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STUDY OF WATER TURBINE PUMP FAILURE

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October 1974

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OAK RIDGE Y-12 PLANT
OAK RIDGE, TENNESSEE

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ABSTRACT

The cast iron discharge head of a 0.347-m³/s (5500-gmp) deep-well vertical turbine pump experienced a rupture at the Melton Hill Lake raw-water intake pumping station of the Oak Ridge water system. Metallurgical studies of the failure showed the presence of some porosity defects in the cast iron, with tensile strengths ranging from 76.0 to 102.0 MPa (11 000 to 14 800 psi)—considerably below the 206.8 MPa (30 000 psi) specified.

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SUMMARY

In January 1974, the cast iron discharge head of a 0.347-m³/s (5500-gmp) deep-well vertical turbine pump ruptured at the Melton Hill Lake raw-water intake pumping station of the Oak Ridge water system. Nondestructive tests and investigative studies of the failure were made to determine the safety and reliability of a replacement casting and the 5 other similar castings in service at this location. Tensile-strength tests made on specimens taken from areas of the failed casting gave values that ranged from 76.0 to 102.0 MPa (11 000 to 14 800 psi)—considerably below the 206.8 MPa (30 000 psi) specified. Replacement-pump discharge heads are to be made of ductile iron or hot-rolled steel having a minimum tensile strength of 413.6 MPa (60 000 psi) and yield strengths in excess of 206.8 MPa (30 000 psi).

INTRODUCTION

On January 31, 1974, the cast iron elbow section of the discharge head of a $0.347\text{-m}^3/\text{s}$ (5500-gpm) deep-well vertical turbine pump ruptured at the Melton Hill Lake raw-water intake pumping station of the Oak Ridge water system. The ruptured pump was one of 6 pumps at the station and was in the number 3 position. It had been in water service for 14 years prior to failure. Position of the failed pump with regard to the other five deep-well turbine pumps at the raw-water intake station is indicated in Figure 1. When the pump head broke apart, a large hole resulted and pieces of the pump casting were hurled at nearby electrical switchgear with the force of the effusing water [approximately 0.8 MPa (120 psi) and $0.347\text{-m}^3/\text{s}$ (5500-gpm)]. In addition, three 2300-volt electrical switchgear compartments and an auxiliary compartment were inundated and rendered inoperable. The switchgear compartments contained the circuit breakers for Pump Motors 2 and 3, and the auxiliary compartment contained the voltage transformers and undervoltage relays.

The hole in the casting was located on one side of the 90-degree elbow section of the discharge head where the water is forced to take an abrupt directional flow change. Since this was the second rupture of a deep-well pump discharge casting at the same general elbow section within the last four years, a study was in order to determine the probable cause of failure and also to determine the degree of safety and reliability under the continued operation of the other 5 deep-well pumps at this location.

Development engineers at the Oak Ridge Y-12 Plant^(a) were asked to study the problem and offer recommendations.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the US Atomic Energy Commission.

Figure 1. LOCATION OF TURBINE PUMPS IN THE INTAKE STATION.

STUDY OF WATER TURBINE PUMP FAILURE

BACKGROUND INFORMATION

Pump Description

A deep-well vertical turbine pump is a centrifugal pump with rotating impellers mounted on a vertical shaft. Vertical turbine pumps consist essentially of three major components: the head and driver assembly, the column and shaft assembly, and the pump-bowl assembly. The head and driver assembly consists of the driver (electric motor) and discharge casting or base, from which the column and bowl assemblies are suspended. The discharge casting includes the discharge elbow which directs the water into the distribution piping system.

The column and shaft assembly contains the column pipe which suspends the pump-bowl assembly from the head assembly and serves as a water-containment delivery pipe from the pump bowl to the discharge elbow. The line shaft (contained within the column pipe) transmits the power from the motor to the pump shaft and is steadied throughout its length by means of bearings. A diagram of the major constructional features of the deep-well vertical turbine pump is presented in Figure 2.

Operational Sequence

Normal operating sequence of stopping a pump is, first, to completely close the cone-type valve, then actuate a switch to stop the motor. The cone valve is a slow-moving valve operated by air pressure on hydraulic oil. Slowness is intentional to minimize surge or shock to the rest of the equipment and pipelines. In view of the slowness of the

Figure 2. MAJOR CONSTRUCTIONAL FEATURES OF A VERTICAL LINE-SHAFT WATER TURBINE PUMP.

valve, it is believed that the pump broke first, spraying water at the switchgear with great force.

Pumphouse Damages

The following information⁽¹⁾ summarizes the major operational disruption and pumphouse damages caused by the rupture of the pump discharge header:

1. Safety and indicator controlling features on the front of the switchgear were broken.
2. Force of the escaping water pushed and turned over a materials and tool cabinet which fell on and broke a battery.
3. The deluge of water wet the entire building floor to an unknown level, putting the supervisory system out of order.
4. Telephone services were disrupted (calls could be received but could not be initiated).
5. Switchgear was damaged and dampened so that it could not be used for Pump 2.
6. An oil lubricating pipe system to the damaged pump was severed, causing oil to spill onto the floor, adding to the slippery conditions.
7. Water spray was so directed up into the motor that the oil reservoir was flushed out and its contents discharged onto the floor. As a result, the motor had to be pulled and sent to the motor shop for a complete checkout along with another motor which was in the building.
8. A cover plate on the floor over a concrete trench was dislodged by either the water flow or the falling cabinet. This action created a safety hazard that resulted in a lost-time accident to a man who was helping an operator right the overturned cabinet.

EXPERIMENTAL STUDY

Various nondestructive testing methods and investigative techniques were utilized to determine the cause of the pump failure. These studies included: photomicrography and metallography studies, radiography, Zyglo penetrant testing, magnetic particle inspection, and ultrasonic inspection.

Photographs showing the general size and location of the ruptured cast iron discharge head are presented in Figures 3 and 4. When facing the discharge flow of the pump, the hole would be located on the left side of the elbow section of the cast iron head where the water takes an abrupt 90-degree directional flow change. When the rupture occurred, pieces of the cast iron head were hurled with great force at the 2300-volt switchgear located near the pump. Some of the larger fragments of the cast iron pump head weighed from 5 to 7 pounds. The relationship and position of the pump to the electrical switchgear is illustrated in Figures 5 and 6. Photomacrographs showing different views of the cracks found in several of the broken pieces of the cast iron head are given in Figures 7 through 9. Examination of

Figure 3. RUPTURED DEEP-WELL-WATER-PUMP CASTING.

AEC-ORO-74-15

Figure 4. BLOWOUT AREA OF THE RUPTURED DEEP-WELL-WATER-PUMP CASTING.

AEC-ORO-74-14

Figure 5. VIEW OF DEEP-WELL PUMP 3 AND ITS ELECTRICAL SWITCHGEAR.

AEC-ORO-74-17

Figure 6. VIEW OF DEEP-WELL PUMP 3 AND ITS STORAGE CABINET.

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Figure 7. PHOTOMACROGRAPH OF A CAST IRON DISCHARGE HEAD FRAGMENT, SHOWING A LARGE CRACK. (Cross-Section View; 4X)

K 50b

Figure 8. PHOTOMACROGRAPH OF A CAST IRON DISCHARGE HEAD FRAGMENT, SHOWING A LARGE WATER-SIDE CRACK. (Face View; 2X)

K 50a

these broken segments revealed that there was a distinct visual difference in the fracture surface of the gray cast iron between the water side and the exterior surfaces. The exterior one third of the wall thickness was very metallic in appearance; whereas, the interior two thirds of the metal wall thickness had a red-brown coloration, indicative of internal water corrosion (iron oxide formation) from existing cracks and/or microcracks in the gray matrix cast iron.

This same difference between the appearance of the interior and exterior matrix metal was also observed on fresh fracture surfaces made on specimens taken from the 12.7-mm(0.5-in)-thick area of the ruptured cast iron heater where an existing crack had been observed. These are seen in Figures 10 and 11.

Magnaglow inspection of a large segment [127 mm wide by 254 mm long (5 in wide by 10 in long)] of the ruptured cast iron header disclosed one large crack that had penetrated completely through the thickness of the casting. This crack measured 31.7 mm (1.25 in) long on the inside (water side) surface and 44.4 mm (1.75 in) long on the outside surface.

Tensile-strength tests were made on specimens taken from the 12.7-mm (0.5-in)-thick area of the pump casting that ruptured and from a 50.8-mm (2-in)-thick area at the base of the casting. Results, as summarized in Table 1, show that the tensile strength of the cast iron was considerably below the minimum tensile strength of 206.8 MPa (30 000 psi) for the grade of gray cast iron specified (ASTM Specification A 48 Class 30)⁽²⁾ when it was manufactured. The minimum tensile strength provided a safety factor of 4, according to the manufacturer's literature.

X-ray radiography tests on the ruptured pump discharge head were made on the internal section of the casting diametrically opposite to the blowout area. An internal crack, approximately 76 mm (3 in) long, was found which did not extend to the exterior wall surface. A photograph showing this crack was made from the X-ray radiograph and is presented in Figure 12. This finding is significant since it provides evidence for the existence of internal casting cracks (water side only) which had probably formed before the pump blowout occurred. Since this crack existed on a section of the pump casting that had remained intact and was not one of the casting fragments that had been blown out, and thus

K 50d

Figure 9. PHOTOMACROGRAPH OF A CAST IRON DISCHARGE HEAD FRAGMENT. (Cross-Section View)

Figure 10. FRESH FRACTURE SURFACES OF CAST IRON FROM THE RUPTURED PUMP DISCHARGE HEAD, SHOWING DIFFERENCES IN APPEARANCE OF THE METAL MATRIX.

Table 1
TENSILE-STRENGTH TEST RESULTS ON A RUPTURED DEEP-WELL-WATER
PUMP DISCHARGE CASTING

Specimen Number	Specimen Source	Tensile Strength		Elongation (%)	Reduction in Area (%)
		(psi)	(MPa)		
1	1/2" (1.27 cm) Wall Area	11 000	76.5	< 1.0 ⁽¹⁾	< 1.0
2	1/2" (1.27 cm) Wall Area	11 000	76.0	< 1.0	< 1.0
3	2" (5.08 cm) Wall Area	14 200	97.9	< 1.0	< 1.0
4	2" (5.08 cm) Wall Area	14 800	102.0	< 1.0	< 1.0

(1) Specimen broke outside the gage mark.

Figure 11. REPRESENTATION OF THE METALLIC AND WATER-OXIDIZED AREAS OF THE FRESH FRACTURE SURFACES SEEN IN FIGURE 10.

subject to impact stresses, it is of even greater significance. Presence of such internal cracks limited to the water-side surface of the casting would readily account for the water-oxidized appearance of the interior matrix of the casting which extended for approximately two thirds of the total metal thickness.

Nondestructive tests were conducted on a new, replacement, cast iron pump housing for the deep-well pump to determine whether it was free of any serious casting defects. No tests had been performed on this housing prior to this time. Zyglo penetrant testing revealed a triangular area of porosity in this new casting and a deep crack at the gusset. A photograph showing the porosity casting defects is presented in Figure 13. The triangular area of porosity coincided exactly with the area of the blowout on the failed pump housing. Another new cast iron housing showed no objectionable defects.

Thickness measurements were made on this new replacement cast iron discharge pump head using an ultrasonic "pulse-echo" technique.⁽³⁾ A total of 70 measurements were taken with a 5.0 MHz Panametrics transducer, beginning in the center of a 152.4-mm-wide by 203.2-mm-long (6-in-wide x 8-in-long) measured area and approximately 25.4 mm (1 in) below the bearing surface. The casting thickness was found to be in the range of 11.2 to 16.5 mm (0.440 to 0.650 in). Thickness readings corresponding to various locations over the measured area are summarized in Table 2.

Figure 12. CONTACT PRINT FROM A RADIOGRAPH THAT SHOWS A CRACK DEFECT IN THE FAILED PUMP CASTING. (Crack was Found in the Quadrant Opposite to the Blowout Area)

Table 2

THICKNESS PROFILE OF THE CAST IRON DISCHARGE HEAD OF A
REPLACEMENT DEEP-WELL-WATER TURBINE PUMP

Vertical Location (in/mm)	Horizontal Location (in/mm)				
	2.5/63.5	1.5/38.1	Center	1.5/38.1	2.5/63.5
1.0/25.4	0.495/125.7	0.500/127.0	0.495/125.7	0.560/142.2	0.650/165.1
1.5/38.1	0.485/123.2	0.495/125.7	0.495/125.7	0.535/135.9	0.625/158.8
2.0/50.8	0.500/127.0	0.510/129.5	0.495/125.7	0.525/133.4	0.615/156.2
2.5/63.5	0.520/132.1	0.500/127.0	0.500/127.0	0.535/135.9	0.625/158.8
3.0/76.2	0.540/137.2	0.535/135.9	0.495/125.7	0.520/132.1	0.615/156.2
3.5/88.9	0.535/135.9	0.535/135.9	0.495/125.7	0.520/132.1	0.625/158.8
4.0/101.6	0.525/133.4	0.520/132.1	0.485/123.2	0.535/135.9	0.635/161.3
4.5/114.3	0.525/133.4	0.520/132.1	0.485/123.2	0.540/137.2	0.610/154.9
5.0/127.0	0.520/132.1	0.510/129.5	0.475/120.7	0.540/137.2	0.575/146.1
5.5/139.7	0.495/125.7	0.500/127.0	0.475/120.7	0.535/135.9	0.575/146.1
6.0/152.4	0.485/123.2	0.495/125.7	0.485/123.2	0.540/137.2	0.565/143.5
6.5/165.1	0.495/125.7	0.475/120.7	0.485/123.2	0.525/133.4	0.575/146.1
7.0/180.3	0.460/116.8	0.475/120.7	0.485/123.2	0.540/137.2	0.585/148.6
7.5/190.5	0.440/111.8	0.475/120.7	0.495/125.7	0.540/137.2	0.575/146.1

154636
Figure 13. TRIANGULAR AREA OF POROSITY CASTING DEFECTS FOUND IN A NEW, REPLACEMENT, CAST IRON PUMP HOUSING.

DISCUSSION OF RESULTS

The crack defect seen in Figure 12 was made from a radiograph of the casting using a 2-minute X-ray exposure at 200 kV and 10 mA, at a target-to-film distance of 1524 mm (60 in), and with a lead-pack film.

It is postulated that the existence of cracks on the the water-exposed surfaces of the casting would have allowed intergranular water corrosion to proceed that could have gradually weakened the casting until metal rupture at an internal operating pressure of 0.8 MPa (120 psi) occurred. Such a crack was found on an integral section of the casting diametrically opposite to the blowout area, despite the well-known, brittle, metallurgical nature of gray cast iron. The existence of such internal cracks is believed to be a major contributory cause of pump failure, together with the substandard tensile strength of this gray iron casting which was found in metallurgical tests. According to the manufacturer's literature, the 76.0 to 102.0-MPa (11 000 to 14 800-psi) tensile strength represents a safety factor of only 1.4.

Presence of internal cracks is also supported by the visual differences between the metallic and brown iron oxide areas observed in the fracture surfaces of the broken pieces of the casting. It could not be determined when such cracks developed in the casting. Recent earthquake tremors in the East Tennessee area, which occurred during the Fall of 1973, might also have been a contributory factor in causing a crack or cracks to appear in the casting, but the significance of this activity can never be known. Since gray cast iron has no ductility, the ultimate and yield strengths are considered to coincide. Fracture occurred at a tensile strength of 11 000 psi. No record of tensile tests was available from the pump manufacturer.

After discussion with the manufacturer of the deep-well pumps, it was recommended⁽⁴⁾ that replacement pump discharge heads be: (1) fabricated from steel plate, or (2) cast from nodular ductile iron instead of gray cast iron. Both of these materials would be more satisfactory than the relatively brittle gray cast iron for service at the raw water intake pumping station in that each would provide higher yield/tensile strengths and be more resilient to pump vibration, earthquake, and/or waterhammer stresses that are normally encountered at the pumphouse. An engineering drawing has been prepared to permit the fabrication of replacement pump discharge heads using hot-rolled steel, Grade ASTM A-516 or ASTM A-285. If ductile iron is decided upon as the material of construction, the existing casting pattern of the pump vendor can be utilized.

CONCLUSIONS AND RECOMMENDATIONS

In a pump failure of this type, the exact cause of failure can never be ascribed with complete certainty because of the complexity and interplay of many factors, some known and some unknown. The major contributory factors causing the pump failure that are known are:

1. Some crack defects found in the discharge header casting by nondestructive testing. The time when these cracks were initiated could not be determined.
2. Substandard tensile strengths of 76.0 to 102.0 MPa (11 000 to 14 000 psi) for the discharge header casting. There was no record of tensile-strength data made by the manufacturer of the pump casting when the casting was poured at the foundry.
3. Porosity defects found in a new, replacement discharge header casting. Since this casting was supplied by the same vendor, it may be inferred that similar porosity defects existed in the failed pump casting before it was installed in water service.
4. Casting tensile tests indicate that a very minimal safety factor (ie, 1.4) was present at the time of installation of the pump housing.
5. Influence of other stresses such as earthquake tremors, waterhammer shocks during routine startup and shutdown operating sequences, and torque stresses applied to the one-inch steel tie rods between the discharge casting and the cone valve are three unknown factors whose significance cannot be evaluated. However, it is indicated by the low tensile strength safety factor of 1.4 that the casting was unsafe even if such other factors as corrosion and cracks are disregarded.

It is recommended that the cast iron housings of the water turbine pumps currently in service and those new cast iron housings on hand as replacements be examined for internal defects and flaws by the following nondestructive procedure:

1. Perform Zyglo penetrant tests on all surfaces that are accessible to perform the operation.
2. Assuming that no defects are observed by Zyglo penetrant testing, perform magnetic particle inspection on the housing quadrant where the two previous pump failures occurred and the adjacent mirror-image quadrant where a porous area was found on a new casting.
3. Make X-ray radiographs of the problem quadrant only. If other methods of testing reveal something in other areas, these areas should be further investigated by X ray.
4. Take ultrasonic thickness measurements on the other castings in the problem quadrant. The number of readings and locations should be the same as reported in Table 2.

If it is decided to procure ductile iron discharge headers as replacement castings, the nondestructive test procedure just outlined would not be followed. Instead, a hydraulic pressure test of 4.1 MPa (600 psi) should be used to determine the reliability of these units. Proper tensile testing of the housing at the time of manufacture must be provided to assure that a reasonable degree of quality control has been exercised to give an acceptable product.

In anticipation of a possible future failure of those cast iron pump discharge heads currently in service, steel-plate safety enclosures have been installed at each pump location. As of August 1974, a third deepwell pump rupture has occurred at the elbow section of the discharge head (Pump 5).

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