

SEMI-ANNUAL REPORT NO. 2

PROTECTIVE COATINGS FOR CHROMIUM ALLOYS

by

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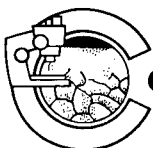
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FOREWORD

This program was initiated under National Aeronautics and Space Administration Contract No. NAS 3-7273 and is administered by the Lewis Research Center, Cleveland, Ohio. The NASA Project Manager during this reporting period has been Mr. Robert Oldreive and the NASA Research Advisor was Salvatore Grisaffe. This report covers the period from May 1, 1966 to November 1, 1966.

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ABSTRACT

The National Aeronautics and Space Administration, Lewis Research Center, initiated a program for the development of protective coatings for chromium alloys. The ultimate goal of this program is to develop coated materials which can operate for 3000 hours in the temperature range of 2100°F to 2400°F.

Three coating approaches are under investigation:

- A nitrification-oxidation resistant, simple aluminum system employing pack-cementation coating techniques.
- A nitrification-oxidation resistant aluminum system incorporating iron, cobalt and/or titanium. (The incorporation of iron and/or cobalt is used in order to form spinel-aluminates upon exposure.)
- An aluminum-type system with an incorporated "glassy-phase".

The experimental activities during this report period centered around attempts at depositing the aforementioned coating systems concurrent with evaluating them according to the provisions set forth in the subject contract. Based upon data obtained in the first six month period, it was decided between cognizant NASA and Chromalloy personnel that two simple aluminum systems would be taken into the Advanced Testing Phase of the work schedule. Ductile bend transition, cyclic oxidation and continuous weight change tests were completed.

The data indicates that although resistance to nitrogen attack was in fact accomplished, high bend transition temperatures (>1500°F)

were seen in the as coated and coated and exposed conditions.

Concurrent with the above mentioned advanced testing work, a considerable effort was expended in determining methods for depositing modified (Ti, Co, Fe) aluminum coatings. Although methods for depositing titanium were established, metallographic examination and cyclic oxidation tests showed no improvement in oxidation-nitirification resistance over that seen in the simple aluminum system. Further, all attempts at depositing cobalt met with little or no success, in that the presence of intergranular attack was always noted. In addition, a fully dense coating was never realized.

Much of the difficulty previously encountered with the deposition of iron has apparently been resolved by the use of an inert atmosphere retort and a high chromium-potential pack. Although the oxidation-nitrification resistance of the coatings attempted thus far is marginal, it would appear that lower aluminizing temperatures employed in this two-step coating system give increased oxidation-nitrification resistance.

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1

INTRODUCTION

1.1 GENERAL

Through the years gas turbine engine manufacturers have sought to sophisticate their engines and minimize operating costs by increasing the thrust-to-weight ratio and necessarily decreasing the specific fuel consumption. To this end, more and more stringent demands have been made of ancillary technologies, i.e. lubricants, fuels, materials, etc. The key to increasing specific fuel consumption lies in increasing the thermal efficiency of the gas turbine engine by increasing the turbine inlet temperatures.

Engine manufacturers and alloy producers have thus concentrated their efforts on the development of turbine blade and stator alloys with high temperature properties superior to those of current generation nickel and cobalt base alloys. However, for application at material temperatures in excess of 2000°F, the use of alloy systems of nickel and cobalt appear prohibitive due to their strength, rigidity, melting point, and corrosive attack limitations. Because of these limitations, ceramic materials, composite (i.e. fiber and/or dispersion strengthened) materials, or refractory metals must be considered. The limitations of these materials are well known. TD nickel, TD-nickel-chromium and similar dispersed particle and fiber composite materials, however, may be of potential use for future engine applications.

A survey of all those materials capable of withstanding the anticipated severe conditions of new-generation turbine engines cannot

discount the extremely attractive properties of chromium. Several investigators have demonstrated quite clearly that chromium base alloys maintain an outstanding degree of resistance to deformation (creep) and oxidation at elevated temperatures. Further, its high melting point (3500°F), low density (relative to the refractory metals and ceramics) and high strength at temperatures in excess of 2000°F surely place it in a position of extreme promise. Although a list of the attractive properties of chromium is impressive, another list enumerating its inherent deficiencies would be of almost equal size. The most significant of these deficiencies are those of low temperature brittleness and severe nitrogen contamination and further embrittlement after high temperature exposure. Since it is not the goal of this development contract to produce ductile chromium, the immediate aims are necessarily the development of coating systems capable of:

- Inhibiting the diffusion of nitrogen into the program alloy, designated Cr-5W-.02Y (a prototype alloy chosen to establish a state-of-the-art for coating Cr alloys).
- Increasing the oxidation resistance in the range 2100-2400°F while not causing embrittlement due to any chemical reactions resulting from the coating process.
- Minimizing chromium losses due to its high vapor pressure at temperature in excess of 2100°F.

This contract encompasses the development and evaluation of aluminum coatings on the designated Cr-5W-Y alloy, with the ultimate goal being the protection of the substrate for 3000 hours at 2400°F. The coating systems under development consist of:

1. Spinel forming coatings:

Al-Fe, Al-Co, Al-Fe-Co.

2. Simple aluminum and solid solution tetravalent types:

Al, Al-Ti.

3. Spinel-tetravalent scavenger types:

Al-Fe-Co, Al-Co-Ti, Al-Fe-Ti.

All of the work conducted during this period was devoted to attempts at depositing those coatings as described above and screening them under a static-oxidation test environment at 2100°F and 2400°F.

2

TECHNICAL PROGRESS

2.1 GENERAL

The work conducted during this reporting period was essentially divided into two separate categories as follows:

- a. The continued evaluation of deposition characteristics and oxidation testing of modified (Ti, Fe, Co) aluminum coating systems.
- b. The advanced testing of two simple-aluminum systems developed during the first six months of the subject contract.

Although some equipment difficulty was encountered during this period, data were obtained which allowed for the development of deposition techniques for iron and titanium.

Modified aluminum coatings are discussed first because the tests conducted on these systems were within the earlier screening phase of the program.

2.2 TITANIUM-ALUMINUM SYSTEMS

As discussed briefly in the Literature Review presented in the first Semi-Annual Report, there have been indications that the addition of certain tetravalent elements (e.g. titanium) improves the oxidation resistance of chromium. The work begun during the last reporting period in an attempt to incorporate titanium into aluminum-type coating systems has been continued. It has been determined that the deposition of titanium on chromium can be accomplished in standard retorts only by

the addition of chromium to the pack. Further, the duplex coating process (titanium and aluminum) could be accomplished by deposition of either aluminum or titanium first. Table I shows the experimental coating trials conducted on the substrate alloy. As can be seen from the data presented, the deposition of a titanium-aluminum coating system, although feasible, must be conducted at extremely high temperatures which may further substrate embrittlement and result in a large recrystallized grain size. Further, the use of an aluminizing pack with equal quantities of chromium and aluminum proved to be the most efficient method for deposition of aluminum on the titanium (i.e. no weight losses seen). The high vapor pressure of chromium at 2200°F makes the adjustment of pack composition and processing time and temperature quite critical, as can be noted in several experiments where a weight loss (after coating) was observed. Figures 2-1 and 2-2 show typical microstructures of Ti and Ti/Al coated Cr-5W-Y. Note that in the duplex coating the aluminum was deposited first. The "cracking" seen in the latter photomicrograph is due to metallographic polishing and was not in fact present in the as coated specimens.

A. The semi-quantitative electron-beam-microprobe traces (EBMP) illustrated in Figures 2-3 and 2-4 show the extent of titanium and aluminum diffusion. Note that both these specimens showed titanium (peak) concentrations of approximately 10 W/o. The specimens run in XP19108 (titanized-aluminized) showed the best oxidation-nitridation resistance and although not shown, EBMP analyses indicated that the maximum concentration of this coating was 1.5 W/o at a depth of .5 mils and decreased rapidly further inward. This would then tend to indicate that the oxidation-nitridation resistance of a titanium modified aluminum system is inversely proportional

TABLE I

TITANIUM-ALUMINUM EXPERIMENTAL COATING TRIALS

ON Cr-5W-Y SUBSTRATE

XP#	PACK COMPOSITION				I ₂	°F/Hrs. Process	Weight Change mg/cm ²	Coating Thickness Mils	Comments
	Ti	Cr	Al ₂ O ₃	TiH ₂					
19076	20	20	60	3	1/4	2200/10	12.8	0.8	Sponge like coating.
19085	37.5	37.5	25		1/4	2200/10	10.6	0.6	Sponge like coating.
19092	25	5	70		1/4	2100/10			Burn out.
19097	25	5	70	3	1/4	2200/10	-10.7		No coating.
19111	37.5	37.5	25		1/4	2100/10			Burn out.
19108	8.36 Al	22.34	69.3		1/4	2000/10 K ₂ SiF ₆	4.56	2.0	Tabs were previously titanium coated XP19085.
19115	37.5	37.5	25	2	1/4	1800/10			No coating.
19117	37.5	37.5	25		1/4	2200/10	6.93	4.0	Tabs were previously aluminized in XP19102. UK.
19118	37.5	37.5	25		1/4	2200/40	-14.1	5.0	Tabs were previously aluminized in XP19102. UK.

FIGURE 2-1

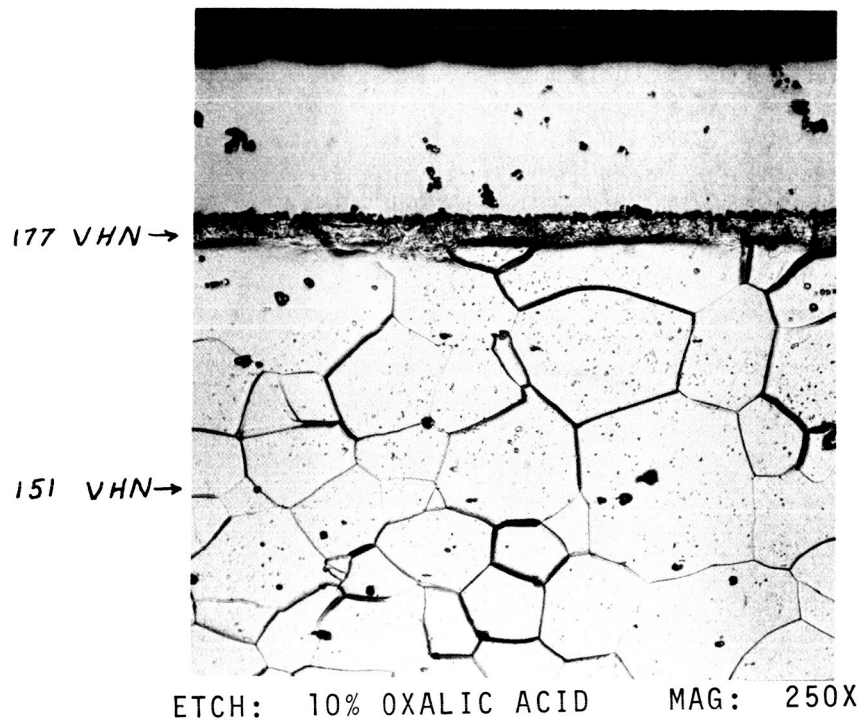
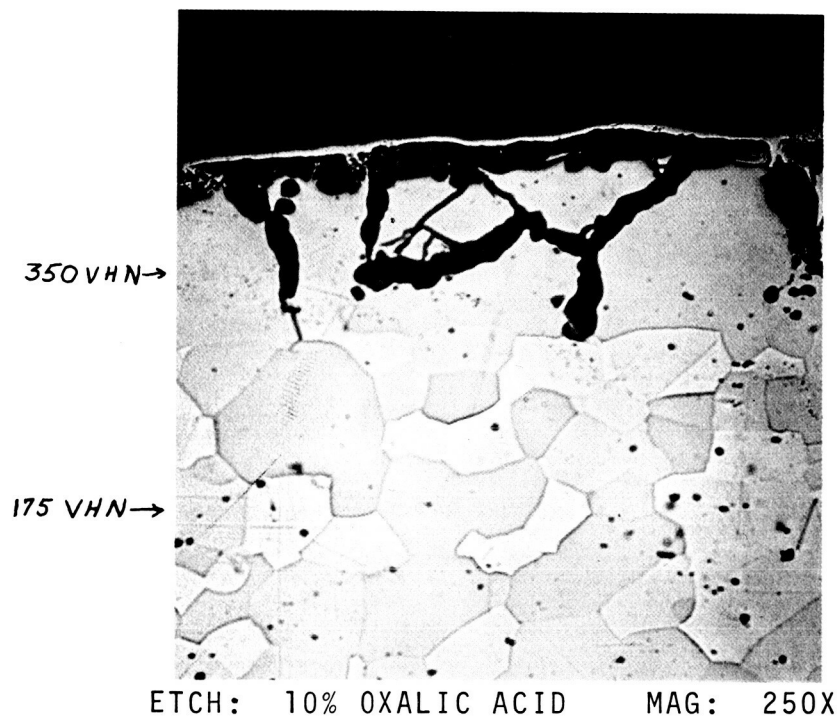
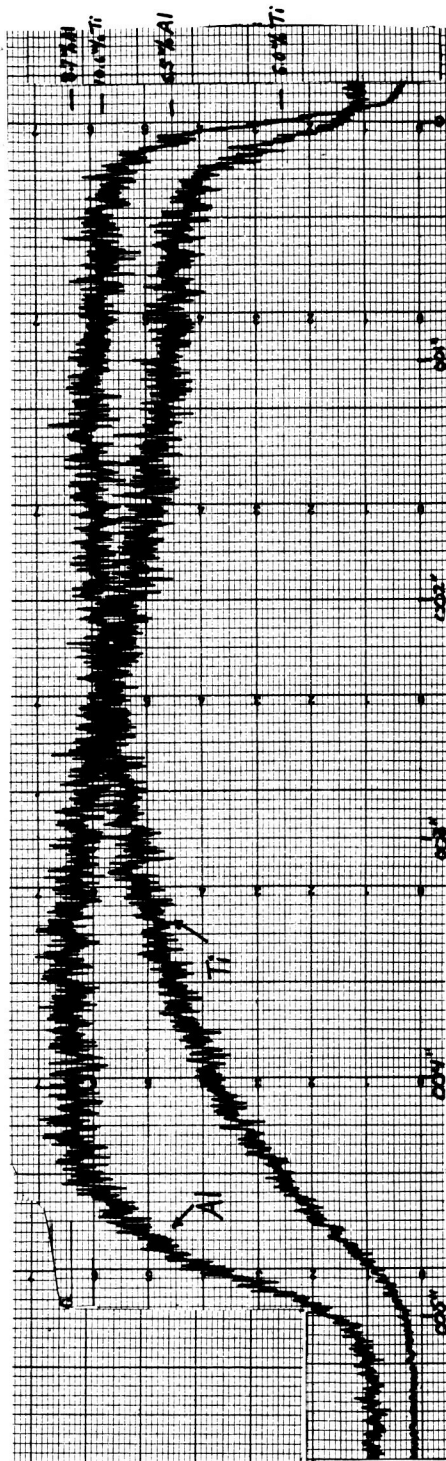


FIGURE 2-2



TITANIUM AND TITANIUM-ALUMINUM COATINGS ON Cr-5W-Y, AS COATED.
FIGURE 2-1 SHOWS TITANIUM DEPOSITED ON BARE SUBSTRATE (XP19118).
FIGURE 2-2 SHOWS TITANIUM DEPOSITED ON PRE-ALUMINIZED SUBSTRATE
(XP19102 + 19118).



ELECTRON BEAM MICROPROBE TRAVERSE OF TITANIUM-ALUMINUM COATED Cr-5W-Y. SPECIMENS WERE ALUMINIZED PRIOR TO THE TITANIUM DEPOSITION.

FIGURE 2-4 (TOP). XP19117. PACK CONTAINS 30% METAL

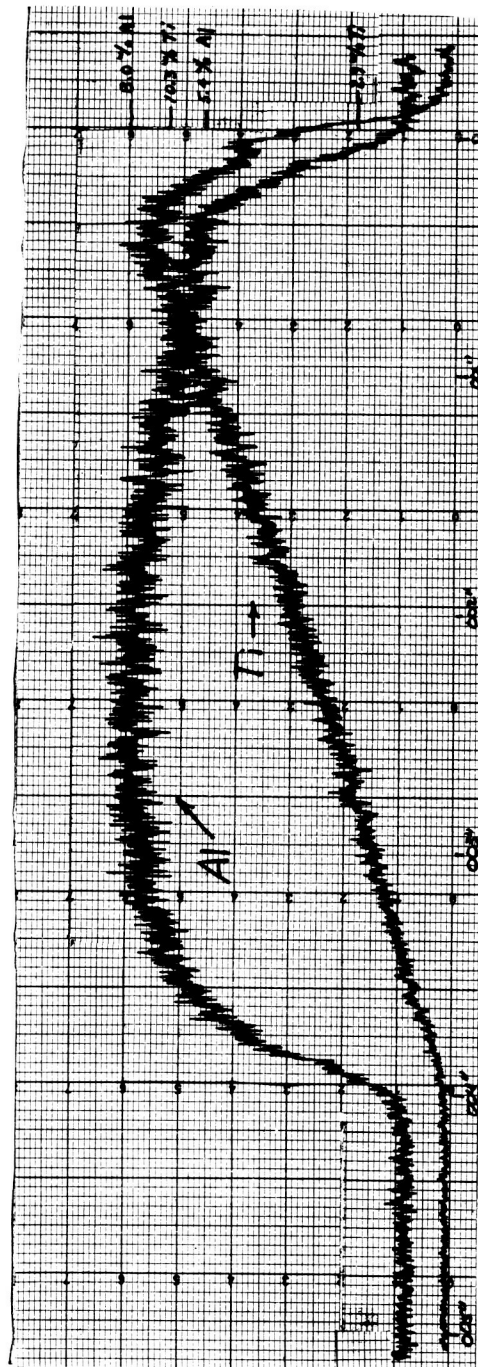
OF EQUAL WEIGHTS OF TITANIUM AND

CHROMIUM, PROCESSED AT 2200°F/10 hrs.

FIGURE 2-3 (BOTTOM). XP19118. PACK CONTAINS 30% METAL

OF EQUAL WEIGHTS OF TITANIUM AND

CHROMIUM, PROCESSED AT 2200°F/40 hrs.



to the titanium concentration. However, it must be reiterated that although the use of titanium as a means of modifying an aluminum system has deleterious effects on oxidation-nitrification resistance, a system such as those described are in fact much more resistant to attack than is the bare substrate.

B. Figure 2-5 shows three tabs from experimental runs after 100-hour exposures at 2400°F. Note the severe attack and coating spalling seen on all three specimens with the specimen from XP19108 (Ti then Al) showing the least attack.

C. Oxidation-weight change curves for several Ti/Al coating systems are shown in Figure 2-6. As can be seen from these data, the oxidation-nitrification resistance of any of these systems at 2400°F, although better than bare material, is poorer than a simple (note curve for two-phase coating) aluminum coating.

D. Based upon much of the above described data, it is felt that there appears to be little promise afforded by titanium modified aluminum systems. Further, it is not within the scope of this program to pursue this approach any further.

2.3 SPINEL FORMING ALUMINUM SYSTEMS

As discussed previously, the formation of Cr_2O_3 on oxidation tested chromium does not deter further oxidation and nitrification of the substrate material. This is due in part to the fact that Cr_2O_3 has a defect lattice structure and is not stable. It is well known that the oxidation resistance afforded by spinels (e.g. $\text{NiO} \cdot \text{Cr}_2\text{O}_3$) on the surface of many alloys is in most cases superior to that of pure oxides. This

2400°F/100 hr's



XP19108

XP19117

XP19118

XP 19108

Titanium 2200°F/10 hours

Aluminum 2000°F/10 hours

XP 19117

Aluminum 2000°F/10 hours

Titanium 2200°F/10 hours

XP 19118

Aluminum 2000°F/10 hours

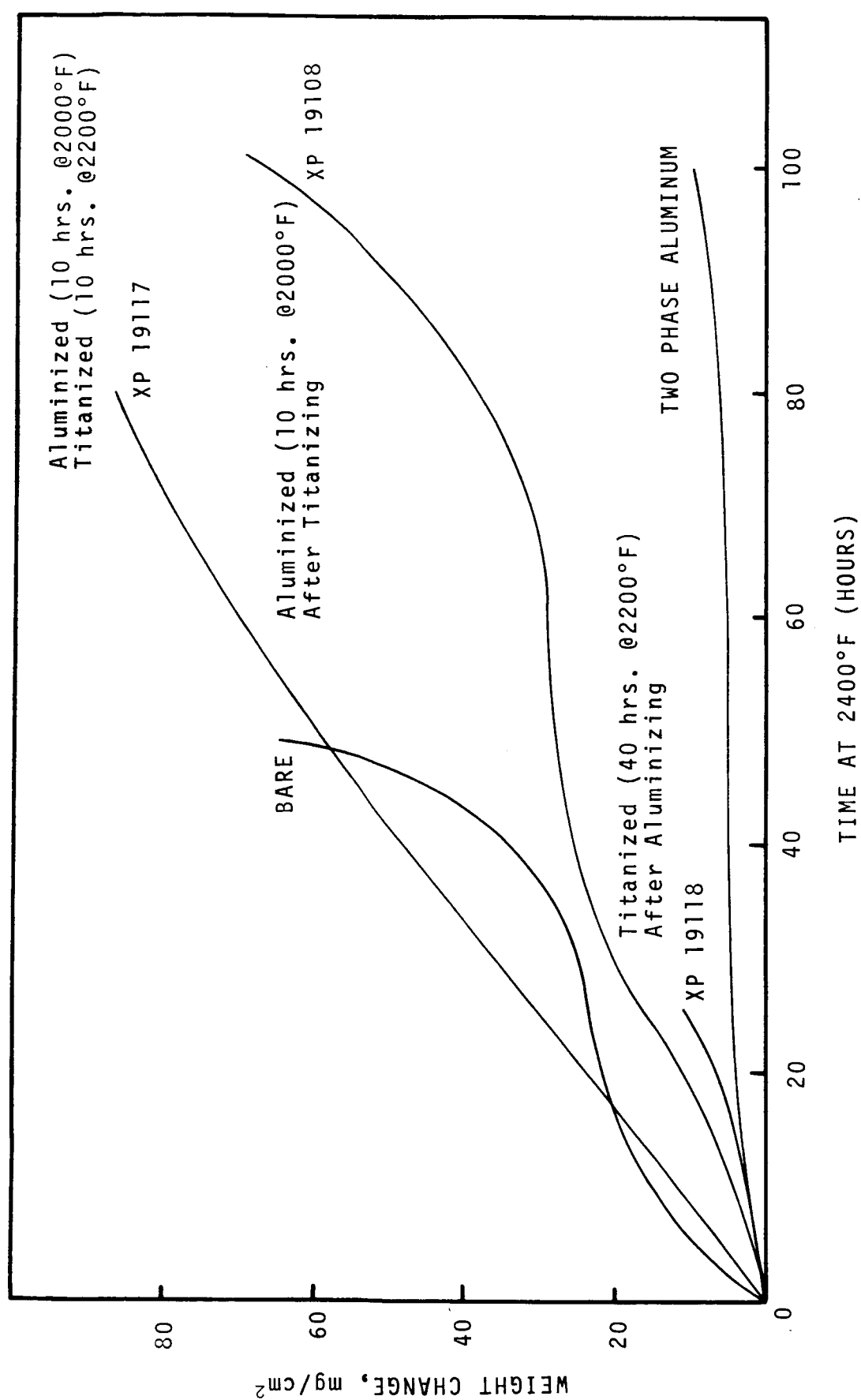
Titanium 2200°F/40 hours

FIGURE 2-5

TITANIUM-ALUMINUM COATINGS ON Cr-5W-Y AFTER 100 HOURS AT 2400°F.
NOTE IMPROVED RESISTANCE TO ATTACK OF SPECIMEN (XP 19108) CONTAINING
LEAST AMOUNT OF TITANIUM.

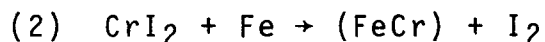
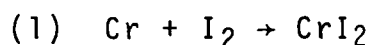
FIGURE 2-6

OXIDATION CURVES AT 2400°F FOR TITANIUM-ALUMINUM
COATINGS ON Cr-5W-Y ALLOY.

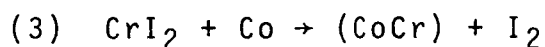


is due in part to the usual superior plasticity (1) and lattice density of these spinels. It is of interest to mention here that the superior oxidation/nitrification resistance of the program alloy (Cr-5W-Y) is in fact believed to be attributable to the formation of an Y-Cr₂O₃ type spinel on the surface of the exposed material (2).

Several experiments were conducted prior to the commencement of this contract which conclusively proved that deposition of either iron or cobalt from packs containing these elements and a halide energizer was impossible. Thermodynamically the deposition of Fe or Co is not favored and the deposition experiments offer confirmation. The reactions with the halides proceed as:



or



The above reactions necessarily can affect a large weight change (loss) in the substrate alloy and consequently the iron and/or cobalt powder in the pack becomes coated with chromium. From these data it was decided to accomplish the deposition of aluminum coatings bearing iron and/or cobalt by one of three methods:

A. Co-deposition with aluminum

B. Deposition from the metal halides followed by aluminizing

C. Deposition from Fe-Cr, or Co-Cr packs followed by
aluminizing.

(1) Journal of Electrochemical Society, E.G. Felton, 1961, Volume 108, Page 490.

(2) Corrosion Science, Seybolt, 1966, Volume 6, Pages 263-269.

An attempt to deposit by Methods A and B met with little or no success and will be discussed below. For the purposes of clarity, the deposition of iron and cobalt will be discussed separately.

2.3.1 Cobalt-Aluminum Systems

The choice of cobalt as a modifier to aluminum coatings on the Cr-5W-Y substrate had as its foundation the same reasoning as for the choice of iron, i.e. that both elements have strong tendencies to form spinels. As has been discussed in the previous Semi-Annual Report, the deposition of cobalt from conventional packs (Co, Al_2O_3 , NH_4FHF) proved to be unsuccessful due to the attendant corrosive attack of the substrate seen. Further, although it was thought that deposition might be best accomplished by the use of cobaltous-halides, this too resulted in corrosive attack and, in addition, lack of uniformity and reproducibility. Finally, the attempts at co-deposition also met with little or no success. Based on these data, all the efforts expended during this period were aimed at depositing the cobalt modified system in a duplex manner. The procedures followed those employed with the previously described titanium system with the exception that in almost all cases the experiments were run under either flowing or static argon atmospheres. Table II shows the results of the experimental coating trials conducted on the cobalt aluminum systems. Figures 2-7 and 2-8 show typical microstructures of cobalt coated Cr-5W-Y substrate. The use of a faulty retort resulted in considerable contamination of the substrate (Figure 2-7). However, as can also be noted, some contamination and voids are also present in the specimen seen in Figure 2-8. At this time the reasons for this

TABLE II
COBALT-ALUMINUM EXPERIMENTAL COATING TRIALS

ON Cr-5W-Y SUBSTRATE

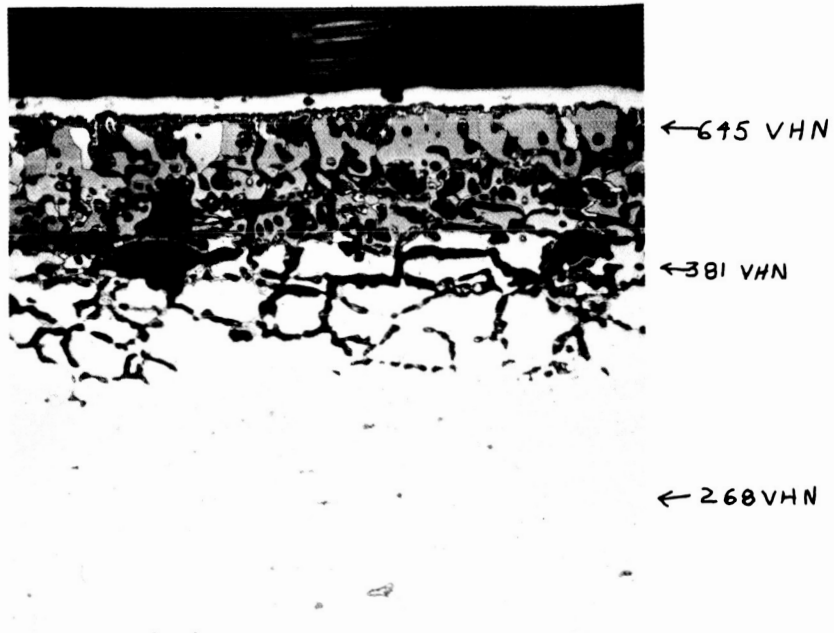
XP#	PACK COMPOSITIONS				I ₂	Process °F/Hrs.	Weight Change mg/cm ²	Coating Thickness Mils	Comments
	Co	Cr	Al	Al ₂ O ₃					
19079	(CoBr ₂) ₅			95		1900/10			Heavy oxide. Non-magnetic.
19083	25	5		70	1/4	2200/10	-82.55		No coating. Low melt phase present. Heavy attack.*
19084	25	2.5		72.5	1/4	2200/10	-63.34		No coating. Low melt phase present. Heavy attack.*
19125	62.5	12.5		25	1/2	2100/10			Powder burn out.
19128	62.5	12.5		25	1/4	2200/10			Tabs were attacked.*
19132	62.5	12.5		25	1/4	2100/10	3.32		Tabs previously aluminized in XP19127. Attack.
19136	62.5	12.5		25	1/4	2200/10	28.0		Heavy attack.*
19137	62.5	12.5		25	1/4	2200/10	-27.0		Heavy attack.*
19144	62.5	12.5		25	1/4	1900/23	-1.94		Heavy attack.**

* Argon

** Argon Flow

FIGURE 2-7

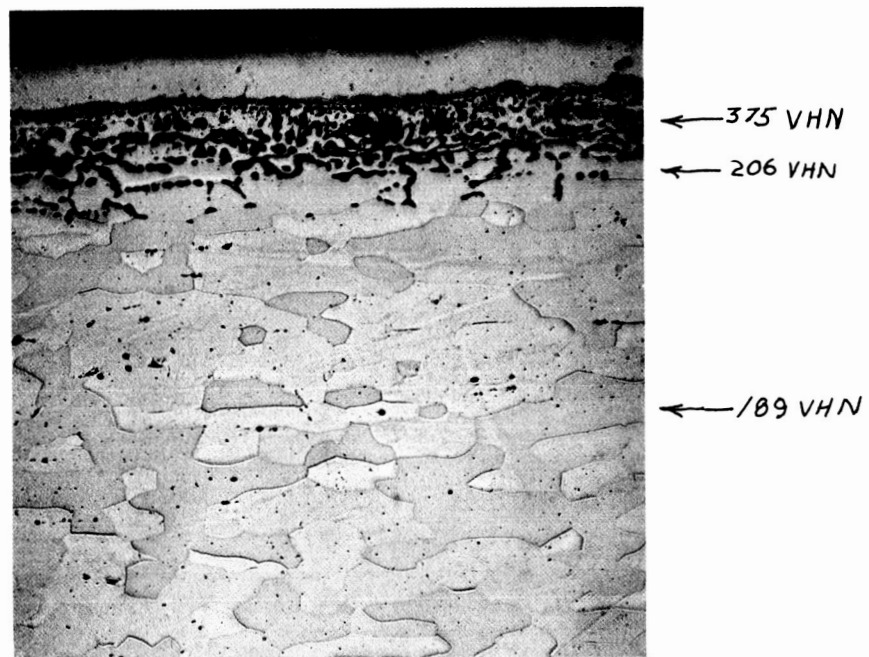
VOIDS AND HIGH COBALT
CONCENTRATION AREAS



ETCH: 10% OXALIC ACID MAG: 250X

FIGURE 2-8

VOIDS AND HIGH COBALT
CONCENTRATION AREAS



ETCH: 10% OXALIC ACID MAG: 250X

COBALT COATED Cr-5W-Y SUBSTRATE. NOTE EXTENT OF INTERGRANULAR ATTACK ON BOTH (FIGURE 2-7 FAULTY RETORT, FIGURE 2-8 NEW RETORT) SPECIMENS CONCOMITANT WITH SEVERE VOIDING. THE HEAVIER ATTACK NOTED ON THE SPECIMEN SEEN IN FIGURE 2-7 IS DUE TO A FAULTY RETORT. AS CAN BE SEEN FROM FIGURE 2-8 LESS CONTAMINATION HAS RESULTED.

are not totally understood, and as in the case for the titanium-aluminum system, time does not allow for the development of information pertaining to the causes for this contamination. However, some of these same effects were found (to a slightly lesser degree) in some work on the cobaltizing of nickel alloys some years ago (3). In this prior work, the contamination was caused by the formation of cobalt oxide which is a liquid at the coating temperatures employed. Cobalt oxide then attacks the grain boundaries of the alloy. What has been seen in the Cr-5W-Y alloy may be caused by the same set of conditions. It would appear that diffusion couple work (in hydrogen atmospheres) would be desirable to definitely determine the cause of this corrosive attack if further work was to be done on this system. However, at this time emphasis shall be placed on the deposition and testing of iron-aluminum and ternary systems for this program.

2.3.2 Iron-Aluminum System

As reported in the last semi-annual report, only mixed success was realized in the attempts at depositing iron-aluminum coatings onto the Cr-5W-Y substrate. Several methods of approach were considered and attempted as follows:

A. Deposition of iron from an iron pack (I_2 energizer) followed by aluminizing.

B. Co-deposition of iron and aluminum from an Fe-Al pack (I_2 energizer).

C. Deposition of iron from packs containing ferrous-halides

(3) Unpublished Data, M. Negrin, Chromalloy Division, 1965.

(with or without elemental iron) followed by aluminizing.

D. Deposition of iron from a pack containing iron and chromium (I_2 energizer) with the latter concentration being sufficient so as to preclude the "dechromizing" of the substrate alloy. As mentioned below, this "de-chromizing" is likely due to the reaction with halide of the chromium substrate at temperatures lower than that necessary for the formation of ferrous halides.

Methods A and B described below were virtually unsuccessful. However, if a larger individual effort were to be expended in only these areas of development, it is believed that a suitable technique could be generated. Method C, although partially successful in earlier experiments, proved to be non-reproducible in many aspects, e.g. weight change, corrosive attack, and surface appearance. Based upon these results, most of the efforts during this reporting period were expended on coating method D. Table III shows the results of the experimental coating trials conducted on the iron-aluminum system. This table shows that the most successful experiments were run in flowing argon. Figure 2-9 shows a schematic diagram of the pack-cementation-type retort employed with inert atmospheres, while Figure 2-10 shows a schematic diagram of the conventional type pack-cementation retort.

After considerable difficulty was encountered with contamination of specimens even when run in argon, a re-check of the inert atmosphere retort employed showed the presence of small cracks. Although several repairs were attempted, experimental

TABLE III

IRON-ALUMINUM EXPERIMENTAL COATING TRIALS

ON Cr-5W-Y SUBSTRATE

XP #	PACK COMPOSITION %				I ₂	Processing °F/Hr.	Weight Change mg/cm ²	Coating Thickness mils	Remarks
	Fe	Cr	Al	Al ₂ O ₃					
19078(4)	5			95		1900/10			Heavy green oxide. Unable to identify.
19081(1)	15	15		70	1/4	2200/10	12.17		Nitride attack.
19082(1)	15	15		70	1/4	2200/10	9.40	2.0	Nitride attack.
19086(1)	15	15		70	1/4	2200/10	7.59		Nitride attack. Slightly magnetic.
19087(1)	15	15		70	1/4	2100/10			Powder burn out.
19089(1)	25	5		70	1/4	2200/10	42.1		Nitride attack. Non-magnetic. Dark green in color.
19090(4)	25	5	1	70	1/4	2200/10	-101.6		Nitride attack. Slightly magnetic.
19091(4)	25	5	5	70	1/4	2200/10	-90.7	3.2	Nitride. Non-magnetic.
19103(1)	25	5		70	1/4	2200/10	6.78		Tabs bright, magnetic, no signs of nitride.
19105(1)	25	5		70	1/4	2100/10			Powder burn out.
19109(1)	25	5		70	1/4	2200/10			Vacuum retort split. Tabs oxidized.
19110(1)	25	5		70	1/4	2200/10			Retort was welded. It again split on the seams.
19116(1)	25	5		70	1/4	2200/10			Heavy nitride attack. Unable to weigh tabs.
19124(1)	25	5		70	1/4	2100/10			Powder burn out.
19131(4)	25	5		70	1/4	2200/10	63.8		Tabs were previously aluminized. Heavy nitride layer.

TABLE III (Cont.)

XP #	PACK COMPOSITION %				I ₂	Processing °F/Hr.	Weight Change mg/cm ²	Coating Thickness mils	Remarks
	Fe	Cr	Al	Al ₂ O ₃					
19134(2)	25	5		70	1/4	2200/10	-0011	0.8	No nitride layer. Slightly magnetic.
19135(4)	25	5		70	1/4	2200/10	-0014		No nitride layer. Slightly magnetic.
19139(4)	25	5		70	1/4	2200/10	-.84		No nitride layer. Slightly magnetic.
19140(2)	25	5		70	1/4	1900/10	2.36	0.8	No nitride layer. Slightly magnetic.
19141(3)	25	5		70	1/4	1900/23	1.38	1.0	No nitride layer. Slightly magnetic.
19142(4)			8	92	1/4	1850/10	2.75	5.4	2 phase aluminum process. Tabs were previously ironized in XP19141.
19143(4)		22.34	8.36	69.3	1/4K ₂ SiF ₆	2000/10	2.76	9.4	UK aluminum process. Tabs were previously ironized in XP19141.
19145(4)			8	92	1/4	1700/10	9.22	5.2	2 phase aluminum process. Tabs were previously ironized in XP19141.
19146(4)		22.34	8.36	69.3	1/4K ₂ SiF ₆	1850/10	7.52	2.2	UK aluminum process. Tabs were previously ironized in XP19141.
19147(3)	25	5		70	1/4	1750/23	1.85	0.8	No nitride present. Slightly magnetic. Dark green.
19148(3)	25	5		70	1/4	1750/23	1.92	0.6	No nitride present. Slightly magnetic. Dark green.
19149(4)			8	92	1/4	1700/10	7.50	2.4	2 phase aluminum process. Tabs from XP19148.

TABLE III (Cont.)

XP #	PACK COMPOSITION %			I ₂	Processing °F/Hr.	Weight Change mg/cm ²	Coating Thickness mils	Remarks
	Fe	Cr	Al					
19150 (4)	22.34	8.36	69.3	1/4K ₂ SiF ₆	1800/10	13.2	5.0	UK aluminum process. Tabs from XP19148.
(1) Static Argon Defective Retort								
(2) Static Argon New Retort								
(3) Flowing Argon New Retort								
								(4) Conventional Pack-Cementation Type Retort

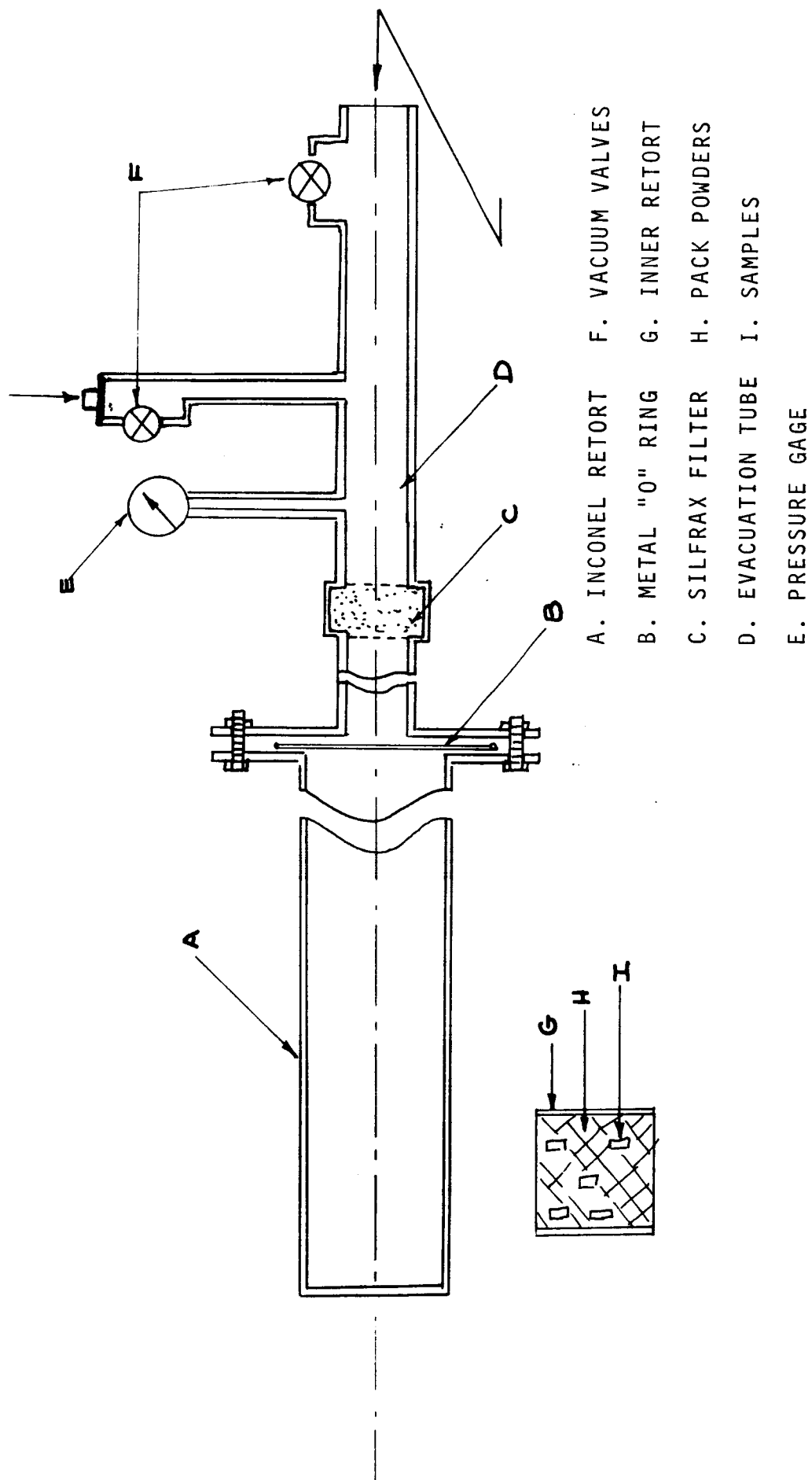


FIGURE 2-9
 SCHEMATIC DIAGRAM OF PACK-CEMENTATION-TYPE RETORT EMPLOYED WITH
 INERT OR VACUUM ATMOSPHERES

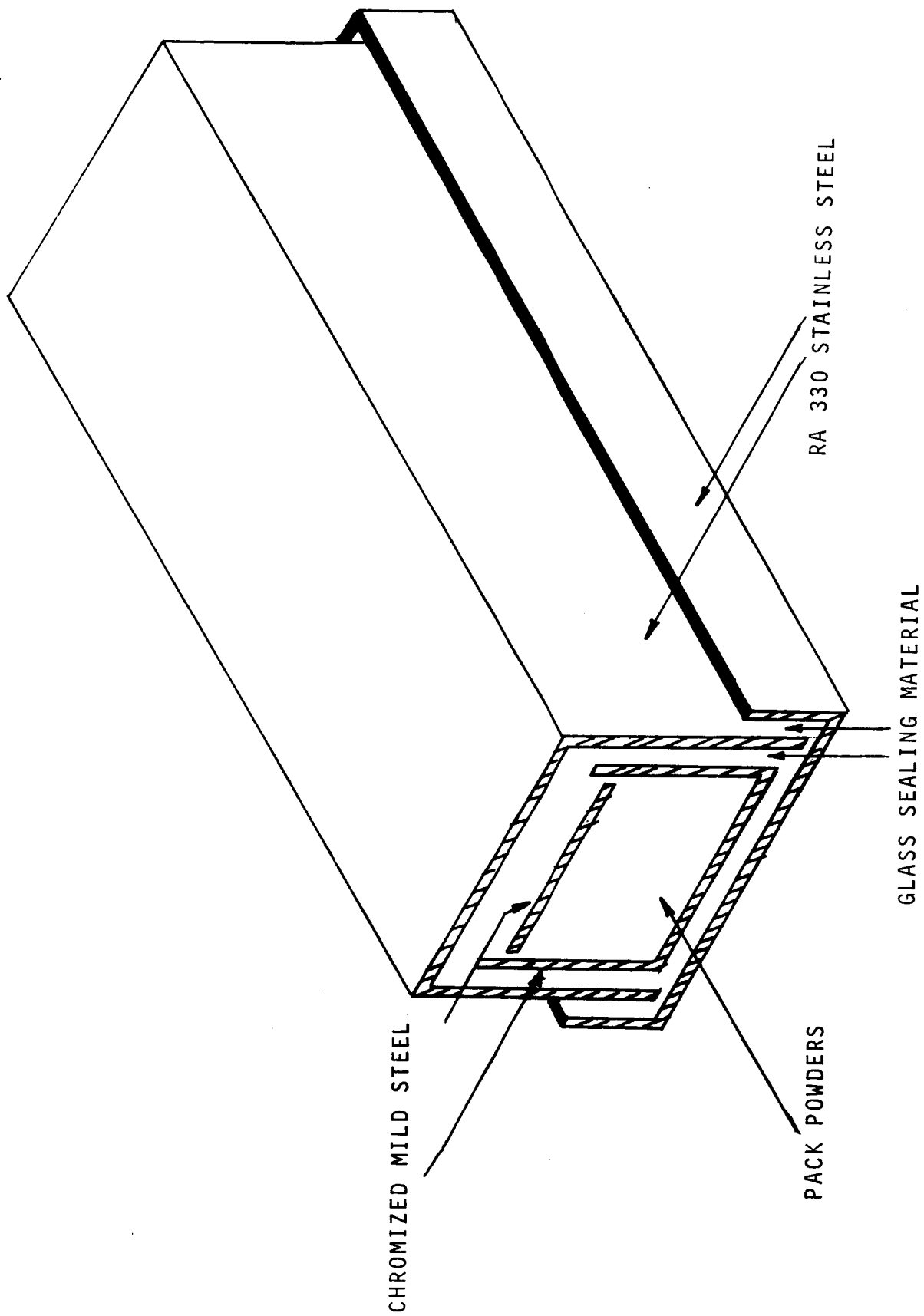
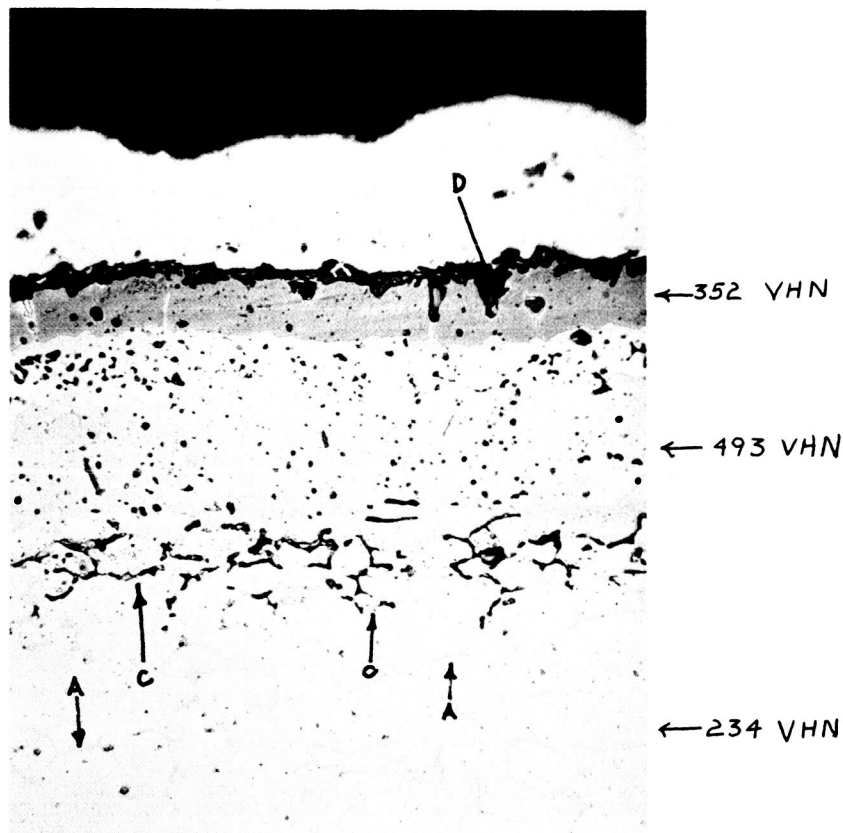


FIGURE 2-10 Schematic Diagram of Pack Cementation-Type Retort

coating trials of additional specimens revealed the same corrosive attack as seen previously. Therefore, a new retort was fabricated and all ensuing experiments showed little or no corrosive attack. It should also be noted that differences were noted when comparing like experiments run in static or flowing argon atmospheres. Coatings deposited under a static argon atmosphere lacked reproducibility. Figures 2-11 and 2-12 show photomicrographs comparing the microstructures of specimens coated at 2200°F/10 hours using packs with a 5:1 and 1:1 Fe/Cr ratio respectively. Although the use of a larger iron concentration in the pack did produce a thicker coating, the appearance of voids and an oxide surface are also seen. Further, the presence of a eutectoid-like structure is seen in Figure 2-12, while Cr_2N is noted in the grain boundaries. These specimens will be analyzed by X-Ray diffraction and EBMP techniques to learn more about the interactions of the Fe/Cr/N alloys formed at the surface. All of the nitride contamination seen in these specimens is attributed to the presence of air in the retort, due to cracks in the cylinder wall.

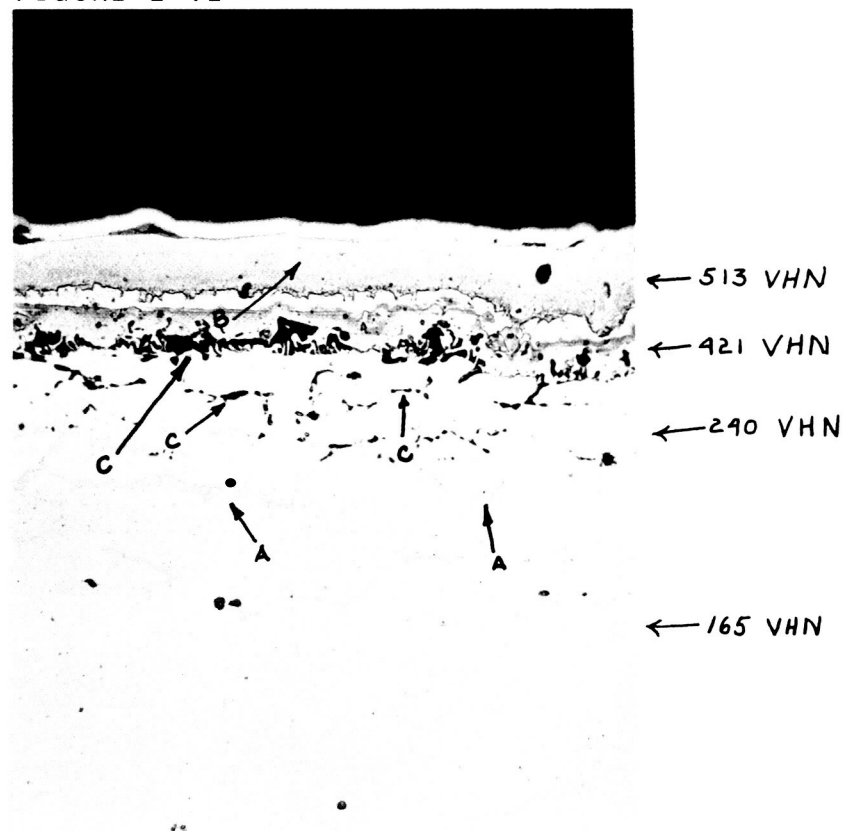
Figures 2-13 and 2-14 show photomicrographs of specimens run in the conventional pack cementation-type retort, similar to that employed in straight aluminizing runs. The addition of aluminum to these packs was made for two reasons: 1) to determine if co-deposition is possible, and 2) to determine if the presence of aluminum will inhibit corrosive attack of the coating and substrate. As can be seen, the aluminum does in fact reduce the tendency towards corrosive attack, but voids in the coating are still prevalent. Further, as the increased hardness values seem to indicate, more aluminum was deposited on the specimen seen in Figure 2-12

FIGURE 2-11



ETCH: 10% OXALIC ACID MAG: 250X

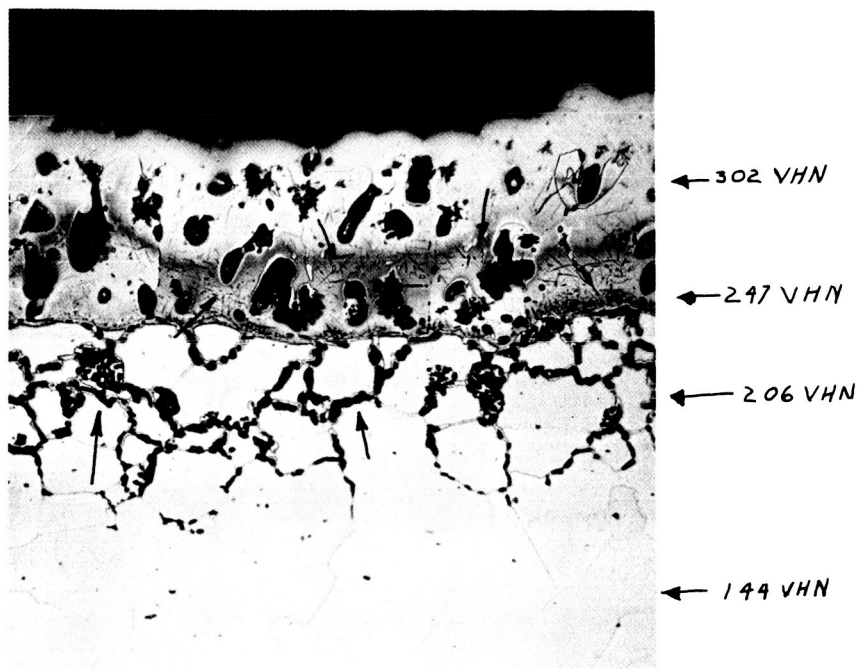
FIGURE 2-12



ETCH: 10% OXALIC ACID MAG: 250X

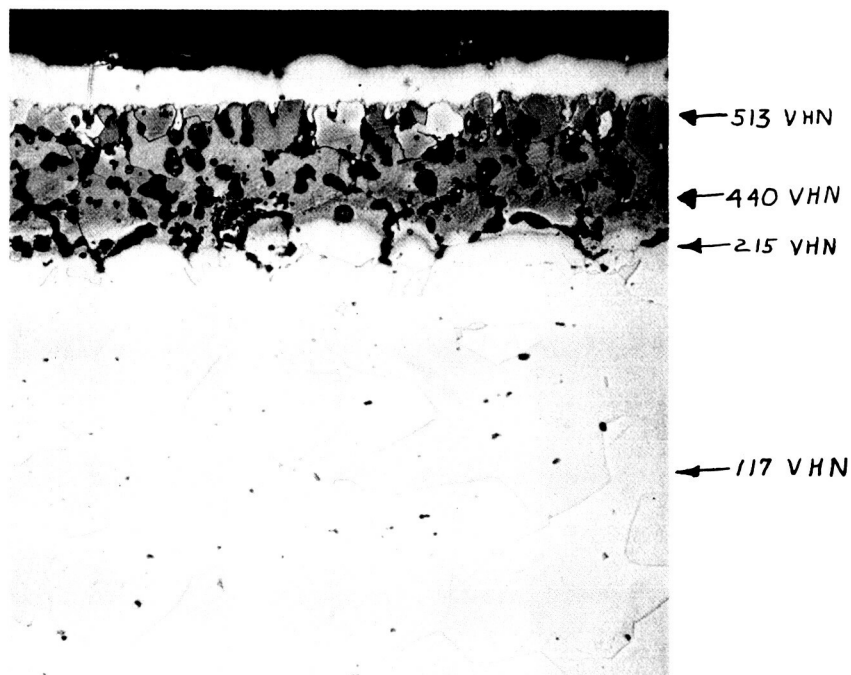
IRON COATED SUBSTRATE. EXPERIMENTS CONDUCTED IN DEFECTIVE RETORT (STATIC ARGON ATMOSPHERE). DEPOSITION AT 2200°F/10 HRS. XP 19089 (FIGURE 2-11) PACK 5:1 Fe/Cr RATIO, XP 19086 (FIGURE 2-12) 1:1 Fe/Cr RATIO. ARROWS A, B, C, D SHOW Cr_2N FORMATION, Fe- Fe_4N EUTECTOID, VOIDS, AND OXIDE FORMATION RESPECTIVELY.

FIGURE 2-13



ETCH: 10% OXALIC ACID MAG: 250X

FIGURE 2-14



ETCH: 10% OXALIC ACID MAG: 250X

IRON COATED SUBSTRATE (STANDARD PACK) WITH 1 W/o (XP 19090 - FIGURE 2-13) AND 5 W/o (XP 19090 - FIGURE 2-14) ALUMINUM ADDED TO 5:1 Fe/Cr PACK. NOTE LACK OF ACICULAR PRECIPITATE (ARROWS) AND INTERGRANULAR ATTACK SEEN IN FIGURE 2-13.

(5 W/o Al additive). In addition to the above, the acicular precipitate seen in Figure 2-13, likely of an (FeCr)N-type is not seen when the aluminum concentration of the pack is increased from 1 to 5 W/o.

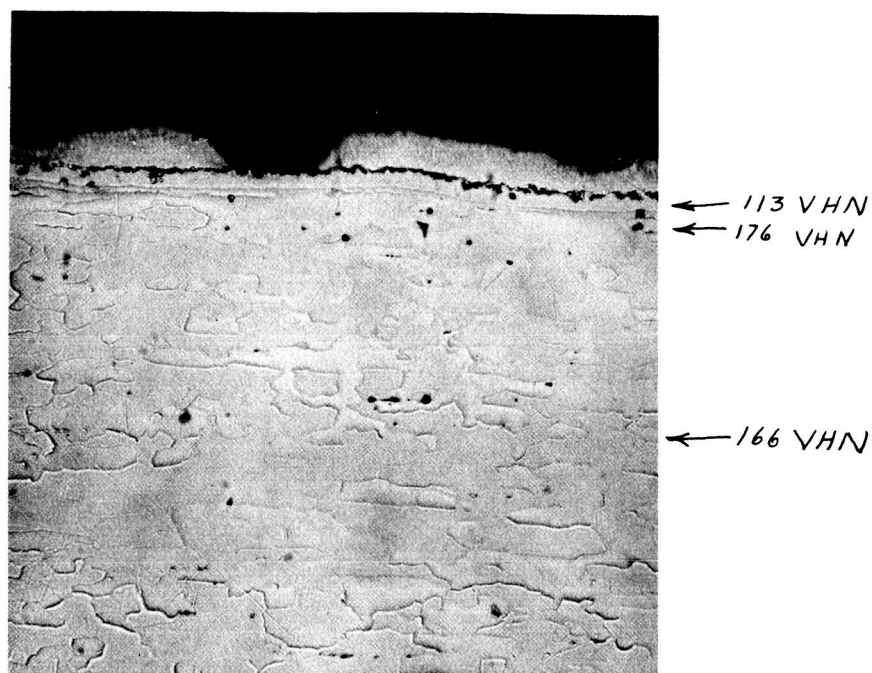
As the data and photomicrographs seem to indicate, the interactions and phase relationships present in high chromium, Fe/N and Fe/N/Al bearing alloys are not fully understood, and this, then, suggests that they warrant close investigation if further development effort were to be made on these systems. There appears to be little information on the aforementioned systems available in the literature. X-Ray diffraction and EBMP analyses would have to be conducted to determine the phases present and their distribution. These data will be reported at a later date.

After a considerable difficulty was encountered with the first inert atmosphere retort (Figure 2-9), the balance of the experiments conducted employed a new retort with flowing argon atmosphere. The results of these experiments (XP's 19041 and 19048) are indicated in Table III. Examination of the microstructures obtained on specimens from these runs showed that the only differences obtained were in the recrystallized grain size of the substrate and coating thickness. Since the differences in thickness were not too great, it was decided that the use of lower temperature-longer time ironizing (1750°F/ 25 Hrs.) as the first step in the duplex Fe/Al coating process would be best. However, some experiments were also conducted with the higher temperature processes. Since these parts, after ironizing, were to be again processed at temperatures in excess of 1750°F (during aluminizing),

it was believed that the resulting substrate grain size would render the substrate too brittle to handle. Figure 2-15 represents the iron coating obtained in XP 19148 processed at 1750°F. Note both the extremely low hardness values of the coating and the smaller-than-usual substrate grain size acquired. Figure 2-16A shows an EBMP trace of an iron-coated substrate (XP 19135). Although this experiment was run at 2200°F/10 hours, experiments run at lower temperature showed the same profiles, the only differences being maximum iron concentration. However, in all cases, the iron and chromium concentrations are approximately equal. Figures 2-16 to 2-18 show photomicrographs of an Fe/Al coating (XP 19148 + XP 19149) as coated and after 100 hours at 2100°F and 2400°F in oxidation. Note that the hardness of the specimen as coated (Figure 2-16) is approximately 200VHN units harder than a comparable simple aluminum coating. However, no nitride formation is noted both in the as coated or 2100°F/100 hour (Figure 2-17) exposed conditions. Also, after the 2100°F exposure, only slight oxidation of the coating has commenced. However, in the 2400°F exposed specimen, considerable oxidation of the coating and severe nitride attack of the substrate can be seen. The intermediate zone of this latter specimen (403VHN) appears to be free of any nitride formation. This would tend to indicate that the coating is porous to nitrogen ingression. EBMP analyses are required in order to obtain an understanding of the diffusional processes occurring.

Figures 2-19 to 2-21 show photomicrographs of Fe/Al specimens as coated and after 100 hours at 2100°F and 2400°F in an oxidation atmosphere. Although the ironizing was carried out at the same

FIGURE 2-15



ETCH: 10% OXALIC ACID MAG: 200X

PHOTOMICROGRAPH OF IRON-COATED SUBSTRATE. PACK EMPLOYED A 5:1 Fe/Cr RATIO AND WAS PROCESSED AT 1750°F/25 HOURS. NOTE LOW HARDNESS READINGS IN COATING AND SMALL RECRYSTALLIZED GRAIN SIZE.

FIGURE 2-16A

ELECTRON BEAM MICROPROBE TRAVERSE ON IRON COATED

Cr-5W-Y. COATING DEPOSITED (XP19135) ON BARE

SUBSTRATE.

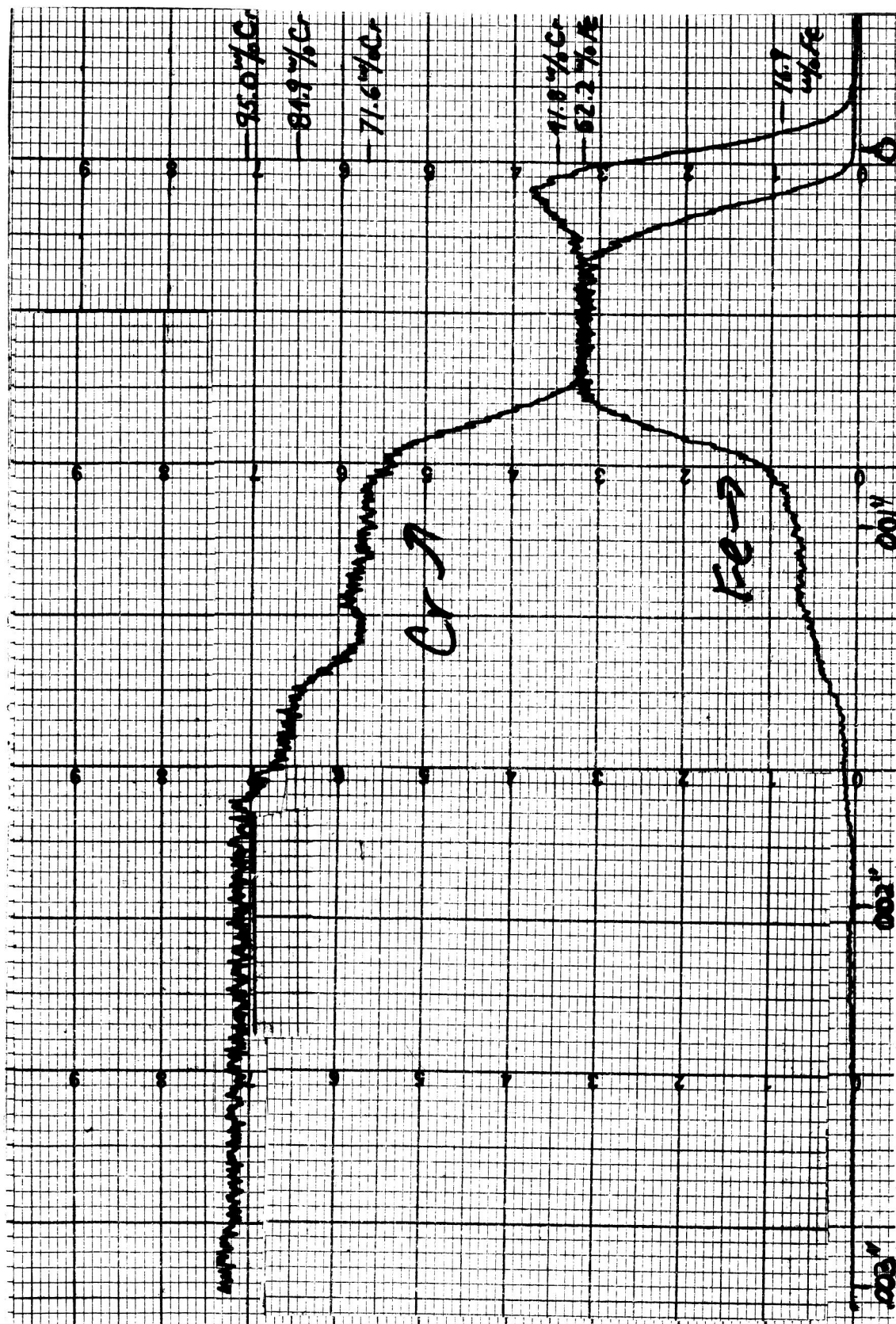
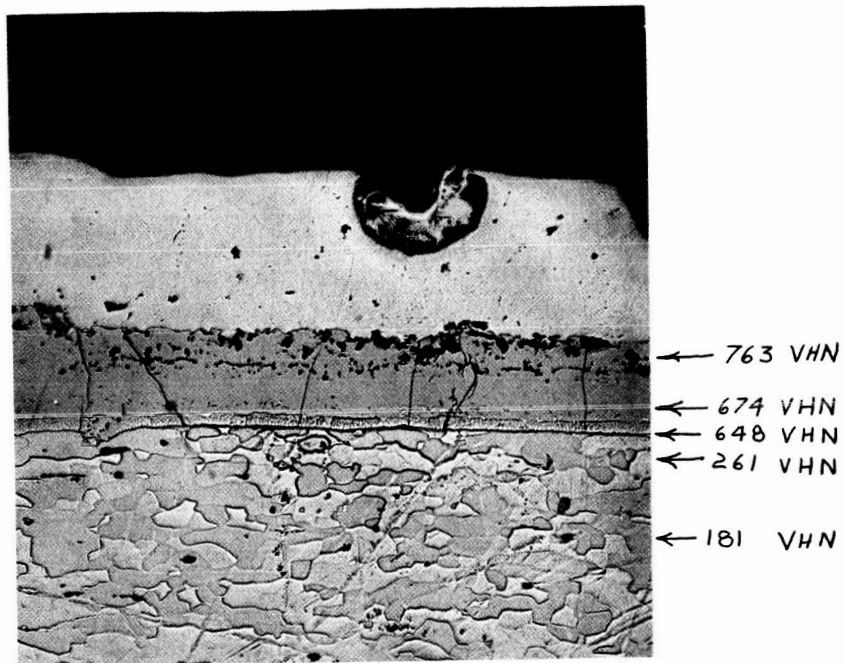


FIGURE 2-16



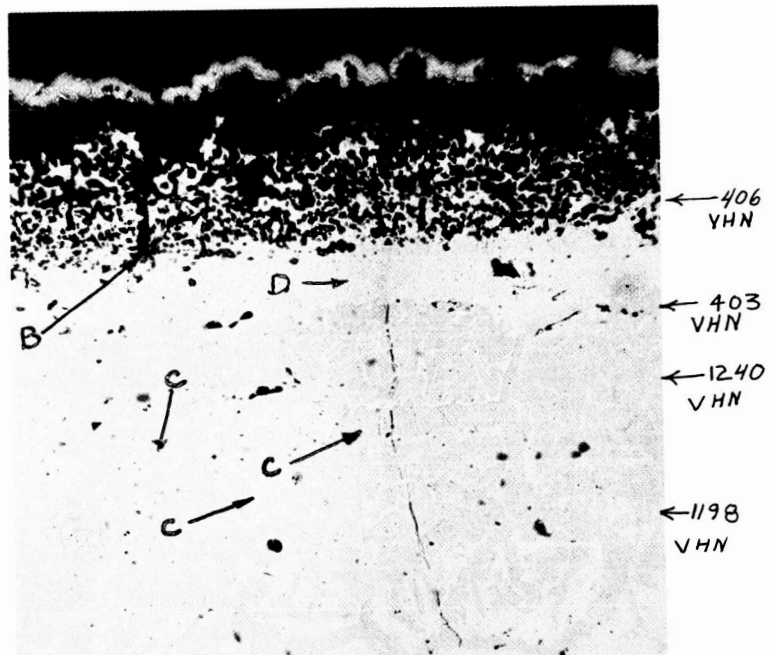
ETCH: 10% OXALIC ACID MAG: 200X
AS COATED

FIGURE 2-17



ETCH: 10% OXALIC ACID MAG: 200X
2100°F/100 HRS.

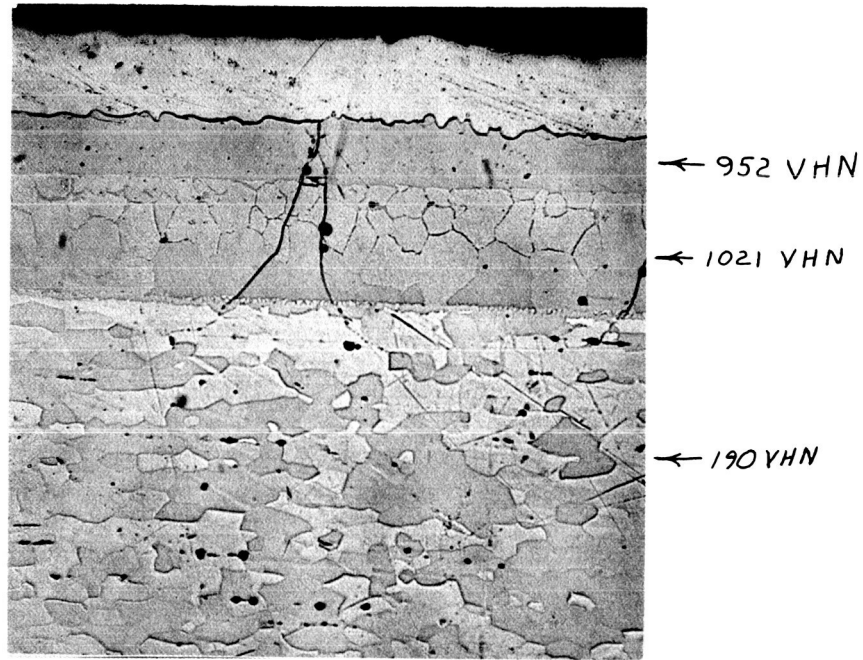
FIGURE 2-18



ETCH: 10% OXALIC ACID MAG: 200X
2400°F/100 HRS.

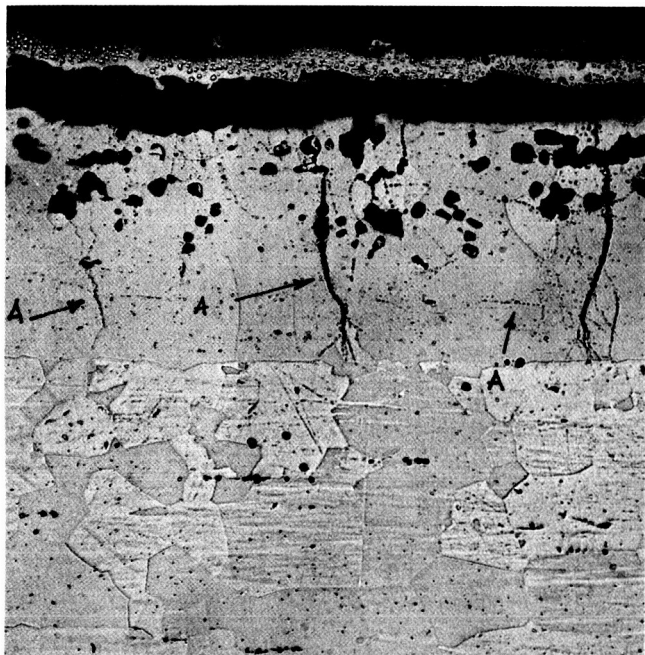
IRON-ALUMINUM COATING ON Cr-5W-Y SUBSTRATE. IRONIZED AT 1750°F/23 HRS.
(XP 19148). ALUMINIZED 1700°F/10 HRS. (XP 19149) 8% Al, I, Al₂O₃ PACK.
NOTE SLIGHT OXIDATION (A), HEAVY OXIDATION (B), NITRIDE FORMATION (C)
AND NITRIDE-FREE ZONE (D).

FIGURE 2-19



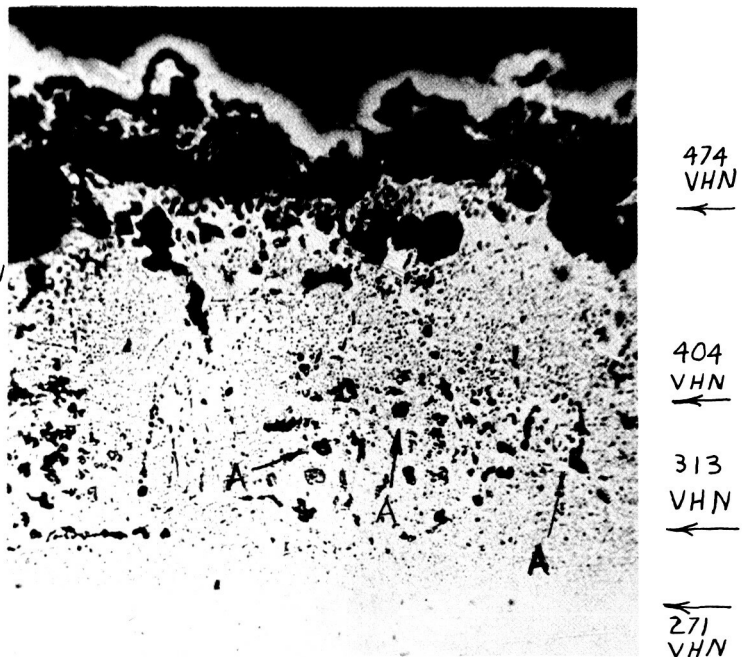
ETCH: 10% OXALIC ACID MAG: 200X
AS COATED

FIGURE 2-20



ETCH: 10% OXALIC ACID MAG: 200X
EXPOSURE TIME (2100°F/100 hrs.)

FIGURE 2-21



ETCH: 10% OXALIC ACID MAG: 200X
EXPOSURE TIME (2400°F/100 hrs.)

IRON-ALUMINUM COATING ON Cr-5W-Y SUBSTRATE. ALL SPECIMENS WERE IRONIZED AT 1750°F/23 HRS. THEN ALUMINIZED AT 1800°F/10 HRS. IN A 22% Cr, 8% Al, K_2SiF_6 , Al_2O_3 PACK (XP 19150). NOTE SOME OXIDATION (A) ON BOTH EXPOSED SPECIMENS, AND LACK OF NITROGEN INGRESSION.

processing conditions as the previously discussed experiments, both a different pack and processing temperature were employed for aluminizing. It should be noted that in the simple aluminum systems when employing non-chromium bearing packs, the coating thickness (for a given coating temperature) is always greater than that seen in packs containing chromium. However, as can be seen from the data presented, when using these two aforementioned packs on previously ironized specimens the results appear to reverse themselves somewhat, in that the chromium-bearing aluminum pack results in thicker coatings. However, this difference might be attributable to the 100°F difference in coating temperature. It is significant to note the very high hardness values obtained on these coatings. These high hardness values appear to be indicative to intermetallic formation and it is felt that an $(\text{Fe}, \text{Cr})_x\text{Al}_y$ similar to that seen in the Cr-Mn-Al $[(\text{Cr}, \text{Mn})\text{Al}_{12}]$ system has formed. Note that although some oxidation is seen on the exposed specimen, no nitride is present in any of the conditions shown.

Although the completion of EBMP analyses of the above described systems was not complete at this writing, Figures 2-22 and 2-23 show EBMP traces of specimens ironized (XP 19141) at 1900°F/23 hours followed by aluminizing under the exact conditions employed for the deposition of the most successful simple-aluminum systems. These conditions are shown in Table III as XP 19143 and XP 19142. Note that at the higher aluminizing temperatures, the iron has diffused to a greater depth (Figure 2-22) and has only half the surface concentration. Further, note the differences in the concentration gradient of the iron as seen with the lower

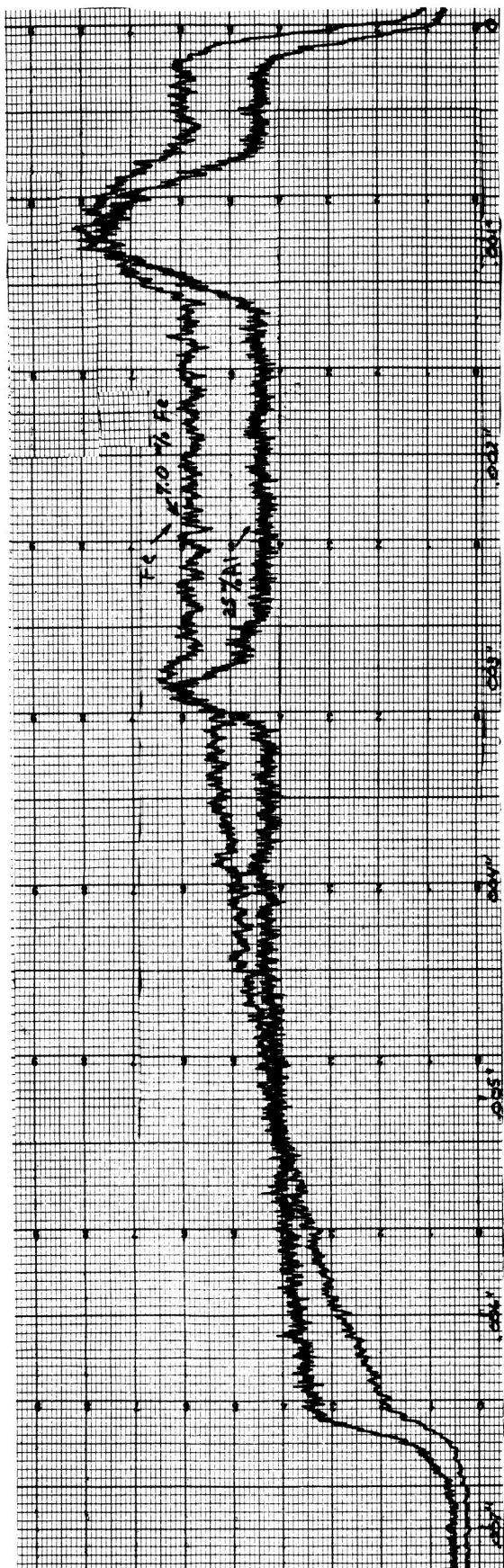
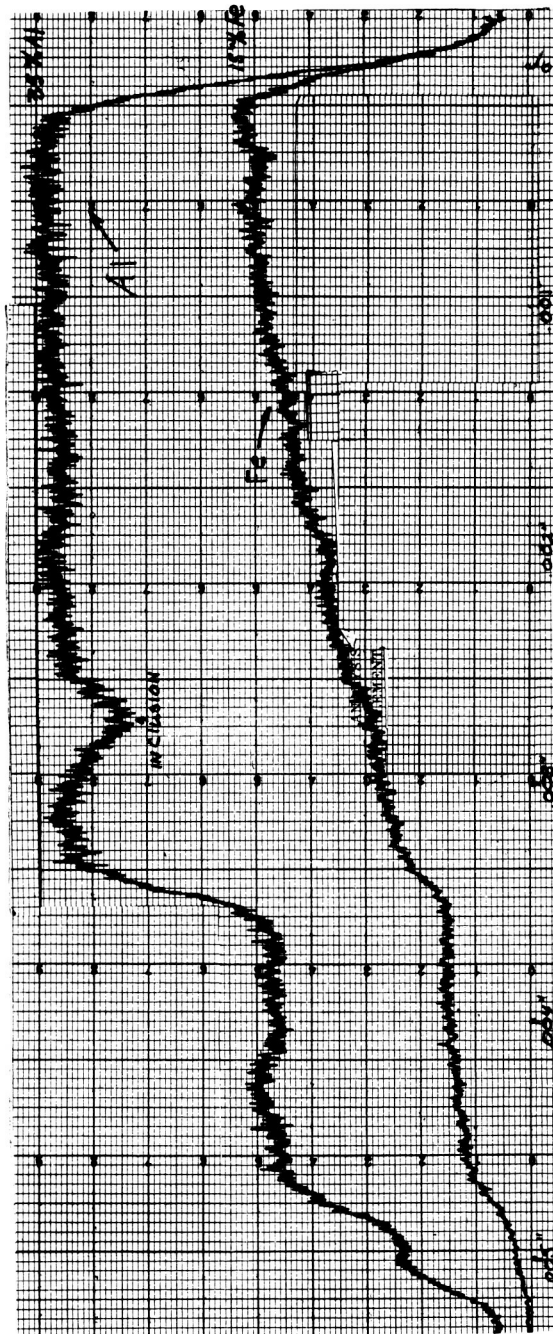


FIGURE 2-22 (TOP). XP 19143 UK TYPE ALUMINIZING
ELECTRON BEAM MICROPROBE TRAVERSE ON IRON-ALUMINUM COATED CR-5H-Y.
SPECIMENS WERE IRONIZED PRIOR TO THE ALUMINUM DEPOSITION.

FIGURE 2-23 (BOTTOM). XP 19142 24 ALUMINIZING



aluminizing temperature. Figures 2-24 and 2-25 show weight change oxidation curves for several of the Fe/Al coating systems discussed above. Based on these curves and the data previously presented, the following tentative conclusions can be drawn from these data:

A. In general the lower the ironizing and aluminizing temperatures, the better the oxidation-nitrification resistance.

B. At comparable thicknesses, the Fe/Al and simple aluminum systems have about the same resistance to corrosive attack (100 hours exposure). The simple aluminum systems suffer from greater diffusional growth.

Additional conclusions may be drawn only after a more complete evaluation of the lower temperature processed systems is completed.

2.3.3 Nickel-Aluminum System

A small number of experiments were conducted with the aim of depositing nickel (as a spinel former) on the Cr-5W-Y substrate. Since the possibility of accomplishing this by halide transfer appears highly improbable, deposition was attempted by means of a nickel-formate pack. As can be seen by Table IV, absolutely no success was achieved and no further work is anticipated. It is, however, felt that nickel deposition could be accomplished by decomposition of nickel carbonyl.

OXIDATION CURVES AT 2100°F and 2400°F FOR
IRON-ALUMINUM COATINGS ON Cr-5W-Y ALLOY.
FIGURE 2-24

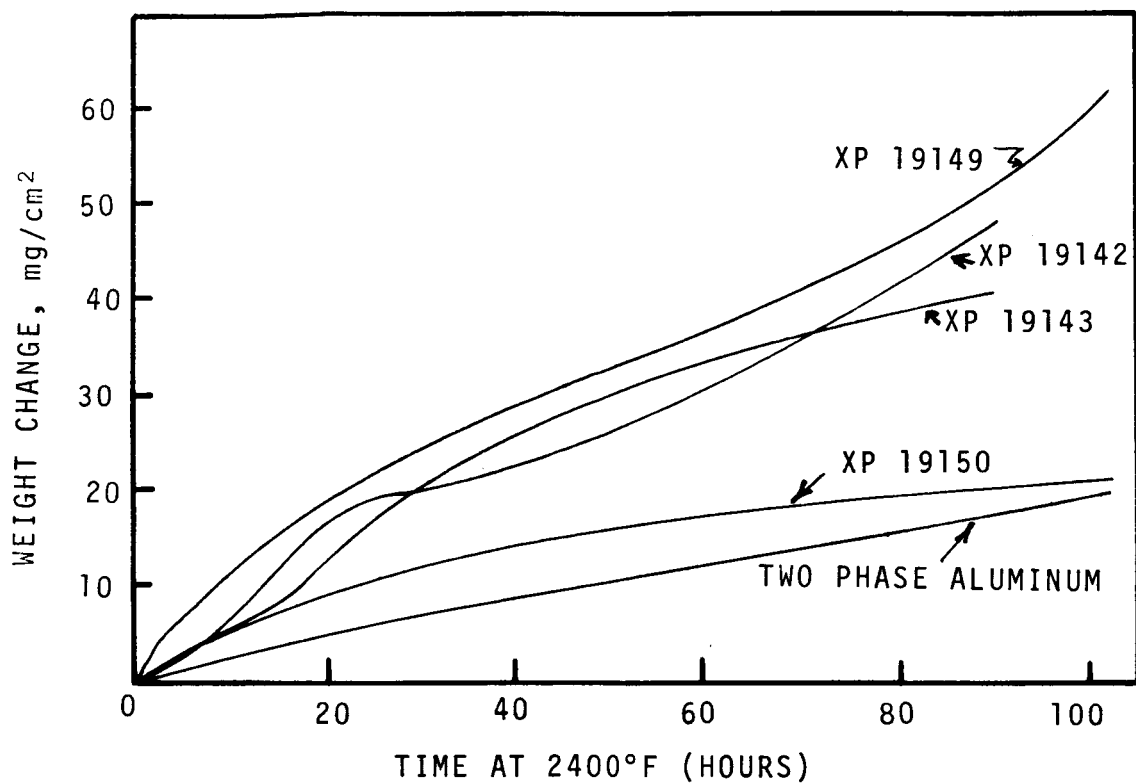


FIGURE 2-25

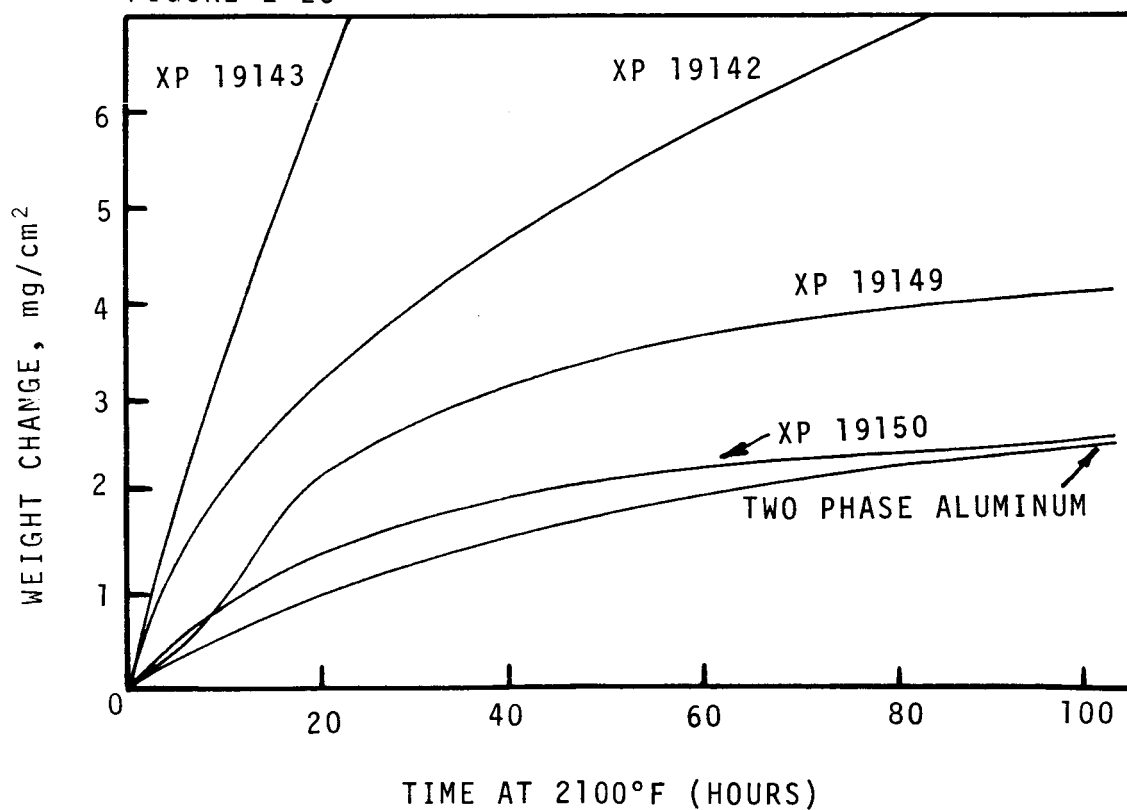


TABLE IV

NICKEL-ALUMINUM EXPERIMENTAL COATING TRIALS

ON Cr-5W-Y ALLOY

XP#	PACK COMPOSITION			I ₂	Process °F/hr.	Weight Change mg/cm ²	Coating Thickness Mils	Comments
	Ni Formate	Ni-Cr	Al ₂ O ₃					
19093		50	50	1/4	2200/10			Surface attack. No coating.
19119	100				1650/10			Dull silver. Pitted. No coating.
19129	100				1750/10			Surface attack. No coating.
19138	100				1400/15			Surface attack. No coating.

3

ADVANCED TESTING

3.1 GENERAL

Cognizant Chromalloy Division and NASA personnel (Project Manager) decided that two simple aluminum coating systems would be taken into the advanced testing phase of the subject contract. The two coating systems chosen are designated UK and 2 ϕ in Table V and in figures which follow.

The descriptions of the tests conducted and the data obtained are presented in the ensuing sections.

3.2 CYCLIC OXIDATION

Five coupons, 2" x 1" x 1/16", were cyclic oxidation tested in static air for each coating-substrate combination and for the uncoated substrate. Three test temperatures were employed which included: one low temperature test at 1800°F, to determine the presence of sigma phase or pest phenomenon, 2100°F and 2400°F. The first one hundred hours involved two (2) hour cycles. These were: insertion into a furnace at the selected temperature, soak for two (2) hours, and removal from the furnace and natural cool to room temperature. Every five (5) cycles, the specimens were weighed and examined for defects or failure.

3.2.1 Test Results

Figure 3-1 shows the results of the cyclic oxidation tests conducted on the bare, UK and 2 ϕ coating systems. Several preliminary conclusions may be drawn from these data as follows:

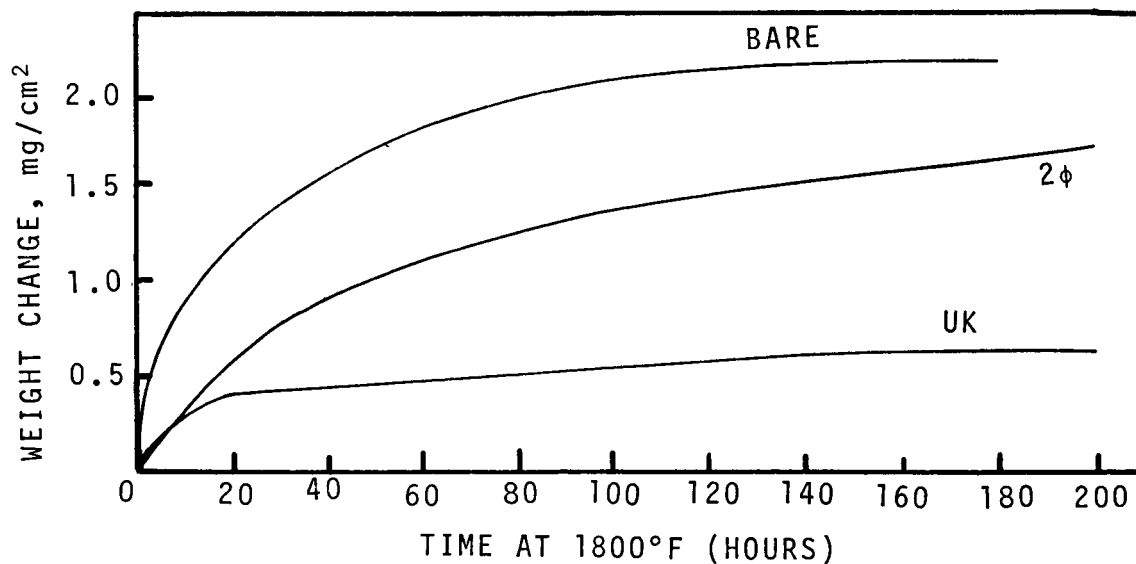
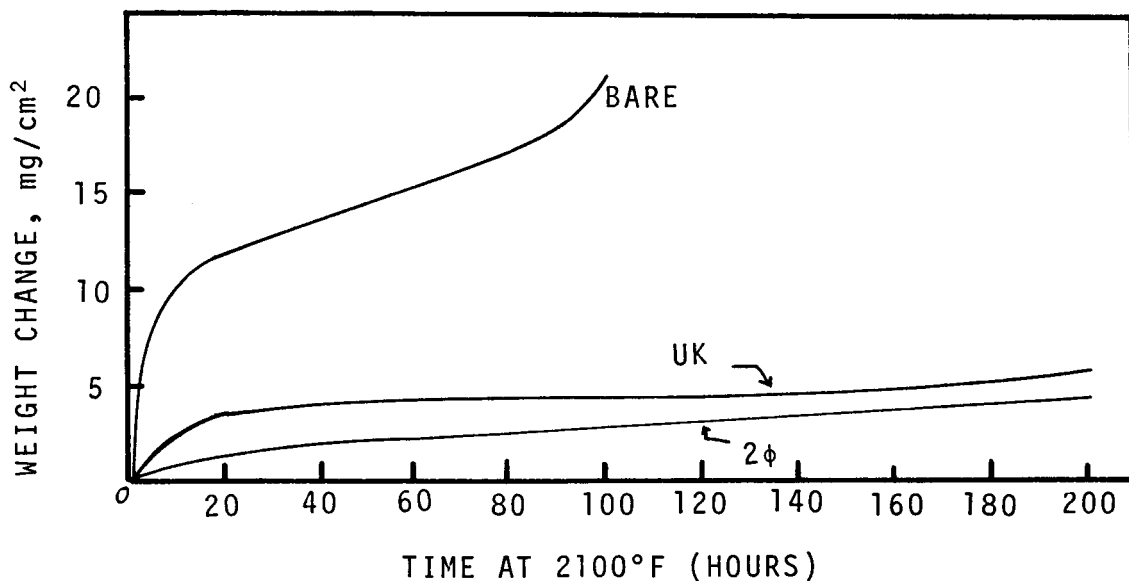
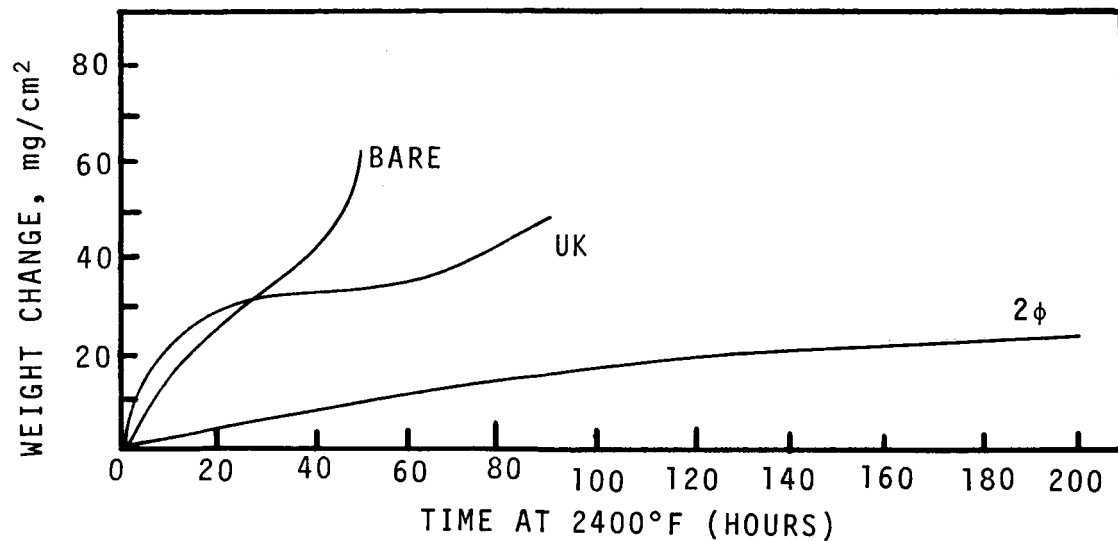
- A. No failures of any type at 1800°F were seen on any of the specimens.

TABLE V

SIMPLE COATING SYSTEMS CHOSEN FOR
ADVANCED TESTING PHASE OF PROGRAM

Coating System	Identification	Pack w/o	Processing °F/Hrs.	Coating Thick. Aim (Mils)	Weight Change Aim (mg/cm ²)
A	UK	22Cr, 8Al, 1/4K ₂ SiF ₆ , 70% Al ₂ O ₃	2000/10	2.2	9.8
B	2φ	8Al, 1/4I, 92% Al ₂ O ₃	1850/10	4.8	18.0

FIGURE 3-1



ADVANCE CYCLIC OXIDATION CURVES OF THE BARE, K_2SiF_6 ENERGIZED ALUMINUM COATED AND TWO PHASE ALUMINUM COATED TEST SPECIMENS.

B. No visual failures of either coating system were seen at 2100°F with the bare specimen failing after 100 hours, much sooner than in the previously run screening tests. It should be noted, however, that the screening test involved lower and fewer test cycles.

C. At 2400°F the bare and UK coated specimens failed visibly in less than 100 hours. The 2φ coated specimens did not visibly fail during the 200 hour test.

D. The oxidation rates at 1800°F and 2100°F appear parabolic, while those seen at 2400°F appear to be of a higher order.

E. Visual appearance of the specimens after intermittent exposure gives virtually no indication as to any nitrogen ingress through the coating or substrate. The only pertinent information obtainable is that of possible coating break through and substrate oxidation. These observations are manifested by the appearance of the characteristic green Cr_2O_3 .

3.3 BEND TRANSITION TEMPERATURE TESTING

Bend transition temperature tests were determined on 3-1/2" x 3/4" x 1/16" specimens in the following conditions:

- (1) Six specimens as received-uncoated and unexposed.
- (2) Six specimens uncoated and exposed to static air for 100 hours in twenty hour cycles at 2100°F.
- (3) Six specimens as coated and unexposed.

(4) Six specimens as coated and exposed as in (2) above.

(5) Same as (4), but exposed at 2400°F.

Conditions (3), (4) and (5) were carried out for each coating modification. Standard Material Advisory Board Procedures (4T Bend Test) in MAB-192-M (National Academy of Sciences, National Research Council) were used. Six specimens from each condition were used to determine the bend transition temperature. Figure 3-2 shows a schematic drawing of the test set-up employed.

3.3.1 Test Results

The results of those tests described above are shown in Table VI. As can be noted from the data presented in Table VI, it is difficult to analyze and evaluate the changes in the DBT based just upon those conditions tested. However, there appears to be no question but that the coatings upon elevated temperature exposure have a deleterious effect on the DBT of the substrate. Preliminary metallographic analysis has shown that the exposure at temperature renders the coating more susceptible to crack propagation on bending. Further, these cracks eventually progress into the brittle (recrystallized) substrate. Only slight evidence of nitride formation was noted.

It should be noted that much of this information is preliminary, and a detailed evaluation of these data, including metallography, chemical analysis, X-Ray diffraction, etc., will be presented at a later date. Simulated coating cycles and inert atmosphere exposure tests will also be performed in an attempt

SCHEMATIC DRAWING OF BEND TRANSITION TEMPERATURE TEST SET-UP.

NOTE NICHROME WOUND FURNACE (A), CHROMIUM-CARBIDE COATED

INDENTER (4T RADIUS) (B) AND SEAT (C).

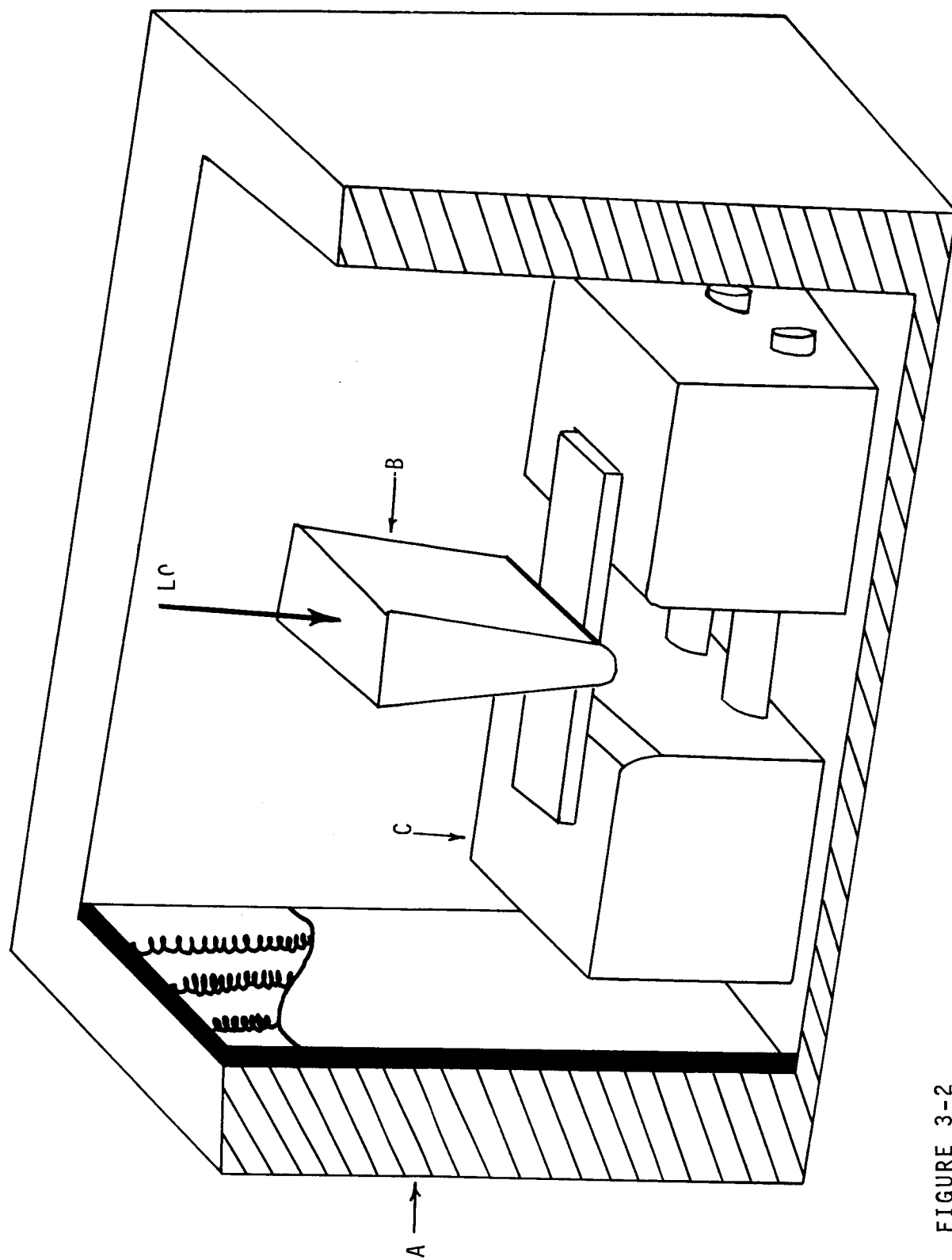


FIGURE 3-2

TABLE VI

BEND TRANSITION TEMPERATURE TEST RESULTS

Condition	Average DBT (°F)	Remarks
a) As Received (1)	750	No surface cracking visible(2)
b) (a) + 1800°F/100 hrs.	900	No surface cracking visible(2)
c) (a) + 2100°F/100 hrs.	930	No surface cracking visible but Cr ₂ N seen microscopically
d) (a) + 2400°F/100 hrs.	---	(3)
e) UK coated	900	Heat #58-100 (2)
f) (e) + 2100°F/100 hrs.	>1600	No bending noted
g) (e) + 2400°F/100 hrs.	>1600	No bending noted
h) 2φ coated	825	Heat #58-100 (2)
i) (h) + 2100°F/100 hrs.	>1600	No bending noted
j) (h) + 2400°F/100 hrs.	>1600	No bending noted
(1) Heat #57-100		
(2) 105° Angle obtained		
(3) No specimens run due to catastrophic oxidation of bare specimens.		

to determine the exact causes for the very large increase in the ductile-brittle transition temperature.

3.4 CONTINUOUS WEIGHT CHANGE OXIDATION TESTING

The bare simple aluminum coated specimens (two specimens for each coating modification at any one temperature) were examined by continuous weight change at 1800°F, 2100°F and 2400°F. Weight change testing on any one specimen was not carried beyond 100 hours. Specimens from these tests were also to be examined for the mechanisms of oxidation/nitridation.

The tests were conducted using an Ainsworth AU-1 recording balance with the specimen suspended from quartz (in the upper areas of the set up) and platinum (in hot zone) wire. Further, the tabs were placed in a recrystallized alumina crucible so as to retain any of the oxidation products which spalled or exfoliated during exposure. A stainless steel assembly was employed above the furnace to minimize the effects of exterior air currents while also allowing for a minimum convection current influences. The stainless steel assembly was connected (with air-tight seals) to a mullite tube which was inserted into a platinum-rhodium wound furnace capable of attaining 3000°F temperatures.

3.4.1 Test Results

Figures 3-3 to 3-5 show the continuous oxidation weight change curves at 1800°F, 2100°F, and 2400°F. Note how the two phase coating system at all three temperatures shows a lower rate of attack (and a change in rate) than does either the bare or UK coated system. Further, the weight changes resulting from this series of tests were far less than those seen in any previous cyclic oxidation tests. These differences are attributable to both

FIGURE 3-3

CONTINUOUS OXIDATION CURVES AT 1800°F OF THE BARE,
TWO PHASE ALUMINUM AND THE K_2SiF_6 ENERGIZED
ALUMINUM COATED SPECIMENS.

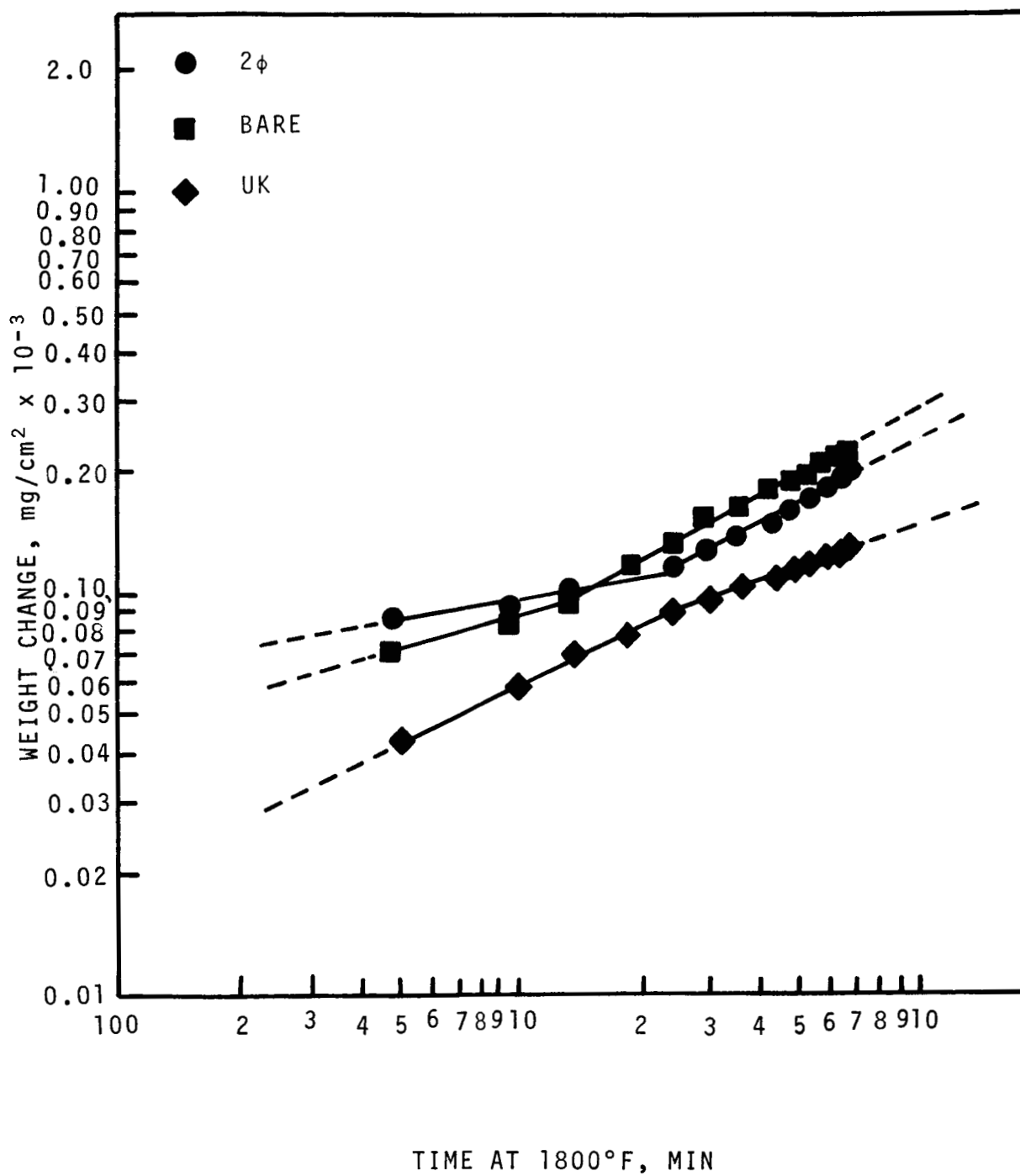


FIGURE 3-4

CONTINUOUS OXIDATION CURVES AT 2100°F OF THE BARE,
TWO PHASE ALUMINUM AND THE K_2SiF_6 ENERGIZED
ALUMINUM COATED SPECIMENS.

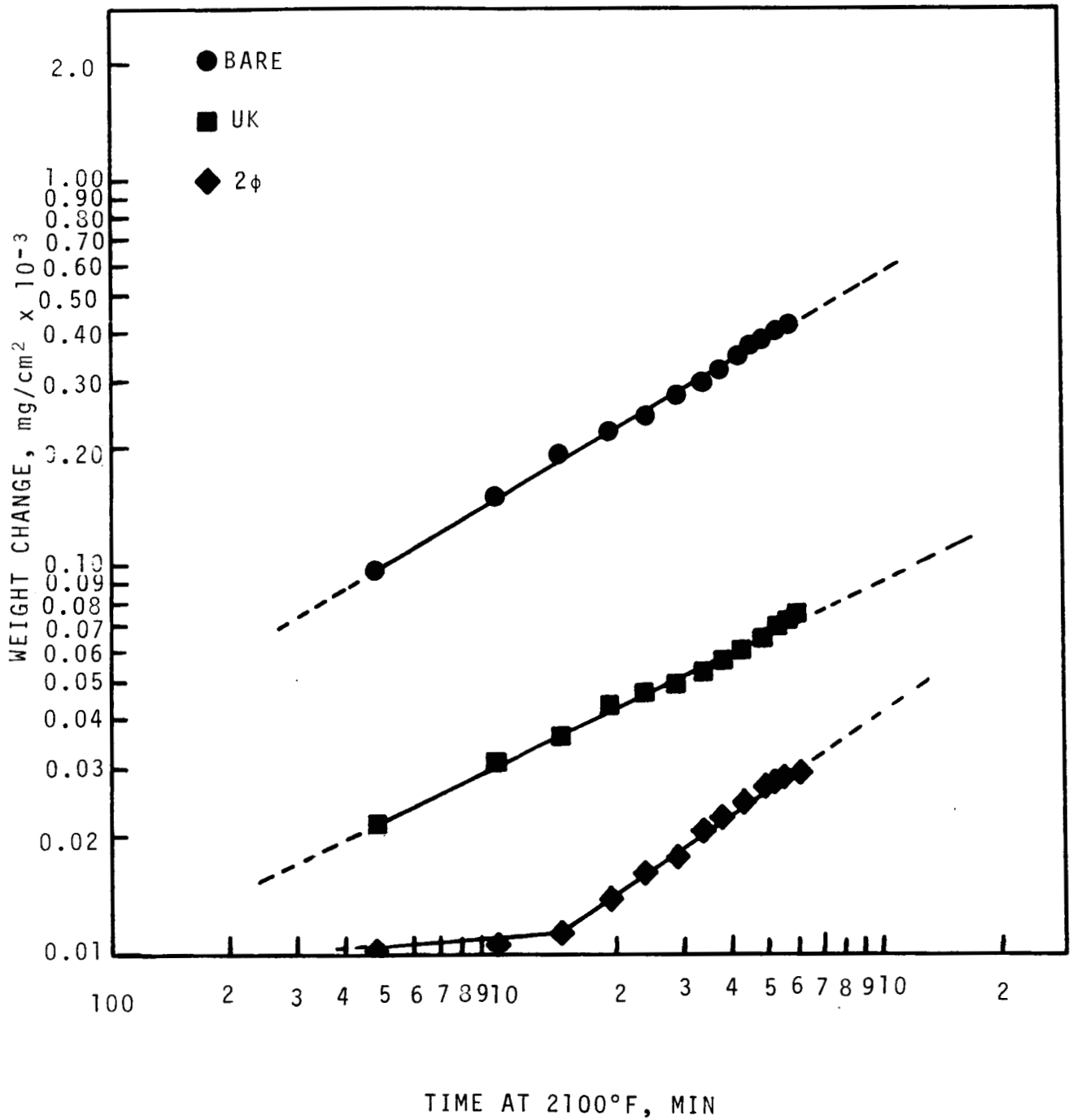
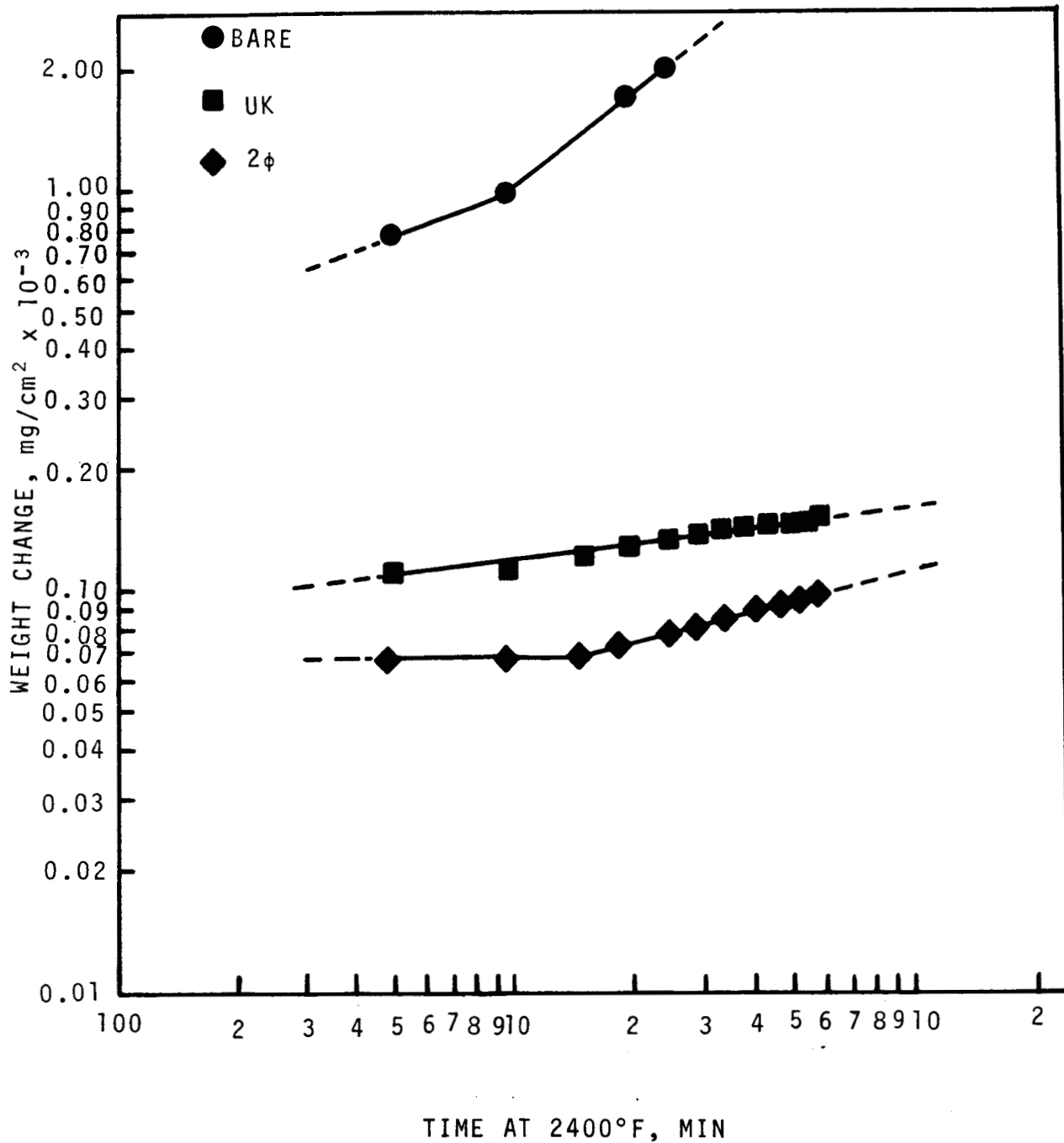


FIGURE 3-5

CONTINUOUS OXIDATION CURVES AT 2400°F OF THE BARE,
TWO PHASE ALUMINUM AND THE K_2SiF_6 ENERGIZED
ALUMINUM COATED SPECIMENS.



a) The lack of induced thermal shock cycling and its usually attendant spalling, and

b) The fact that only a limited supply of air is available within the tubular furnace.

Although many of the curves are parabolic, parilinear relationships were also indicated. A complete study of the specimens from these tests may fully reveal the nature and causes for parilinearity. Obviously, these changes in behavior are associated with alterations in the oxidation/nitrification mechanisms.

3.5 LONG TIME OXIDATION TESTING

These tests which have not as yet commenced will be conducted as follows:

Two of the most promising coatings (as determined by the Contractor subject to NASA Project Manager approval) are to be examined under static oxidation in 20 hour cycles at 2100°F and at 2400°F, for a maximum of 600 hours. Five standard specimens 2" x 1" x 1/16" shall be used for each temperature level. Testing shall terminate upon visible failure. After forty (40) hours of testing, two sets of six bend transition temperature test specimens shall be introduced into the furnace and cycled with the oxidation test specimens. If no coating failure occurs, one set of six bend transition specimens shall be removed after 300 hours and the other set after 600 hours. Bend transition temperature samples shall be removed when oxidation test specimens fail. Bend transition temperature determination shall be made as previously described.

3.6 GAS STREAM EROSION TESTING

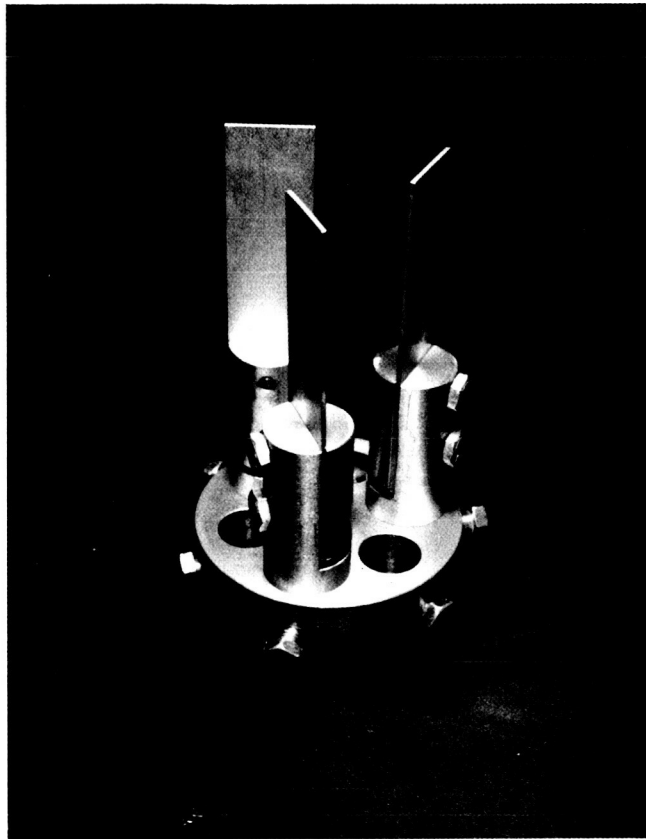
Although some gas stream erosion testing is to be conducted on some simple aluminum systems as called for in the screening phase of the program, the final or as advanced testing will proceed as follows:

Three (3) specimens for each of the final three evaluated coatings will be tested, until failure, in gas stream erosion at each of two temperatures: 2100°F and at 2400°F.

Nine (9) additional specimens will be gas stream erosion tested by heating to 2000°F for two (2) hours followed by one hundred (100) two minute heating and cooling cycles. This procedure shall be followed until failure.

The erosion rig is of a basic converging burner design in which kerosene is employed as fuel. Flame velocities are approximately Mach 0.6 and the parts are rotated at approximately 350 RPM. Preliminary tests have shown the system capable of reaching temperatures of 2400°F with modification, which allows for less heat losses during testing. Figure 3-6 shows the specimen holder employed. This holder is fabricated from Inconel and stainless steel materials. These test results are to be reported shortly.

FIGURE 3-6



EROSION RIG SPECIMEN HOLDER TO BE EMPLOYED IN GAS-STREAM EROSION
TESTED AT 2100°F AND 2400°F.

4

CONCLUSIONS

4.1 TITANIUM-ALUMINUM SYSTEM

The addition of titanium to aluminum coating systems appears to have a deleterious effect on the oxidation-nitrification resistance of the Cr-5W-Y alloy. The specimens crumbled after 100 hours at 2100°F and/or 2400°F. Although these systems have less weight gain than the bare material in oxidation, this gain varies inversely as the titanium concentration. No more effort will be expended on the development of these systems. Both titanium and aluminum and aluminum on titanium were investigated as (duplex) coating systems.

4.2 SPINEL FORMING ALUMINUM SYSTEMS

4.2.1 Cobalt Aluminum System

Deposition of cobalt on the chromium alloy was found to be possible by the use of high chromium bearing packs. However, cobaltizing has proven to provide unsuccessful coatings due to the corrosive attack (even when coated in inert atmosphere) of the substrate. It is believed that CoO_3 is responsible for this corrosive attack.

4.2.2 Iron Aluminum System

Deposition of iron was accomplished at several temperatures with the same (iron) concentration noted for each (by EBMP analyses). Lower temperatures were found to deposit a larger amount of iron free of nitride attack. A high chromium bearing pack run in an argon atmosphere was found to be necessary for deposition. Flowing

argon provided better coatings than did static argon. Indications are that the oxidation/nitrification resistance improves as the aluminizing temperature is lowered. Further, the Fe/Al and simple aluminum systems have about the same resistance to corrosive attack, (100 hours) with the latter suffering from greater diffusional growth. Although oxidation of the Fe/Al coatings was noted, in most cases, no nitrification of the substrate was observed. Necessarily, as in the case of Fe/Cr/Al alloys, the aluminum concentration is the most important variable to be controlled, if an oxidation/nitrification resistant coating is to be obtained.

4.3 ADVANCED TESTING

4.3.1 Cyclic Oxidation

- A. No failures of any type were seen at 1800°F on either bare or coated material.
- B. No visual failures of either coating system tested were seen at 2100°F with the bare specimen failing after 100 hours, much sooner than in previously run screening tests under less severe cycling conditions.
- C. At 2400°F the bare and UK coated material visibly failed in less than 100 hours. The 2 ϕ coated material did not visibly fail during the 200 hour test.
- D. Visual appearance of the specimens after intermittent exposure gives virtually no indication as to any nitrogen ingress through the coating or substrate. The only pertinent information obtainable is that of possible coating

break-through and subsequent oxidation manifested by the formation of the characteristic green Cr_2O_3 .

4.3.2 Bend Transition Testing

Although the effect on bend transition temperature of coating processing is reasonably small, exposure of these coatings at elevated temperatures has a deleterious effect. This effect is felt to be due not to nitrogen penetration to the substrate, but rather to interaction of the coating with the gaseous atmosphere, thus rendering it more brittle and susceptible to crack propagation.

4.3.3 Continuous Weight Change Oxidation Testing

In general oxidation rates are parabolic, with para-linear relationships also noted. No clearly delineated relationships were observed.

4.3.4 Gas Stream Erosion Testing

Preliminary trials have shown the test system capable of reaching temperatures of 2400°F with some thermal gradients noted across the width of the specimen.

5

FUTURE WORK

5.1 COATING DEVELOPMENT

5.1.1 Co-Al, Ti-Al Systems

No further work is anticipated.

5.1.2 Iron-Aluminum System

A. An optimum aluminizing cycle (Temperature, Time) will be established.

B. EBMP and X-Ray Diffraction data will be obtained on the best systems.

C. Cyclic oxidation tests will be run on various systems (optimized).

5.2 ADVANCED TESTING

5.2.1 Evaluation

Complete metallographic, X-Ray Diffraction, EBMP, and chemical analyses will be conducted on all cyclic oxidation, continuous weight change, and bend transition tested specimens.

5.2.2 Long Time Oxidation Testing

Tests will be conducted on the most promising of all the systems thus far tested.

5.2.3 Gas Stream Erosion Testing

As above, the most promising systems will be evaluated in gas-stream erosion tests at 2100°F.

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