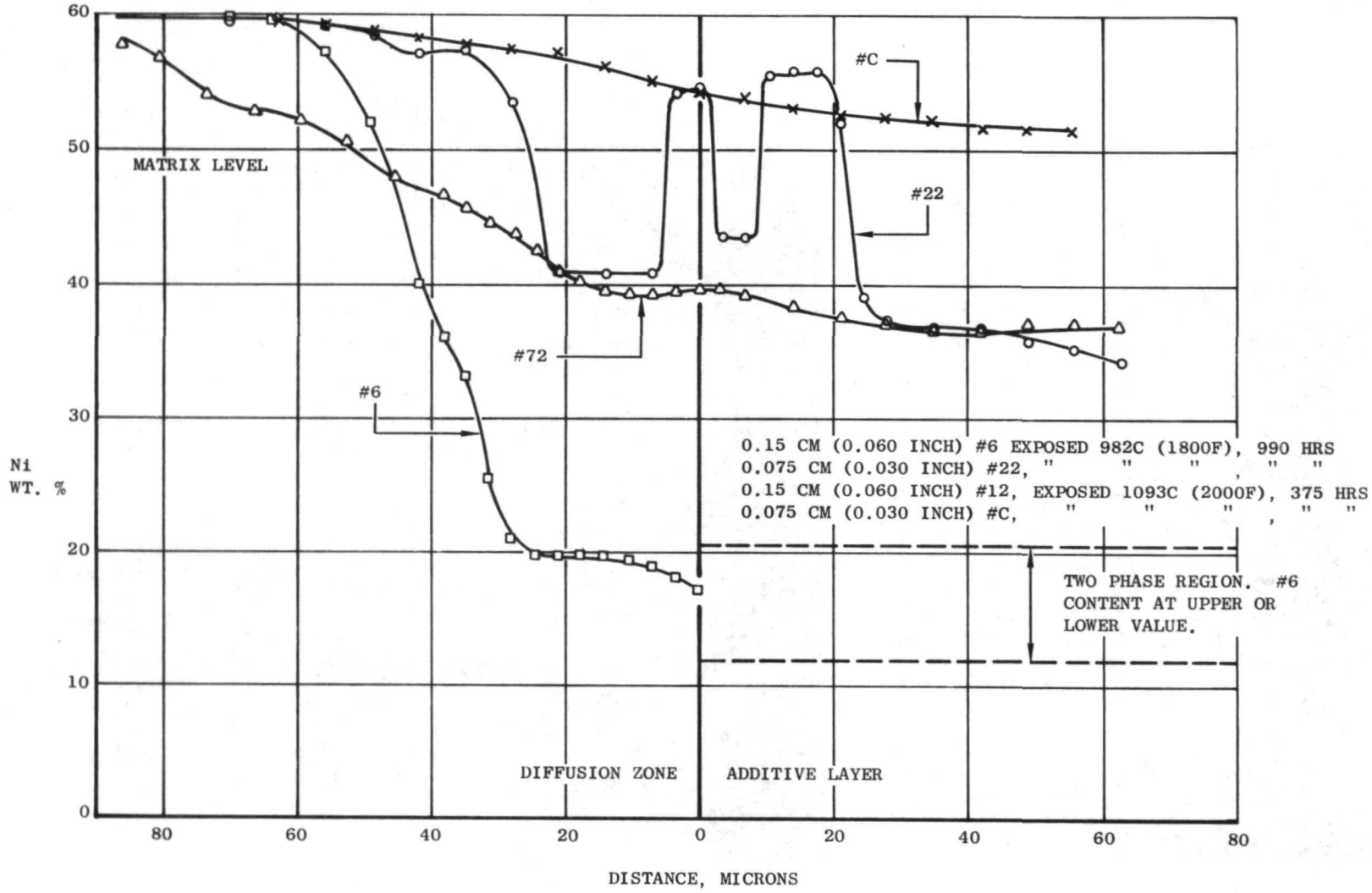
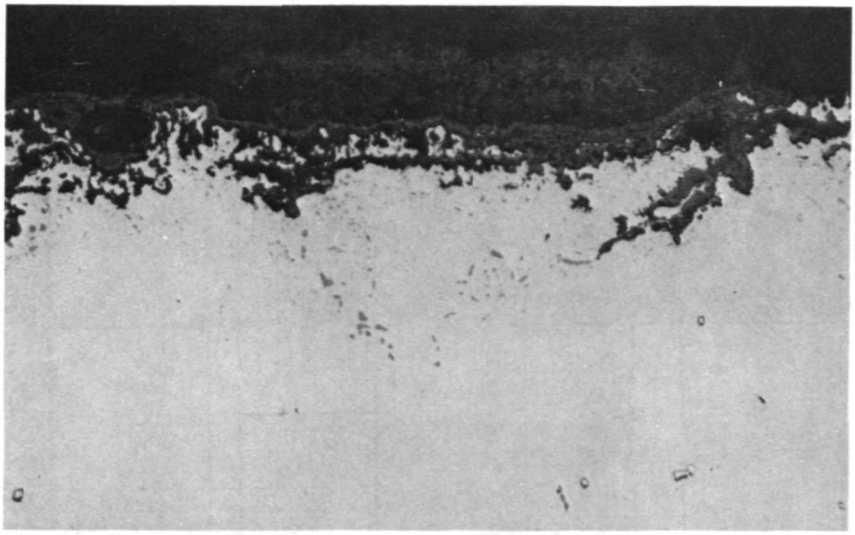
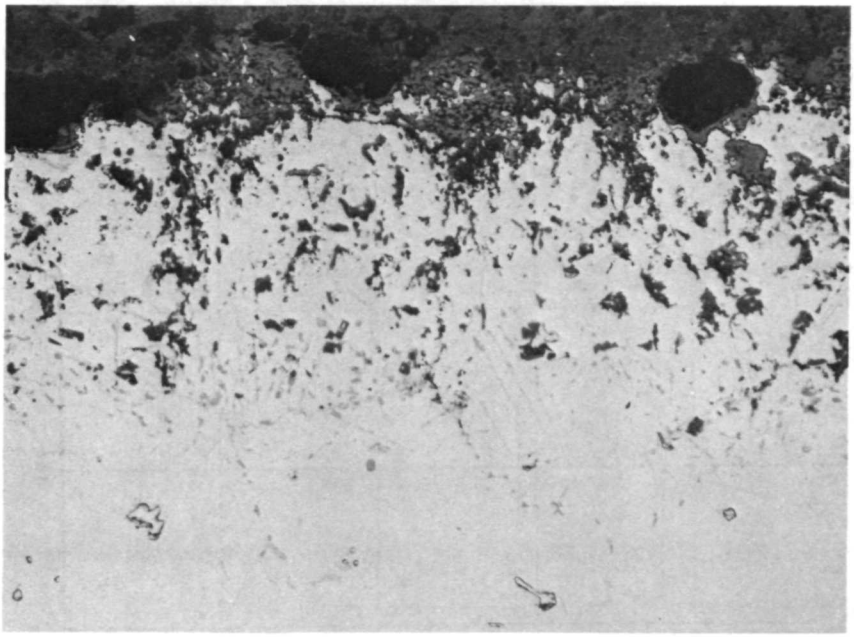


Figure 58 CoCrAlY Coating, After Exposure, Nickel Content, Weight Percent

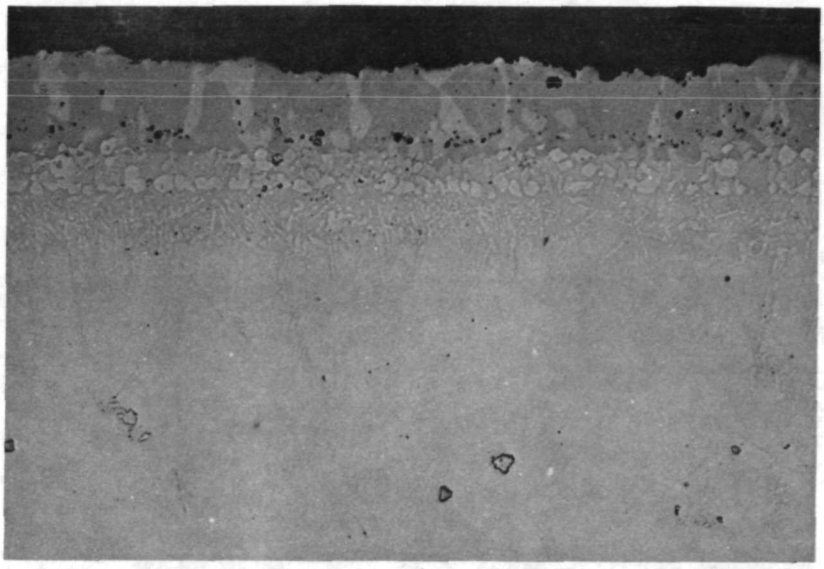


(A) SPEC. #G, UNEXPOSED, TESTED 473-1/2 HRS.

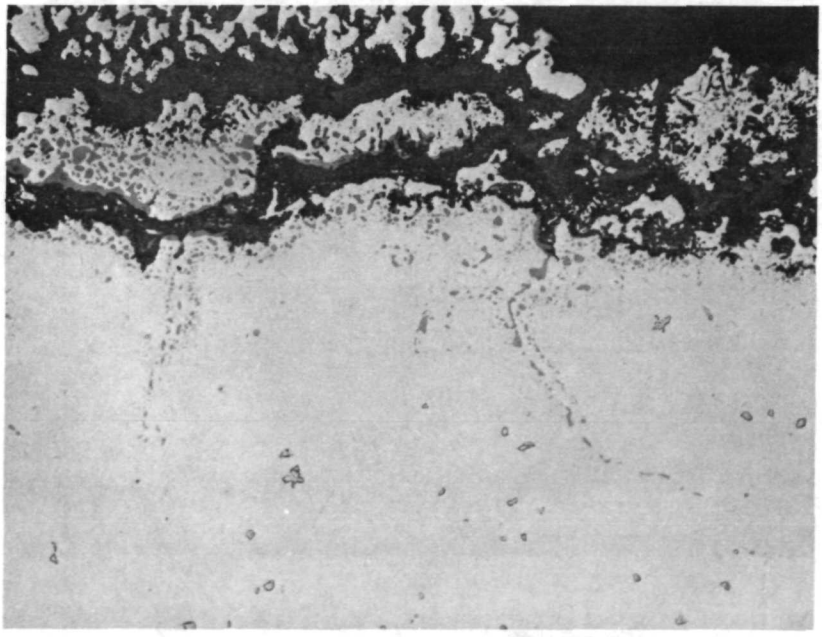


(B) SPEC. #19, EXPOSED 982C (1800F) 758 HRS, TESTED 346 HRS.

Figure 59 Structures After Hot Corrosion Test at 927C (1700F) Bare Rene'80, Unetched, 400X

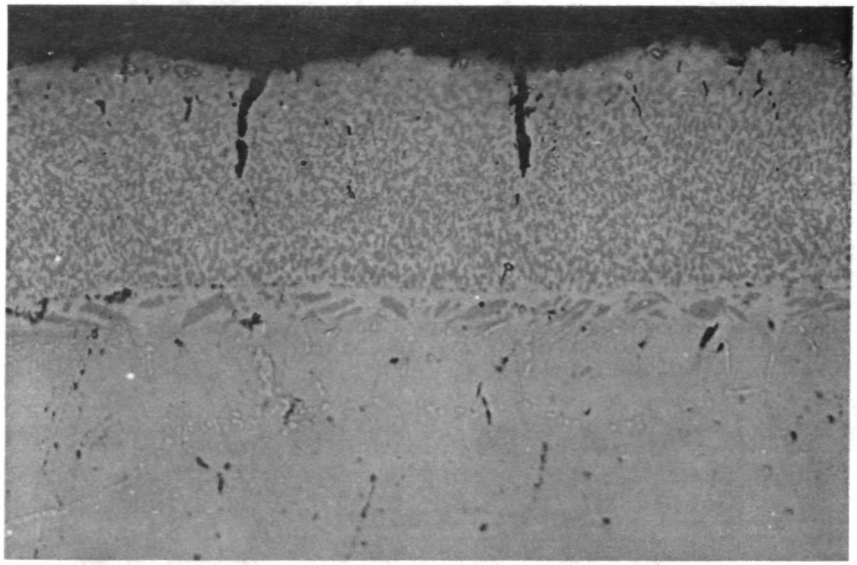


(A) SPEC. #10, EXPOSED 982C (1800F) 962 HRS, TESTED 61 HRS.

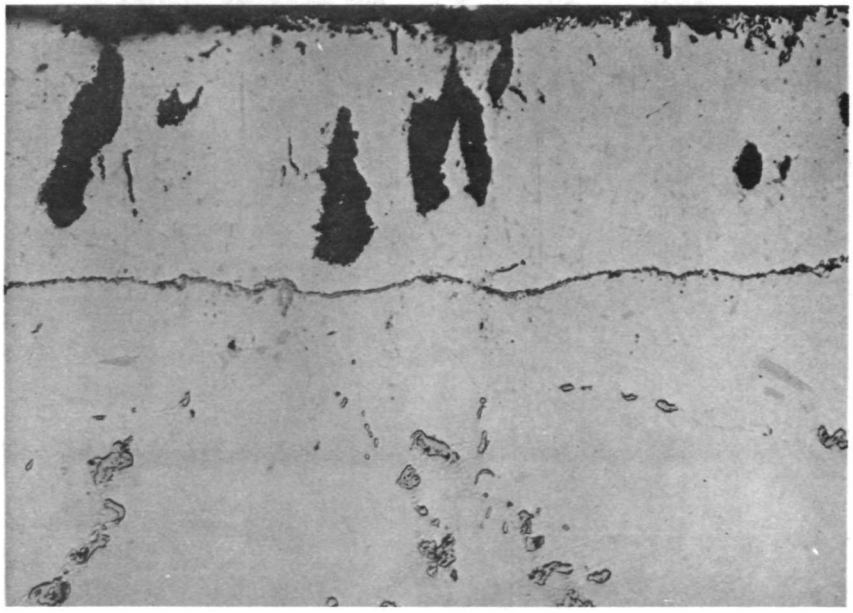


(B) SPEC. #C, UNEXPOSED, TESTED 435 HRS.

Figure 60 Structures After Hot Corrosion Test at 927C (1700F) Codep B-1 Coated Rene'80, Unetched, 400X



(A) SPEC. #10, UNEXPOSED, TESTED 473-1/2HRS.



(B) SPEC. #106, EXPOSED 1093C (2000F) 532 HRS, TESTED 184 HRS.

Figure 61 Structures After Hot Corrosion Test at 927C (1700F) CoCrAlY Coated Rene' 80, Unetched, 400X

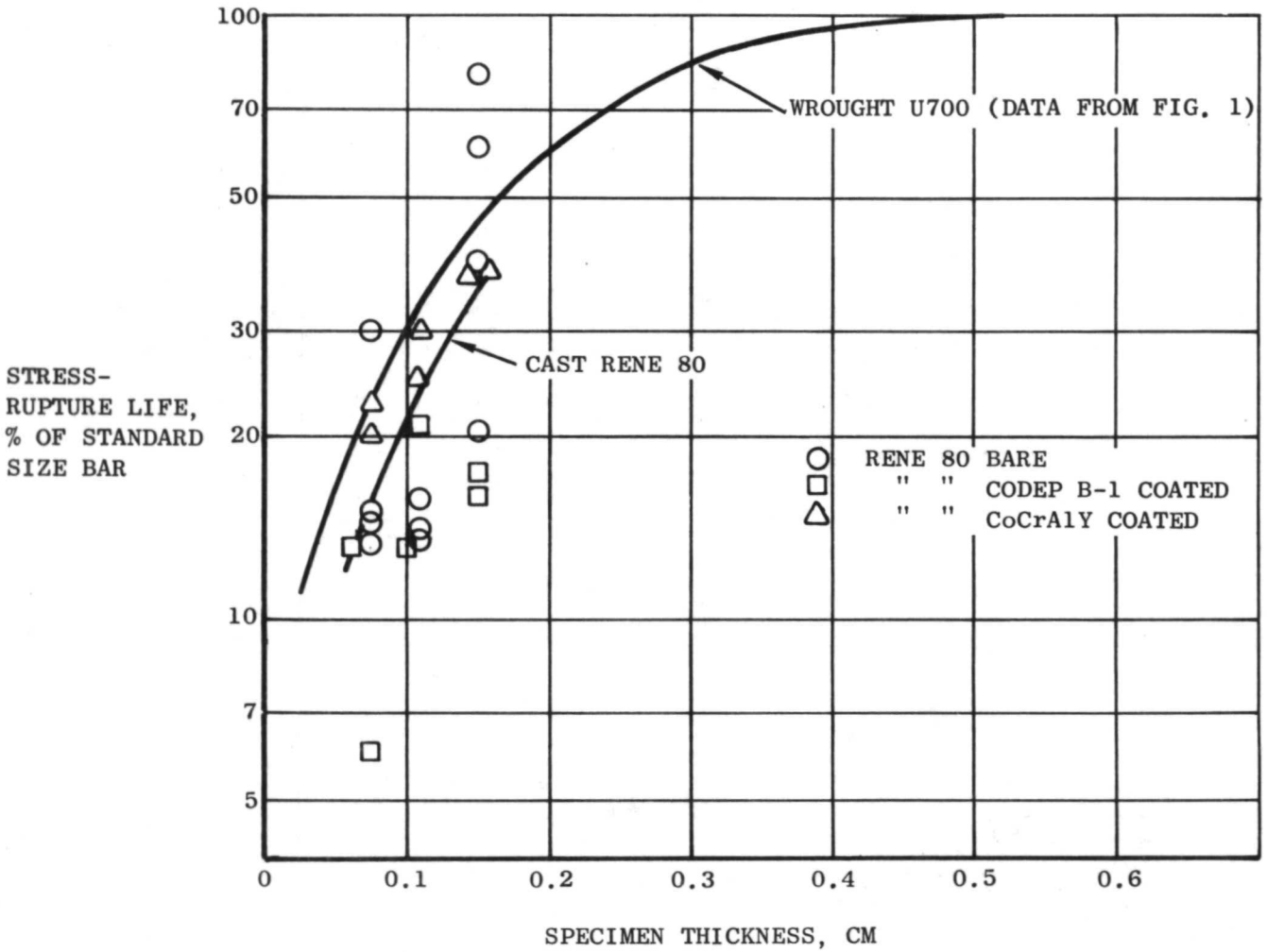


Figure 62 Relative Stress-Rupture Life of Cast Rene 80 and Wrought U700 at 982C (1800F)