# CASE STUDIES SERIES

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# NUCLEAR SERVICE WATER PIPING

## OSKARSHAMN NUCLEAR POWER PLANT, FIGEHOLM, SWEDEN

Coastal nuclear power plants, which use brackish and often polluted water in their service water systems, face one of the most demanding service environments in the industry. The Swedish utility OKG AKTIEBOLAG has this operating environment at their Oskarshamn Nuclear Power Plant in Figeholm, Sweden. The brackish, polluted Baltic Sea water used in the service water system caused extensive corrosion of the original system materials. Material replacement, testing, and evaluation have been on-going since 1978, giving OKG some of the most extensive operating experience with 6 Mo austenitic stainless steels, titanium and other high performance replacement materials of any nuclear power plant in the world. This case study reviews the problems experienced with original system materials; replacement material evaluation programs; and actual performance of the alloys in service; therefore, providing valuable insight for utilities with equally severe operating environments.

## THE SYSTEM

The 0skarshamn Nuclear Power Plant has three operating units. The start-up dates for these units and other basic operating data for the service water system can be found in Table 1. The units all have open emergency service water systems and have both closed and open once-through portions of their regular service water system. The condensers in all three units are fed by the open portion of the service water system.

Both the standard and emergency service water system piping was originally rubber-lined carbon steel. The emergency service water system in all three plants is normally only operated during shut-down periods. A constant low flow rate is maintained through the system when it is not in operation to prevent water stagnation. The emergency systems in all three units were designed so that, even if the pumps stopped, the operating system would never be empty. The return pipes go to the highest point in the system.

*Table 1*
*System Description*

| DESCRIPTION | UNIT 1 | UNIT 2 | UNIT 3 |
|---|---|---|---|
| Start-Up | 1972 | 1974 | 1985 |
| System Testing | 1970 | 1972 | 1983 |
| Power Output (MWe) | 460 | 620 | 1,210 |
| Regular System Flow Rate (kg/s) | 700 | 1,000 | 1,700 |
| Emergency System Flow Rate (kg/s) | 25 | 400 | 700 |
| Main Condenser Flow Rate (kg/s) | 20,000 | 26,000 | 45,000 |

The open sections of the service water systems use brackish, polluted water from the Baltic Sea. The water enters the plant through culverts and is pumped through a short section of underground piping before entering the units. The closed portions of the service water system use demineralized water. Units 1 and 2 have open, once-through service water systems in all but the reactor building, which has a closed system. The majority of the piping and over 100 heat exchangers in these units are in the open portion of the service water system. These are the older units with start-up dates in 1972 and 1974, respectively. Corrosion problems became evident in both units within two to three years after commencement of commercial operation. The first problems arose in the main condensers. These were followed by problems with the heat exchangers, and then, with the piping.

Unit 3, which began operation in 1985, has both closed and open sections in its service water system with eleven titanium plate heat exchangers made by Alpha Laval as the interface between them. Since this unit is fairly new and since titanium was initially installed in both the heat exchangers and the condenser, there have been no significant corrosion problems to date. Corrosion problems with the pipe are anticipated when the rubber lining begins to crack or wear.

## THE WATER

The brackish, polluted water used in the open, once-through portions of the service water systems is drawn from the Baltic Sea. All three units were tested two to three years before the unit start-up date and may have had some stagnant water in them during that time. The basic characteristics of the water supply are outlined in Table 2. The high chloride content of the water and presence of pollution would be highly corrosive to many alloys. The increased solubility of oxygen at lower water temperatures and the increased corrosion rates that normally result under these conditions are probably an important contributing factor to the plant's problems. The facility is not aware of any microbiologically influenced corrosion (MIC) in any portion of the system. It is possible that the low water temperature during much of the year has prevented a MIC problem. The water source and description have not changed since initial testing of the system.

*Table 2*
*Water Description*

| | |
|---|---|
| Source | Baltic Sea |
| Type | Brackish, polluted |
| Temperature | 0 - 20°C (32 - 72°F) |
| pH | 7.5 - 8.0 |
| Chloride level | 4,000 ppm |
| Magnesium level | 250 ppm |
| Calcium | 100 ppm |
| Silica | 0.8 ppm |

During July and August, crustaceans can accumulate in the system. At one time, a trial study was done in which hypochlorite was added to the service water system to prevent crustacean growth. Although this worked well, the use of hypochlorite additions was not adopted by the plant because of environmental concerns. No additional chlorine or other chemicals are currently added to the water except during system shutdown. A cathodic protection system is used to prevent deterioration of the condenser tubesheets and waterboxes.

## MATERIAL EVALUATION AND REPLACEMENT

Oskarshamn selects materials by reviewing technical literature, laboratory tests, and actual in-plant experience. The laboratory-based testing program is sponsored by Vattenfall, the Swedish State Power Board, with financial support from participating power stations. The testing program simulates the corrosion and erosion problems common to the participating plants but at an accelerated rate. The materials included in the program are titanium, SAF 2507® (UNS S32750) duplex stainless steel, 254 SMO® (UNS S31254) and 654 SMO® (UNS S32654) austenitic stainless steels. All the stainless steels are produced by Avesta Sheffield AB. The samples are evaluated on an annual basis. Oskarshamn also closely monitors the performance of those materials already in service during the regularly scheduled inspection program.

Initial material replacement began in 1978 when a large number of aluminum brass heat exchanger tubes in Units 1 and 2 were replaced with titanium. The replacement program for Units 1 and 2 has been ongoing since that time. Subsequently, the rubber lining on the carbon steel pipe began to crack (due to age) and wear away. As the

*Table 3*
*Underground and In-Plant Replacement Materials*

| 254 SMO COMPONENTS | | 1984 | 1985 | 1986 | 1987 | 1988 | 1991 | TOTAL |
|---|---|---|---|---|---|---|---|---|
| Pipe | | | | | | | | |
| length | m | 26 | 160 | 48 | 36 | 146 | 42 | 458 |
| | ft. | 85 | 524 | 157 | 115 | 479 | 138 | 1,500 |
| diameter | mm | 206-306 | 60-408 | 206 | 206 | 60-168 | 306 | |
| | in. | 5-12 | 2-16 | 8 | 8 | 2-7 | 12 | |
| Elbows 90° | | 2 | 15 | 12 | 9 | 75 | 4 | |
| Cone Pipe Fittings | | 2 | 1 | 1 | - | - | - | |
| T-pieces | | - | - | - | - | - | 2 | |
| Condenser Tubes | | | | | | | | |
| length | m | - | - | - | - | - | 54,000 | 54,000 |
| | ft. | - | - | - | - | - | 177,120 | 177,120 |
| diameter | mm | - | - | - | - | - | 24 | |
| | ft. | - | - | - | - | - | 0.94 | |
| **TITANIUM COMPONENTS** | | **1978** | **1979** | | | | | **TOTAL** |
| Condenser Tubes | | | | | | | | |
| length | m | 288,000 | | | | | | 540,000 |
| | ft. | 944,640 | 826,560 | | | | | 1,771,200 |
| diameter | mm | 24 | 25 | | | | | |
| | in. | 0.94 | 0.98 | | | | | |

carbon steel is exposed to the service water, it corrodes quickly, making replacement of problem sections necessary. 254 SMO, a 6% molybdenum stainless steel, has been the replacement material of choice for pipe, tube and other system components since 1984 because of its corrosion resistance, availability and strength. Although titanium also provides the necessary corrosion resistance, it is more difficult to weld than 254 SMO stainless. Increased inert gas shielding is required, and skilled titanium welders were difficult to obtain. The higher strength of 254 SMO stainless was also an important factor in its selection.

Table 3 provides a summary of the titanium and 254 SMO stainless installed to date at Oskarshamn. It should also be noted that small amounts of 2205 stainless steel have been used in the past. This material is no longer used because of the problems experienced with crevice corrosion in some of the flanges.

### Underground and In-Plant piping

Since the service water enters the plant through culverts, there is very little underground piping. Submerged pumps for the three units pull the water from the culvert into short sections of underground piping to bring it into the plant. The return pipes are submerged 1 m (3.28 ft) below the water surface to prevent foaming and splashing of the brackish water. The original underground and in-plant piping (including the emergency service water system piping) were carbon steel with a rubber coating on both the outside and inside of the pipe. It was installed in the following years: Unit 1, 1969; Unit 2, 1971; and Unit 3, 1982. As the rubber began to age and crack, Oskarshamn began to experience corrosion problems severe enough to require pipe replacement. The same corrosion problems exist in both the normal and emergency portions of the system. The rubber cracking and corrosion problem has been particularly severe in the crevices of flange joints. The corrosion originated almost entirely on the inside of the pipe.

In 1984, Oskarshamn started replacing sections of the underground pipe and the in-plant pipe in Units 1 and 2. 254 SMO stainless and titanium were selected as replacement materials. No signs of corrosion have been observed in subsequent pipe inspections, and Oskarshamn is pleased with the performance to date. Both materials have worked well, but, since they have found 254 SMO stainless to be much easier to weld, it will be used for all future installations. The 254 SMO stainless has been the primary in-plant piping replacement material. A summary of the 254 SMO stainless piping sizes, elbows, fittings and other components installed to date is shown in Table 3.

All of the in-plant piping system components are obtainable in 254 SMO stainless.

It should be noted that there is still a great deal of rubber-lined pipe in the plant. Replacement is occurring as necessary, when leaks appear or when detached sections of the rubber lining adversely affect the water flow rate.

### Heat Exchangers

The original aluminum brass heat exchanger tubes were installed in Units I and 2 in 1969 and 1971, respectively. Each of these units has over fifty shell and tube heat exchangers cooled directly by the open portion of the service water system. The only closed loop intermediate cooling system is in the reactor building. Unit 3 was built with only eleven plate heat exchangers exposed directly to service water. It also has several closed loop intermediate cooling systems for localized components which use demineralized water. Unit 1’s and Unit 2’s heat exchanger tubes failed faster than anticipated because of the high water velocity. As of 1991, Unit 3’s titanium heat exchangers have not required replacement.

The tubes and tubesheets in fifty heat exchangers in Units 1 and 2 have been replaced with titanium. To avoid the vibration problems which can be caused by the modulus difference, six support plates were added to each “church window”. The titanium has performed well in this application, but, because of difficulties experienced in welding titanium, 254 SMO stainless has been the replacement material of choice for heat exchangers since 1984. The replacement of aluminum brass heat exchanger tubes and tubesheets is an ongoing program.

### Condensers

The original condenser tubes installed in Unit 1 in 1969 and Unit 2 in 1971 were aluminum brass. Due to corrosion problems that started within two to three years of installation, the condensers were retubed in 1978 and 1979 with 544,000 m (1.77 million ft) of titanium. The condenser tubesheets in Units 1 and 2 are carbon steel clad with Type 304 (18Cr-10Ni) stainless steel, and, in Unit 3, they are clad with titanium. The steam side of the outer most titanium condenser tubes in Units 1 sand 2 began showing signs of steam droplet erosion as early as 1988. This has resulted in tube leakage and plugging of problem tubes. All the Swedish and Finnish power plants with titanium condenser tubes have reported similar problems. Frequent inspections of the outer tubes are done. OKG retubed the Unit 2 condenser with a total of 54,000 m (177,120 ft) of 254 SMO in 1991. Unit 3’s original main condenser tubes are titanium and have not had any problems to date.

## SYSTEM INSPECTION AND CLEANING

Routine inspections are conducted by shift personnel as a part of normal plant operation. Water flow rates are monitored in the central control room and by local flow meters in the plant. Shift personnel look for leakage and other potential problems. In addition, the plant has a regularly scheduled maintenance program which began in 1978 and has not changed significantly since its inception. Cleaning and inspection of the system occurs during the annual refueling outage. Whenever the system is shut down, the system is flushed with “drinking” water, and ferrosulphate is added to any remaining brackish water to prevent deterioration. During outages, the culverts are drained and cleaned using high pressure equipment.

Much of the piping is still rubber-lined carbon steel. This is not generally inspected other than for through-wall leaks or for partial detachment of the rubber lining which causes reduced flow through the pipe. If either problem exists, the section is replaced with 254 SMO stainless. The sections which have already been replaced with 254 SMO stainless are inspected visually every five years in accordance with the requirements of a 20-year warranty provided by the manufacturer. The inspection is done by Oskarshamn personnel.

The aluminum brass seawater cooled heat exchangers in Units 1 and 2 are cleaned and eddy current tested during the annual refueling outage. Since the titanium heat exchanger tubes have performed well, they are cleaned and generally only visually inspected. Unit 3 has a high pressure water strainer with 3 mm (0.12 in) filter holes installed behind the intake pumps to prevent crustaceans from entering the system. Because of this, the titanium heat exchangers in Unit 3 are cleaned every five years. Suspended solids are not considered to be a problem in any of the units. Ball cleaning equipment is run continuously to keep the main condenser free of biofouling. When the system is stopped, the condenser is flushed and dried. Extensive testing of the titanium condenser tubes is required due to the erosion-corrosion problems that have occurred in the outer rows of tubes. Eddy current testing of these tubes is done annually.

The pumps are visually inspected every year. Normally, one out of four pumps is replaced with an overhauled unit so that each pump is overhauled an average of once every four years. There is no formal program for inspecting valves, but, if a valve is temporarily removed from the system because of other repair work, it is inspected.

## FABRICATION

Since 0skarshamn currently uses only 254 SMO austenitic stainless steel, it will be the only material discussed. All the field and shop fabrication was done by an outside contractor. The welding procedure used by Oskarshamn was provided by the steel producer, Avesta Sheffield AB. The following is a brief summary of information provided. Several welding techniques are suitable: Gas Tungsten Arc Welding (GTAW or TIG); Gas Metal Arc Welding (GMAW or MIG); or Shielded Metal Arc Welding (SMAW). The weld pool should be protected from atmospheric oxidation by an inert gas cover. Preheating, hot spots, and post-weld heating are not recommended and can be detrimental to the material properties. A filler metal with a chemistry equivalent to Alloy 625 is recommended. The 0skarshamn plant used Avesta P-12 filler metal which is produced by Avesta Welding. The interpass temperature of the work piece should not exceed 212°F (100°C). This welding procedure is similar to the procedures recommended by other producers of 6Mo austenitic stainless steels. Flange joints were used instead of welding to join dissimilar materials.

Any heat tint should be removed after welding by either grinding with a fine abrasive, by abrasive blasting with 75-100 micron soda-lime glass beads, or by using pickling paste or pickling acid. Carbon steel brushes are not allowed under any circumstances. Even common grade stainless steel brushes are not suggested unless subsequent chemical cleaning of the weld is done. Brushing can potentially cause iron contamination of the surface which may initiate pitting in an aggressive chloride environment.

## CONCLUSIONS

The demanding service water environment that exists at the Oskarshamn plant led the materials decision-makers to use and gain experience with highly corrosion resistant materials. This large scale, long-term experience with titanium and a 6Mo austenitic stainless steel in a highly demanding service water system environment provides valuable assistance to materials decision-makers encountering similar problems. Titanium; the duplex stainless steel, 2205; and the 6Mo austenitic stainless steel, 254 SMO, have all been used as replacement piping materials in the plant. Titanium has performed well in all applications except the outermost rows of the condenser tubes, but, due to problems associated with welding, Oskarshamn does not plan to use titanium in the future. Crevice corrosion problems with 2205 eliminated it from future consideration. The preferred replacement material since 1984 has been the 6Mo austenitic stainless steel alloy 254 SMO because of its corrosion resistance, availability, relative ease of fabrication, and strength. Although 254 SMO is the only 6Mo austenitic to have been tried, it is assumed that the other alloys in this family would also perform well. Two alloys that are currently being tested, SAF 2507 duplex stainless steel and 654 SMO austenitic stainless steel, may be considered for future installations.

The 6Mo austenitic stainless steels are readily available in all the common product forms needed in constructing a service water system. This makes it possible to replace all existing system components to provide maximum system cost-effectiveness and efficiency. Since there are several 6Mo austenitic stainless steel alloy producers from which to choose, materials specifiers can generally select from a variety of sources based on the properties and components required, quality, technical support, service, delivery, and price.

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