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FROM: J. C. Griess, T. M. Kegley, J. L. Gregg

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317-1

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During the past several years titanium and titanium alloys have been subjected to corrosion testing in uranyl sulfate solutions in the concentration range of 0.02 to 1.34 m and at temperatures of 100 to 320 C. Without exception, the corrosion resistance of titanium in the above media has been outstanding, and usually the specimens have shown negligible weight changes. In addition to the ordinary corrosion specimens, six titanium impellers have been in use in the Westinghouse 100A pumps employed in the dynamic test loops. In all cases except the one to be discussed below the corrosion damage to the impellers has been nil.

Recently titanium impeller No. 1 (Rem-Cru 70 titanium with 0.3% carbon) was severely damaged during a run. The impeller had been in use for more than 12,000 hours under a variety of conditions and an examination of the impeller 3000 hours before the failure had shown no measurable corrosion damage. All indications from the operation of the pump were that the impeller was functioning properly and had not undergone extensive corrosion until the time of failure.

The impeller was being used in the all-titanium loop, loop G, when the heavy corrosion damage was noted. The solution being circulated was 0.11 m uranyl sulfate at 250°C under a partial pressure of about 400 psi oxygen (Run G-35). This environment had not caused attack of titanium in other similar runs. Run G-35 was started in a normal fashion and the pump was operating satisfactorily. However, two hours after start-up it was noted that the pump was vibrating and as a result the run was terminated.

Upon disassembly of the pump it was found that the rear hub of the impeller and the seal and spacer rings had corroded severely. In fact, the hub and seal rings looked as though they had been burned. Figures 1 and 2 show the appearance of the rear impeller hub. Figure 3 is a photograph of the front face of the impeller and shows the complete lack of attack on the front hub. All surfaces of the impeller except the rear hub were free of damage. Figure 4 is a photograph of the seal and spacer rings as removed from the thermal spacer of the pump. Furthermore it was found that the front Graphitar bearing had worn badly. The wear of the bearing probably allowed the hub of the impeller to rub the rings.

Samples of corrosion products were taken from the hub and submitted for X-ray diffraction and chemical analyses. Sections of the hub were examined metallographically. The results of the analyses are discussed in the following sections:

Chemical and X-Ray Analyses:

On the hub of the impeller there were two different types of corrosion products. In the large hydraulic balance holes (see Figure 2) there was a loose black material which could be removed by light scraping. The second material appeared to be smeared on the

back surface of the hub and in some places on the side of the hub. This material was metallic in appearance and brittle enough so that it could be chipped from the surface. It had a cracked appearance which is evident in Figure 2. The black material obtained from the holes gave an X-ray pattern which could not be completely identified although it appeared to contain some titanium dioxide. However when this material was heated to 900°C in air for one hour, it changed from black to tan and X-ray examination showed that the tan material was rutile (TiO₂). An X-ray examination of the metallic appearing material showed titanium monoxide as the major constituent.

Chemical analysis of the black material indicated 54% titanium and 0.3% uranium; the metallic material contained 62% titanium and 0.2% uranium. Spectrographic analyses showed no other metallic elements in greater than trace quantities.

Metallographic Examination:

Metallographic sections of the rear impeller hub were taken at A and B as indicated in Figure 5. Sections of the seal and spacer rings were also examined.

Photomicrographs of the seal and spacer rings are given in Figures 6, 7 and 8. The seal and spacer rings consisted of transformed beta with a region of high-oxygen material at the surface adjacent to the impeller hub. The high oxygen region consisted of four layers arranged in the order: Inner core of transformed beta titanium.

1. α Ti + transformed β Ti
2. α Ti (stabilized by oxygen)
3. α Ti + TiO
4. TiO

Surface adjacent to hub.

The high oxygen region of the seal and spacer rings is shown in Figure 7. Figure 8 shows a portion of α Ti + TiO and α Ti layers. The microstructures found in the high-oxygen region agree reasonably well with the structures found by Bumps, et. al.¹ in their study of the titanium-oxygen system. It should be noted from Figure 6 that in several places the seal rings were fused to the spacer rings.

Sections A and B of the rear impeller hub consisted of α titanium, transformed β titanium, and a region of high oxygen content near the outer surface. The high oxygen content region shown in Figure 10 was similar to that observed in the seal and spacer rings. A deterioration found at the hole surface is shown in Figures 11 and 12.

¹ E. S. Bumps, H. D. Kessler and M. Hansen, "The Titanium-Oxygen System", Trans., American Soc. for Metals, 1953, V.45, p.1008-1025.

The presence of transformed beta titanium in both the seal and spacer rings and the impeller hub is evidence that both were heated above the alpha-beta transformation temperature which for pure titanium is 885°C. The presence of impurities may lower this temperature somewhat. Only a portion near the edge of the hub was heated above the transformation temperature since alpha (low temperature alpha titanium not stabilized by oxygen) remained in the interior of the hub.

Conclusions:

Visual examination, microscopic examination, X-ray diffraction measurements, and chemical analyses all indicate that the hub was damaged by oxidization. The oxidization must have been very rapid, because portions of the oxidized titanium were melted and thrown from the hub. Moreover, the surface gave the appearance of having been at least partially fused. It, therefore, seems probable that the surface temperature rose to the neighborhood of 2000°C.

The failure of the hub must have taken place in a very short period of time. It must have been initiated by rubbing between the spacer rings and the hub, possibly after a ring broke. The rubbing or even machining action of the rings probably removed the protective oxide film on the titanium and raised the surface temperature sufficiently to permit very rapid oxidation of the metal by the environment. The rapid oxidation or probably actual burning of the titanium in the oxygen-water mixture presumably produced the great increase in temperature. The oxidization of the titanium probably proceeded until the water and oxygen in the limited space enclosing the hub were consumed or until the layer of molten or semi-molten titanium-oxygen alloy smothered the reaction. The heat of formation of TiO₂ is approximately 135,000 cal/mol at room temperature as compared to 58,800 cal/mol for water.

5

Fig.1. A Photograph of the Rear Face and Hub of Titanium Impeller No.1.

Fig. 2. A Photograph of the Rear Impeller Hub. *A* and *B* show the two different types of corrosion products found on the impeller.

317-5

Fig. 3. A Photo of the Front Face of Titanium Impeller No.1. Note absence of attack.

Fig. 4. A Photograph of Some of the Seal and Spacer Rings as Removed from the Thermal Spacer.

317-6

Fig. 5. Rear Impeller Hub Showing Locations of Sections *A* and *B*. 1.7X. 14.5% Reduction.

Fig. 6. Sections of Impeller Hub Seals and Spacer Rings. Note partial fusion of seal and spacer rings. Etch: 2 glycerine: 1 HF: 1 HNO₃. 11X. 14.5% Reduction.

Fig.7. Surface of Impeller Hub Seal and Spacer Rings. Location is at (A) in Fig. 6. Etch: 2 glycerine : 1 HF : 1 HNO₃. 100X. 14.5% Reduction.

Fig. 8. α -Ti (High O) + TiO and α -Ti Layers in High Oxygen Portion of Seals and Spacer Rings. Polarized Light. 750X. 14.5% Reduction.

317-8

Fig.9. Section *A* of Rear Impeller Hub. Note extent of overheating as indicated by transformed beta region. Etch: 2 glycerine: 1 HF: 1 HNO₃. 10X. 17.5% Reduction.

Fig.10. Surface of Section *A* of Impeller Hub. Location is at (*b*) as indicated in Fig.9. Etch: 2 glycerine: 1 HF: 1 HNO₃. 100X. 17.5% Reduction.

Fig. 11. Deterioration at Hole Surface of Section 4 of Impeller Hub. Location is at (c) as indicated in Fig. 9. Etch: 2 glycerine: 1 HF: 1 HNO₃. 50X. 9.5% Reduction.

Fig.12. Enlarged View of Deterioration at Hole Surface of Section *A* of Impeller Hub. Etch: 2 glycerine: 1 HF: 1 HNO₃. 250X. 9.5 % Reduction.

317- 10

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