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EXAMINATION OF ORNL 1 AND 2 INTERMEDIATE HEAT EXCHANGERS, TYPE IHE-3Introduction

The following report discusses the post-test examination of intermediate heat exchangers ORNL Nos. 1 and 2, operated on IHE Stand B. These heat exchangers were an all-Inconel 100-tube design, shown in Figure 1, utilizing 0.25-in. OD, 5.6 ft. long, 0.025-in. wall tubing (Type IHE-3). Details as to the flow circuit and operating temperatures are given in Figure 2. A stoppage of flow in the fluoride¹ circuit of ORNL No. 1 resulted in termination after a total of 1809 hours of operation. Approximately 993 hours were under ΔT conditions with NaK and salt temperatures reaching a maximum of 1600°F and 1500°F respectively. Isothermal operation was carried out for 680 hours with only NaK in the system and 136 hours with both NaK and salt. Temperatures under these conditions ranged from 1200 - 1500°F. A listing of fuel analyses taken during the course of examination is presented in Table 1.

Results of Visual Inspection of ORNL No. 1

In order to locate the site and cause of the failure, the side plates and filler bars were removed from the heat exchanger, keeping the headers and connecting tubes intact. Constricted flow in the fluoride circuit had made it impossible to drain the fluorides from either heat exchanger before termination, and as a result the interstices between the tubes and outer shell

¹ NaF-ZrF₄-UF₄ (50-46-4 mole %)

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were completely filled with solidified fuel. The area of failure was made evident by changes in the characteristics of this fluoride along the length of the heat exchanger. The usual green color prevailed except for an area starting immediately below the NaK inlet header and ending at the right angle bend beneath the header (Figure 1). In this area the color of the fluorides graded from green to a dark gray to a yellow at the fluoride outlet; dense black deposits of UF_3 occurred along Inconel surfaces exposed to these fluorides. The dark gray fluorides, which appeared to emanate from the front row of tubes (those with short bends), were impregnated with NaK and became quite reactive when exposed to air. The cause of failure was thus indicated to be a NaK to fuel leak near the front row of tubes between the header and tube bends. Further examination of the header welds and portions of the tubes immediately below the headers was made by the Welding and Brazing Group and showed severe cracking in several tubes at this point. A report covering the results of this examination was issued previously.²

The bend angle of the tubes under each of the headers in this heat exchanger was found to have distinctly shortened from the original 90° bend to a smaller angle. The bends at each end were deformed in the same manner, the cold NaK end being illustrated in Figure 3. Part of this deformation may be due to the freezing of salt around the tubes at $970^\circ F$ and the subsequent prevention of further contraction of the tubing as temperature decreased. However, relaxation effects resulting from thermal cycling during operation may also have accounted for the apparent lengthening of the tubes.

² Letter to W. D. Manly, Subject: Metallographic Examination of IHE-3 Failure.

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A substantial amount of mass transfer was seen in the NaK circuit of this heat exchanger, resulting in very evident crystal deposits on the inside walls of the tubes. Lengths of tubes exactly 4 inches long were taken from several locations along the heat exchanger in order to determine what differences in deposit buildup existed at varying distances from the NaK inlet. Because of the small size of tubing, it was impossible to make a separation of the deposits from the tube walls, this being the method normally used to evaluate mass transfer in ΔT -V loops. Consequently the tubes were weighed with the deposits intact and were then compared with an as-received section of tubing. Assuming uniform dimensions from tube to tube, the difference in weight between the heat exchanger tubing and as-received tubing then represents the weight of deposit. Micrometer measurements made on the tubes showed dimensions to be quite uniform among the tube samples taken, and good correlation was obtained from duplicate samples from similar areas, indicating that the weights obtained have a fair degree of reliability. A plot of the amount of mass transfer vs. location in the heat exchanger was thus compiled and is given in Figure 4. As will be discussed in the section covering metallographic examination, the profile obtained agrees quite well with the thickness of deposit measured at intervals along the tubes. It will be noted that the deposit reaches a maximum at approximately 1/4 of the distance from the NaK inlet to outlet, and decreases to a very small value at the NaK outlet. A difference was observed between tubes leaving the NaK header with longer bends and those with shorter bends, the latter reaching a maximum in deposit weight at a shorter distance from the NaK inlet header.

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Referring to the diagram of the heat exchanger in Figure 1, it is seen that salt reaching the back row of tubes (long bends) is slightly hotter than salt at the front row (short bends), which may account for this apparent shifting in deposit with the tube location.

Visual Inspection of ORNL No. 2

This heat exchanger was dissected in the same manner as ORNL No. 1. No striking changes in the color of the fluorides were revealed from header to header, a green color prevailing except for a slight yellowing where fluorides entered from the failed heat exchanger. However, an analysis of the fluorides from the fluoride outlet of this heat exchanger indicates the presence of 1 - 2% potassium and a drop in uranium from the original 8.5% to 3%. Thus it is probable that considerable NaK pick-up occurred throughout the fuel before flow stoppage occurred.

The tube bends below each header showed some distortion in the same direction as noted in ORNL No. 1 but to a much smaller degree. NaK headers from this heat exchanger also were forwarded to the Welding and Brazing Group and will be discussed in a later report.

Metallographic Examination

The location of metallographic samples, taken at intervals along the heat exchanger tubes, is shown in Figure 5. The NaK headers and connecting tubes immediately below the headers are being examined separately, as noted above, and consequently are not included in this report.

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Leg No. 1

In leg No. 1 (ORNL 1) the fluoride circuit, which was heated by NaK entering at a maximum temperature of 1600°F, revealed a maximum depth of attack of 12 mils. This attack, pictured in Figure 6, appeared as general subsurface void formation and occurred at the point where the tube bundle had been separated from the NaK inlet header. (In examining this header it was found that attack continued to increase from this point of separation to the tube-to-header welds.) At the tube bends below the NaK inlet header attack was only 8 mils. A further reduction in attack occurred along the tubes in the direction of NaK flow, reaching a minimum of 5 mils at the fluoride inlet.

It was found in examining the NaK inlet header³ that the tubes near the tube to header welds differed in attack from the forward or compression side to the rear or tension side of the tubes. Cracking, however, was evident in the majority of these tubes on the tension side; thus it was impossible to determine whether attack was increased directly as a result of tensile stresses or from a combination of stress cracks and corrosion voids. Specimens of tubes were consequently examined from sections approximately two inches below this header. Cracking was absent at this point, although based on the distortion of the tube bends discussed previously, considerable stress must have been present in the tubes. A difference in attack was found from front to back in these tubes, as seen in Figure 7, although the difference was much less than that noted for tubes immediately below the header. In the worst case attack was 12 mils on the tension side compared to 8 mils on the compression side. Specimens from the front row

³ Ibid.

of tubes, i.e. those with the shortest distance between the tube bends and header, where stresses should have been the highest, showed approximately the same range of attacks as specimens from the back row of tubes.

Metallic deposits were encountered on the NaK side of the tubes throughout leg No. 1. The manner of buildup of these deposits was discussed under the results of visual inspection; at the point of maximum buildup (Figure 4) the deposit thickness was 15 mils. Near the NaK outlet the thickness of deposit had decreased to less than 4 mils. Crystals comprising this deposit, shown in Figure 8, were analyzed as follows:

Element	Al	Cr	Cu	Fe	K	Mn	Mo	Na	Ni	Si	Ti	Zr
Wt. %	.2	> 5	.02	1	.01	.3	<.02	.03	>>5	.1	.1	.2

The crystals were predominantly nickel but were non-magnetic at room temperature indicating the presence of at least 6% chromium.

Leg No. 2

Fluoride attack in leg No. 2 (CRNL 2) was relatively uniform from header to header. Moderate intermittent void formation was found on the outer tube surfaces to a depth of 4 mils near the fluoride inlet and decreased to 3 mils near the fluoride outlet. The inside of the tubes, which contained NaK, were attacked intergranularly to depths ranging to one mil as shown in Figure 9. This attack also decreased slightly with decreasing NaK temperature. No deposits, either in the fluoride or NaK circuits, were seen in the sections of the heat exchanger examined, which, as mentioned previously, did not include the two NaK headers. However,

a precipitate was seen to occur along the tube surfaces exposed to NaK to a depth of about 10 mils. This precipitate, which may be seen in Figure 9, is of unknown origin, although it is similar in appearance and etching characteristics to precipitates found in carburized Inconel.

Conclusions

1. Failure, which resulted in the stoppage of fluoride flow in ORNL No. 1, occurred as a NaK to fuel leak in the vicinity of the NaK inlet header. The reaction of NaK with fuel at this point caused the deposition of nearly pure UF_3 around the tubes and, finally, a sufficient increase in the melting point of the fuel to produce solidification. Fluorides throughout the heat exchangers were found to be depleted in uranium and to contain some potassium. Thus it would appear that stoppage of flow occurred after considerable NaK pick-up had taken place.
2. Fluoride attack observed in these heat exchangers, with the exception of the area of failure, agreed substantially with what would be predicted from other dynamic systems. However, in those tubes near the point of failure attack on the "tension" side of the tubes occurred to depths approximately twice those observed in "unstressed" tubes at comparable temperatures.
3. Mass transferred particles were present in the NaK circuit of ORNL No. 1 to a maximum thickness of 15 mils. Deposit thicknesses varied markedly from header to header.

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Table 1

Chemical Analysis of Fuel Samples Taken From THE Type 3 Heat Exchangers,
ORNL Nos. 1 and 2

Description of Sample	%				PPM		
	U	Zr	Na	K	Fe	Ni	Cr
Operating Fuel Before Test	8.53	38.1	11.3	-	30	30	250
Fuel From Pump Bowl After Failure	3.35	39.8	11.9	1.83	65	400	20
Fuel From Outlet of ORNL No. 2	2.98	39.3	12.3	2.22	105	240	120
Fuel From Outlet of ORNL No. 1	2.36	23.4	35.3	3.14	640	8100	1575
Black Deposit Surrounding Tubes Near Point of Failure	79.3	-	3.85	-	-	-	-

Fig. 1 - Schematic Diagram of Type IHE-3 Heat Exchanger

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ORNL-LR-Dwg.-15115

Fig 2. Operating Conditions of Intermediate Heat Exchangers ORNL Nos. 1 & 2

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Fig. 3 - Distortion of Tube Bends Below NaK Outlet Header, ORNL No. 1

Fig. 4 - T-10685 - Distribution of Mass Transferred Deposits in NaK Circuit of ORNL-1.

Fig. 5 ~ Letters designate areas of metallographic examination

Fig. 6 - Fluoride Attack Below NaK Inlet Header in ORNL No. 1. Sample Location A
T-10690

Compression Side

Tension Side

Fig. 7 - Photomicrographs Showing Comparison of Corrosion on Tension and
Compression Sides of Tubes Below NaK Inlet Header. Sample Location A.
T-10689

Fig. 8 - T-10263 - Metal Deposit Seen in NaK Circuit of ORNL No. 1.
Sample Location D.

Fig. 9 - Precipitate Occurring Along Tube Surfaces Exposed to NaK in ORNL No. 2.
T-10694