EFFECTS OF Zr VARIATIONS ON THE MICROSTRUCTURAL
STABILITY OF ALLOY 713C

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Abstract

Samples of low iron Alloy 713C with varying Zr contents were given a number of thermal treatments to simulate homogenizing, preconditioning, or coating cycles. The structural changes produced by the various heat treatments were studied by optical and electron microscopy while the precipitated phases were identified by X-ray diffraction of extracted residues. The effects of Zr on the as-cast structure and subsequent structural stability are discussed.

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INTRODUCTION

The development of Ni base super alloys for long time service at elevated temperature has proceeded with additions of major elements such as Mo, W, and Ta to raise the melting point. At the same time, additions of Al and Ti have been made to provide increased strength, while simultaneously decreasing the melting point. The degree of success of any cast part is related to the homogeneity of the ingot structure since the incipient melting point, the γ' solutioning temperature, and grain size change with degree of heterogeneity of the ingot.

The primary carbides, TiC, NbC, and TaC, formed in high temperature alloys during the melting process can contain a large amount of other alloying elements, and thus the primary carbides are denoted as MC carbides. The detailed analysis of the carbide composition must be determined by chemical techniques as the parameters supplied by X-ray analyses alone do not reflect the amount and nature of the alloying elements present. The amount, size, and shape of the primary carbide precipitation is determined by carbon content of the alloy, amount of minor elements present, (iron, boron, and Zr) and by the melting history, i.e. pouring temperature, cooling rate and mold temperature. As the primary carbides take more alloying elements into solution, the resultant γ and γ' change in composition and stability during heat treatment and service. Heavily alloyed primary carbides break down very quickly and discontinuous or detrimental precipitation can occur.

PHASE REVIEW OF ALLOY 713C

While large amounts of Alloy 713C are made into hardware, very little has been published pertaining to the phases present in this alloy and the temperature range in which these phases exist.

The phases which have been found in Alloy 713C are:

1. MC carbide where the M can be Ta, Nb, and Ti.
2. $M_{23}C_6$ carbide which is very rich in Cr and existing between 1400° - 1900° F.
3. M_6C carbide being rich in Mo and found at temperature of 1900° - 2100° F.
4. A Mo rich M_3B_2 when the boron level in the alloy is 120 ppm or higher.
5. Sigma phase composed of Cr - Mo - Ni and found from 1400° - 1800° F.

In recent studies of Alloy 713C with iron contents of nearly 2%, a body centered cubic phase (termed J phase) similar to α Cr has been found. The appearance of the J phase is associated with the σ phase but it can exist at temperature as low as 1250° F after long exposures.

The above phases appear to be normal from the composition of 713C with the exception of the M_6C carbide phase. Generally the M_6C phase will appear in alloys or areas where the Mo + W content is about 10%.

After a study of large numbers of Alloy 713C samples from various vendors, it has become apparent that apart from the melting and solidification variables, the minor elements play an important role in the structural behavior of Alloy 713C and probably all superalloys.

A program dealing with the effects of minor alloying elements on microstructure and alloy stability has been underway for some time in our laboratory. Research programs dealing with alloy stability predictions, effects of iron on Alloys 713C and 713LC, and effects of Zr on Alloy 713C have been completed. The effect of Zr on Stability of low iron Alloy 713C will be the subject of this paper.

PROCEDURES

Samples of low iron (.1% Fe) Alloy 713C with Zr contents of 0.01%, .09%, and .19% Zr were obtained from the Allison Division of General Motors Corporation. The chemistry is 13.24 Cr, 4.46 Mo, 2.44 Nb + Ta, .6 Ti, .012 B, .25 Co, .15 C, 6.08 Al and balance Ni.

A number of thermal treatments were imposed on these samples to simulate various homogenizing, preconditioning or coating cycles which this material may undergo. The following heat treatments were run and compared to as - cast material.

1. As-cast + 1975° - 4 hrs + 1600° - 24 hrs - air cool.
2. As-cast + 2150° - 1 hr + 1600° - 24 hrs - air cool.
3. As-cast + 2150° - 1 hr + 1975° - 4 hrs + 1600° - 24 hrs - air cool.
4. As-cast + 1825° - 4 hrs - air cool.

In addition, samples which has been stress-rupture tested at 1550°F - 42,000 psi were evaluated at the same time. The mechanical properties are given in Table 1 and are courtesy of the Allison Division of General Motors Corporation.

The heat treated samples were ground through Linde A polishing slurry, electropolished, and etched in Marbles' reagent.

The surfaces were examined optically, replicated with Collodion direct replicas, shadow cast with Cr, and representative areas were recorded at a magnification of 1500x with an RCA EMU electron microscope.

Portions of samples of the same thermal condition were ground free of oxide, and the inert phases were electrolytically extracted in a 10% HCl-methanol solution. The extracted particles were separated into "large" and "small" size residues, and X-ray diffraction patterns were obtained with a Philips X-ray diffraction unit using Cu radiation, a PHA counter and a monochromator. The results of the X-ray study are given in Table 2.

RESULTS

A. X-ray Diffraction

The results of the X-ray diffraction study are given in Table 2.

The main phases found in this heat are MC, $M_{23}C_6$, M_3B_2 , M_6C , ZrN, and a high parameter MC phase.

(1) As-Cast Condition

The as-cast structure in the .01 Zr sample contains only MC and a boride, M_3B_2 . The extraction did not produce any γ matrix. As the Zr content is increased, the residue contains a small amount of γ reflecting a difference in extraction behavior with higher Zr. In addition, the fine residue of the higher Zr sample contains a small amount of an MC phase having a high parameter of $4.43^\circ A$ as compared to the normal $4.40^\circ A$ MC carbide phase.

(2) 1825° - 4 hrs Condition

The phases formed in the $1825^\circ F$ exposure show the presence of strong $M_{23}C_6$ in addition to the MC and M_3B_2 phases. The γ phase does not extract in any of the samples after this treatment. The second MC with a high parameter seems to be most noticeable in the .19 Zr sample. While it is difficult to state conclusively the relative amounts of MC to $M_{23}C_6$ formed at $1825^\circ F$, the data from the large residue indicates a lessening of $M_{23}C_6$ formation and/or less decomposition of MC with increasing Zr content.

(3) Stress-Rupture Condition

The phases found in the stress-rupture tested samples at $1550^\circ F$ showed MC, $M_{23}C_6$, σ , and a weak boride phase. The amount of the MC decreases while the $M_{23}C_6$ increases with increasing Zr content. The amount of σ phase varies slightly from one sample to another.

(4) "A" Treatment ($1975^\circ + 1600^\circ$)

The $1975^\circ F$ heat treatment has produced an M_6C phase which decreases in amount as the Zr content increases. Less MC is present in the higher Zr samples and a high parameter, $4.43^\circ A$, phase is present at the .19 Zr level. The presence of the $M_{23}C_6$ phase is due to the $1600^\circ F$ temperature.

(5) "B" Treatment ($2150^\circ + 1600^\circ$)

The 1 hour at $2150^\circ F$ has accelerated the formation of the second MC phase in the .19 Zr sample. No M_6C is found in any samples as the 2150° temperature is above the M_6C precipitation range. The presence of $M_{23}C_6$ is attributed to the $1600^\circ F$ step.

(6) "C" Treatment ($2150^\circ + 1975^\circ + 1600^\circ$)

Only a slight amount of M_6C phase is found in the .01 Zr sample. Two MC phases are again found in the higher Zr samples, and a small amount of ZrN is detected in the .19 Zr level sample. The $M_{23}C_6$ reflects the effect of the $1600^\circ F$ heat treatment.

RESULTS

B. Optical Microscopy

Optical studies were conducted on all samples but only a few optical micrographs were taken of selected samples at 800x. The resolution of the optical microscope limits the study of fine structural changes:

(1) As-Cast Condition

The as-cast structures show that the regular γ' in the .01 Zr sample is large and no primary γ' islands are present. As Zr is added, the primary γ' islands appear and grow more plentiful with increasing Zr.

In the .01 Zr sample the MC precipitation follows each grain boundary and many Chinese script MC particles are in the matrix. With increasing Zr content, the amount and nature of the MC precipitation changes such that discrete MC are formed, and few MC particles remain at grain boundaries in the 0.19 Zr sample. Figure 1A and 1B show the .01 Zr and .19 Zr samples in the as-cast condition etched to show MC precipitation

(2) 1825° Condition

The continuous or heavy grain boundary precipitation of MC is present still at 1825°F. There is evidence of additional precipitation occurring in the grain boundaries and also, in some cases, adjacent to the grain boundaries. Fig. 2A illustrates the .01 Zr sample after 1825° for 4 hours.

Again, in the .19 Zr sample, the MC is not concentrated in the grain boundaries and it is easier to see the discrete $M_{23}C_6$ precipitation in the boundaries, Fig. 2B.

(3) Stress-Rupture Samples

The σ plates produced at the 1550°F temperature during testing are associated with the as-cast segregated structures. With the high degree of MC precipitation in the boundaries, the areas adjacent to the boundaries are highly populated with the σ plates. The amount of the σ falls off slightly with increasing Zr levels.

The $M_{23}C_6$ precipitate is dispersed in and around the σ prone areas and grain boundaries in the .01 Zr sample, and mostly only in the grain boundaries of the .19 Zr sample. Figure 3A and 3B represent the .01 and .19 Zr samples after the stress-rupture test.

(4) "A" Treatment (1975°F + 1600°F)

The regular γ' appears to be still large in the .01 Zr sample but this γ' becomes smaller with increasing Zr content. The primary γ' islands are still present in the higher Zr samples. The precipitation at the grain boundaries is difficult to resolve in the .09 and .19 Zr samples while the original MC formed during casting is still present in the grain boundaries. Figures 4A, 4B, and 4C.

(5) "B" Treatment (2150°F + 1600°F)

The 1 hour solutioning at 2150°F has solutioned considerable γ' near the grain boundaries and less in the matrix in all three samples. The primary γ' islands are still present in the higher

Zr samples. There is apparently more γ' remaining in the .19 Zr sample. A grain boundary phase can be $M_{23}C_6$ and MC carbide in the .01 and .09 Zr samples, but it could be $M_{23}C_6$, MC carbide, and high parameter MC carbide in the .19 Zr sample.

The original MC precipitation in the .01 Zr sample has solutioned at 2150°F. The carbon has reacted with Cr at the grain boundaries to form $M_{23}C_6$ at the 1600°F step.

Figures 5A, 5B and 5C illustrate the solutioning of the γ' at 2150°F.

(6) "C" Treatment (2150°F + 1975°F + 1600°F)

The use of an intermediate step of 1975°F after 2150°F causes large γ' to precipitate in the areas where γ' was solutioned at 2150°F. The resultant γ' resembles wrought γ' such as might be found in Udimet 700. The grain boundaries show a heavier precipitate in the .01 Zr sample, probably $M_{23}C_6$, and decreasing amounts of precipitation with increasing Zr contents.

Figures 6A, 6B, and 6C illustrate the decreasing grain boundary precipitation with increasing Zr contents.

RESULTS

C. Electron Microscope

(1) As-Cast Condition

The electron microscope study shows that the as-cast γ' is irregular and large with jagged edges in the .01 Zr level. There is a great deal of MC particles outlining the grain boundaries. With increasing Zr contents, the γ' becomes smaller and more regular while at the same time the primary γ' nodules become more plentiful. Many areas adjacent to the primary γ' show irregular smaller γ' indicating segregation in these areas. The MC phase becomes more discrete in shape and more uniformly dispersed with increasing Zr content. Figure 7A shows the .01 Zr as-cast structure; Figure 7B shows the .09 Zr microstructure; Figures 7C and 7D illustrates the various structures in the .19 Zr sample.

(2) 1825°F- 4 hours Condition

The square γ' is missing when the 1600°F heat treatment is not applied. The regular γ' has rounded off and has become smaller and more wrought-like in appearance at the higher Zr levels.

The grain boundary precipitation decreases with increasing Zr levels. There is a heavier precipitation on the periphery of the primary γ' nodules coinciding with the presence of a higher parameter MC phase and $M_{23}C_6$ carbides.

A close study of the various MC particles indicates that a breakdown of the MC is occurring but the tendency for breakdown decreases with increasing Zr content.

Figure 8A is the .01 Zr sample structure; Figure 8B represents the .09 Zr microstructure; Figure 8C illustrates the types of

structures found in the .19 Zr sample.

(3) Stress-Rupture Samples

There is very little difference in the overall precipitation of the sigma phase in all samples. Sigma plates are more profusely located near the grain boundaries and around the primary γ' nodules. The occurrence of sigma phase is always accompanied by grain boundary precipitation of $M_{23}C_6$ particles.

Figure 9A, 9B, and 9C illustrate the sigma phase precipitation near grain boundaries in the .01, .09, and .19 Zr samples.

(4) "A" Treatment (1975°F + 1600°F)

The jagged edges of the regular γ' have disappeared in the .01 Zr sample, and the γ' particles have grown in size. In addition there is a square γ' dispersed between the regular γ' ; the square γ' precipitates at 1600°F. The irregular areas around the primary γ' islands in the .09 and .19% Zr samples also show the fine square γ' .

The .01 Zr sample shows a large precipitation in the grain boundaries—partly the MC phase and partly the M_6C phase. The amount of this combined precipitation decreases with increasing Zr levels.

Figure 10A shows the structure of the .01% Zr sample; Figure 10B shows the .09% Zr structures; Figure 10C illustrates the .19% Zr sample.

(5) "B" Treatment (2150°F + 1600°F)

The 2150°F treatment has solutioned a large majority of the MC present in the grain boundaries and also has solutioned large amounts of the γ' especially near the grain boundaries. These areas free of large γ' particles appear to be white areas optically due to insufficient resolution. Due to the 1600°F heat treatment, the small square γ' reprecipitates out in the solutioned areas. The square γ' appears to be larger in the higher Zr level samples and less apparent γ' solutioning has occurred with the .19% Zr sample.

The grain boundary precipitation in these samples is $M_{23}C_6$ and the amount of this carbide phase is about the same for each sample. Some of the grain boundary particles may be the high parameter MC phase in the .19% Zr sample.

Figure 11A and 11B illustrate the .01 Zr microstructure while Figures 11C and 11D represent the .19 Zr sample structures.

(6) "C" Treatment (2150°F + 1975°F + 1600°F)

The 1975°F step after solutioning at 2150°F has produced a large γ' in the solutioned areas which were clear of γ' after the 2150°F step. There is a tendency for much of the γ' to be large and square similar to the wrought-like γ' seen in Udimet 700 after 1975°F. The small square γ' precipitation seen in the A and B treatments due to the 1600°F is infrequently seen excepting in small patches near primary γ' nodules in the .19% Zr sample. The precipitation of large γ' at 1975°F has

decreased greatly the amount of Al + Ti available for γ' precipitation at 1600°F.

The grain boundary precipitation is mostly due to the 1600°F step and $M_{23}C_6$ carbide precipitation tendency. There may be some M_6C carbides in the .01 Zr sample and high parameter MC carbides in the .19 Zr sample.

The typical microstructural variations with Zr variations are given in Figures 12A and 12B, Figures 12C and 12D, and Figures 12E and 12F which represent the .01, .09, and .19% Zr samples respectively.

DISCUSSION OF RESULTS

The as-cast microstructure of Alloy 713C in the .01 Zr sample shows a γ' with irregular edges and the size of the γ' varies. The MC size and distribution varies from large Chinese script to discrete precipitation in the matrix and the grain boundaries. Both the γ' and MC conditions are related to the low Zr level.

The addition of Zr promotes the formation of primary γ' nodules and modifies the size and shape of the regular γ' . At the .09 and .19 Zr levels, the MC forms in a discrete form and less MC is formed. A high parameter MC is also detected. The grain boundaries contain only a few primary MC and perhaps M_3B_2 particles.

When the samples are held at 1825°F for 4 hours such as in a low temperature coating cycle, a grain boundary precipitation of $M_{23}C_6$ is found in addition to the original MC precipitation which decreases in amount with increasing Zr content. In the .01 Zr sample the jagged edges of the as-cast γ' have rounded off indicating chemical changes are occurring in the γ' . A precipitation occurs on the periphery of the primary γ' nodules which can be $M_{23}C_6$ or high parameter MC or both. With the increase of Cr and Mo in these areas, the $M_{23}C_6$ is the more logical phase. The primary MC begins to break down, and an $M_{23}C_6$ precipitation is apparent near the MC particles. The amount of the breakdown decreases with increasing Zr. Hence, the MC phase in the higher Zr samples is chemically different and more stable than at low Zr levels.

As the temperature is increased to 1975°F, an M_6C precipitation occurs in the grain boundaries which decreases in amount with higher Zr contents. The regular or as-cast γ' precipitation loses its jagged edges and there is an apparent growth of γ' size. The subsequent 1600°F treatment causes small square-like γ' to form between the normal γ' and around the edges of the primary γ' . The $M_{23}C_6$ phase which is found in all three samples by X-ray diffraction is due to the 1600°F step and not the 1975°F step.

During the 1 hour at 2150°F heat treatment, considerable regular γ' goes into solution, especially noticeable near grain boundaries;

however, considerable γ' in the matrix also dissolves. This γ' solutioning indicates chemical differences in the γ' near grain boundaries wherein instability reactions may be prone to occur. The subsequent 1600°F heat treatment step produces a small regular γ' near the grain boundaries and between larger γ' precipitation. The size of the γ' formed at 1600°F is similar to that formed at the same temperature after 1975°F heat treatment. The 2150°F step causes the MC precipitation in the grain boundaries in the .01 Zr sample to dissolve. It is not known whether a grain boundary film forms upon cooling prior to the 1600°F treatment.

The effect of an intermediate 1975°F step after 2150°F solutioning is to produce a large γ' in the areas normally void of γ' . Except for a small amount in Sample 1, no M_6C was found because of the 1975°F heat treatment; thus, a homogenizing effect has occurred during solutioning which reduces the Mo available for M_6C formation. The square γ' generated at 1600°F is nearly completely gone except for areas near primary γ' nodules. The formation of the larger γ' at 1975°F has depleted the Al and Ti contents below levels which γ' can precipitate freely at 1600°F.

The formation of high parameter MC is greatest when a 2150°F solutioning step is employed. This is due to the greater solutioning effect on the regular MC and re-precipitation of high parameter MC. The amount of high parameter MC is greater with increasing Zr contents.

The 2150°F solutioning has homogenized the areas around primary γ' nodules to a degree which prevents a precipitation of carbides at 1975°F.

The stress-rupture tested samples at 1550°F show that a σ phase is found in all three samples. The σ seems to be associated near grain boundary areas and around the primary γ' islands. These areas are the ones which change the greatest during high temperature heat treatment indicating differences of chemistries. There seems to be less σ with higher Zr contents, and the σ plates appear to be larger in the high Zr samples.

CONCLUSIONS

The effect of Zr on low iron Alloy 713C has been mainly related to changes in γ' and MC carbides. At low Zr levels there are no primary γ' nodules and the regular γ' is large with ragged edges. With increasing Zr content, the regular γ' becomes more uniform and wrought-like in nature while primary γ' islands become plentiful.

Higher additions of Zr to Alloy 713C produces a second MC phase which has a higher parameter. The parameter of the normal MC is 4.40°A and shifts to 4.43°A with higher Zr. This high parameter approaches that of the CbC or TaC phases.

Alloy 713 with very low Zr content precipitates the MC phase in all the as-cast boundaries. It has a large Chinese script appearance and the amount of the MC phase is greatest in the .01

Zr sample. This MC phase seems to be less stable as it readily dissolves at 2150°F.

The formation of σ in all as-cast samples tested at 1550°F signifies that considerable micro-segregation is produced during casting. The segregated areas produces γ' which is easily solutioned at 2150°F and these areas are the locations of the unstable reactions at the lower temperatures.

The use of high temperature thermal treatments during coating or homogenization may produce various phase reactions which can lead to inconsistencies in mechanical properties in the temperature range of 1800° - - 2100°F. Research on thermal treatment of Alloy 713LC has shown that a 2100°F step without an intermediate 1975°F step will lower stress-rupture properties. The formation of detrimental phases occurs in the areas in which the γ' has been solutioned.

The phases found in this study are expected, but the lack of considerable M_6C formation normally found in other Alloy 713C samples is unexpected. Upon a review of the chemistries of the previous heats studied, it was concluded that wide fluctuations of the iron content caused the variations of the M_6C formation. The interaction of minor elements iron and Zr seems to have a profound effect on microstructural and mechanical behavior.

In conclusion the effect of Zr on the stability of low iron Alloy 713C is noticeable on both MC and γ' formations and subsequent phase reactions during heat treatment. There have been no studies of the combined effects of Zr and iron on Alloy 713C or other cast superalloys coupled with different casting conditions. Certainly, metallurgists should wonder about the role minor elements play in the complex cast alloys. It is little wonder that Phacomp doesn't work too readily on cast alloys as it does on wrought products.

Table 1. Stress-Rupture Results on Alloy 713C As-Cast Bars*

Hours to Rupture and Elongation in 4D-%

<u>Test Temp.-°F and Stress- psi</u>	<u>.01% Zr</u>	<u>.09% Zr</u>	<u>.19% Zr</u>
1550 - 42,000	491 - 2.3	779.4 - 4.3	457.2 - 6.0
1800 - 22,000	19.0 - 2.1	133.4 - 10.2	118.4 - 12.2
1900 - 10,000	121.5 - 4.8	195.0 - 10.0	236.2 - 11.2

* Courtesy of Allison Division, General Motors Corp., Report 64SR5-3.

Table 2. X-ray Diffraction Data of Extracted Residues

<u>Phases and intensities</u>							
Thermal Condition	Sample	Normal MC*	High P MC**	M ₂₃ C ₆	M ₆ C	M ₃ B ₂	Others
As-Cast	1L	40	-	-	-	2	-
	2L	40	-	-	-	2	γ-1
	3L	25	-	-	-	1	γ-2, ZrN-2
	1S	40	-	-	-	1	-
	2S	17	$\frac{1}{2}$	-	-	1	γ- $\frac{1}{2}$
	3S	15	1	-	-	1	γ- $\frac{1}{2}$, ZrN-1
1825°F 4 hrs.	1L	20	-	8	1	1	-
	2L	20	1	7	1	$1\frac{1}{2}$	-
	3L	25	2	$3\frac{1}{2}$	-	$1\frac{1}{2}$	-
	1S	13	-	7	-	-	-
	2S	6	-	$4\frac{1}{2}$	-	$\frac{1}{2}$	-
	3S	15	2	4	-	1	-
Stress Rupture 1550°F-42KSI	1L	15	-	3	-	$\frac{1}{2}$	sigma- $2\frac{1}{2}$
	2L	15	-	4	-	1	sigma- $3\frac{1}{2}$
	3L	12	-	5	-	$\frac{1}{2}$	sigma-2
	1S	8	-	4	-	-	sigma- $1\frac{1}{2}$
	2S	6	-	6	-	-	sigma-2
	3S	7	-	8	-	-	sigma- $1\frac{1}{2}$
"A" Treatment	1 All	13	-	7	2	2	-
	2 All	13	-	6	$3\frac{1}{2}$	$1\frac{1}{2}$	-
	3 All	14	4	2	-	$1\frac{1}{2}$	ZrN-2
"B" Treatment	1 All	20	-	3	-	1	-
	2 All	20	-	4	-	1	-
	3 All	9	5	4	-	-	-
"C" Treatment	1 All	13	-	6	1	1	-
	2 All	14	-	9	-	1	-
	3 All	14	5	5	-	-	ZrN- $\frac{1}{2}$

Treatment:

"A" - 1975°F- 4 hrs. + 1600°F- 24 hrs. air cool.

"B" - 2150°F- 1 hr. + 1600°F- 24 hrs. air cool.

"C" - 2150°F- 1 hr. + 1975°F- 4 hrs. + 1600°F- 24 hrs. air cool.

MC*— parameter of 4.40 °A

MC**— parameter of 4.43 °A

L — large residue

S — small residue

A

B

Figure 1 As-Cast Structures A—.01 Zr, B—.19 Zr 800X

A

B

Figure 2 1825°F- 4 hrs. Structures A—.01 Zr, B—.19 Zr

Reduce 20% for publication

A

B

Figure 3 Stress-Rupture Structures A—.01 Zr, B—.19 Zr 800X

A

B

C

Figure 4 "A" Treatment A—.01 Zr, B—.09 Zr, C—.19 Zr 800X

A

C

Figure 5 "B" Treatment A—.01 Zr, B—.09 Zr

A

B

C

Figure 6 "C" Treatment A—.01 Zr, B—.09 Zr, C—.19 Zr 800X

Figure 7A .01% Zr As-Cast Structure ----- 7500X

Figure 7B .09% Zr As-Cast Structure -----

Figure 7C .19% Zr As-Cast Structure ————— 7500X

Figure 7D .19% Zr As-Cast Structure —

Figure 8A .01% Zr 1825°F - 4hrs. ----- 7500X

Figure 8B .09% Zr 1825°F - 4 hrs. -----

Figure 8C .19% Zr 1825°F - 4 hrs. ————— 7500X

Figure 9A .01% Zr 1550°F - 42,000 psi - 4

Figure 9B .09% Zr 1550°F - 42,000 psi - 779 hrs. ————— 7500X

Figure 9C 19% Zr 1550°F - 42,000 psi - 457

Figure 10A .01% Zr "A" Treatment (1975°F + 1600°F) — 7500X

Figure 10B .09% Zr "A" Treatment (1975°F +

Figure 10C .19% Zr "A" Treatment (1975°F + 1600°F) — 7500X

Figure 11A .01% Zr "B" Treatment (2150°F)

Figure 11B .01% Zr "B" Treatment (2150°F + 1600°F) — 7500X

Figure 11C .19% Zr "B" Treatment (2150°F)

Figure 12B .01% Zr "C" Treatment(2150°F+ 1975°F+ 1600°F) — 7500X

Figure 12C .09% Zr "C" Treatment(2150°F+ 1975°F+ 1600°F) — 7500X

Figure 12D .09% Zr "C" Treatment(2150°F+ 1975°F+ 1600°F) -- 7500X

Figure 12E .19% Zr "C" Treatment(2150°F+ 1975°F+ 1600°F) -- 7500X

Figure 12D .09% Zr "C" Treatment(2150°F+ 1975°F+ 1600°F) -- 7500X

Figure 12E .19% Zr "C" Treatment(2150°F+ 1975°F+ 1

Figure 12F .19% Zr "C" Treatment(2150°F+ 1975°F+ 1600°F) - 7500X