Shot Peening to Prevent Stress-Corrosion Cracking of Nuclear Steam Generator Tubes

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ABSTRACT

The steam generator tubing in nuclear power plants forms part of the primary pressure boundary between the highly radioactive primary water and the non-radioactive water in the steam cycle. In approximately 15 nuclear plants in the United States and others overseas, the Alloy-600 steam generator tubing is susceptible to primary water stress corrosion cracking (PWSCC). This cracking occurs at the transition zone where the tubing is roll expanded into the tubesheet and is caused by a combination of properties which include the operating environment, tube material properties and a tensile stress on the inner diameter of the tubing. Laboratory testing and field experience have shown that shot peening the inner surface of the tubing to impart a layer of uniform compressive stress is effective in preventing the initiation of new cracks. The Babcock & Wilcox Company (B&W) and Metal Improvement Company (MIC) teamed together to develop a shot peening system which has been successfully applied in a number of field applications as a remedial measure for this concern. In this teaming agreement, the MIC shot peening technology was combined with B&W's experience in performing service work in radioactively contaminated nuclear power plants using advanced robotic equipment. B&W's control system expertise was also employed to develop an automated control system for application of the process.

NUCLEAR STEAM GENERATOR DESCRIPTION

In the United States today, approximately 20% of our electricity is generated by nuclear power plants. There are 112 plants in commercial operation in the United States and 76 of these are of the pressurized water reactor (PWR) design. In this particular type of nuclear power plant, the nuclear steam generator is the primary heat exchanger between the radioactive primary water that passes through the nuclear fuel core and the non-radioactive secondary system water that passes through the turbine and condenser. Each PWR system contains from two to four nuclear steam generators. Each steam generator, depending upon the manufacturer and design, contains between 3,400 and 15,500 tubes, ranging in size from 0.625-inch O.D. to 0.875-inch O.D. Typical wall thicknesses are in the range of 0.040 to 0.050-inch. The tubes are manufactured from Alloy 600 -- a composite consisting primarily of nickel (72%), chromium (16%) and iron (8%).

The integrity of this tubing is extremely important to the safe operation of a nuclear power plant because it forms part of the primary pressure boundary, that is, the boundary between the radioactively contaminated primary system water and the non-radioactive secondary system water. If a leak in one of these tubes develops, radioactive water would leak to the secondary plant, and if no corrective measures were taken, radioactivity could eventually be released to the outside environment.

Typical operating conditions in a PWR are temperatures of approximately 600°F and 2200 psi on the primary side of the tubes (ID); 550°F and 1000 psi on the secondary side (OD). The primary coolant water flows on the inside of the tubes and the secondary side water, which is turned into steam, flows on the outside of the tube (Fig. 1).

BACKGROUND

In the United States, approximately 15 PWRs (and other plants overseas) have been identified as having tubing that is particularly susceptible to primary water stress-corrosion cracking. This is a tube degradation mechanism that results from a combination of three factors: an aggressive environment, a tensile stress and a material susceptible to stress-corrosion cracking. In this particular group of plants, the tubes were hard rolled into the tubesheet and high residual stresses remained in the roll transition between the hard roll area and the non-rolled area which is right at the top of the tubesheet (Fig. 2). In addition, the metallurgical properties of the tubing resulted in a microstructure that left the material susceptible to stress-corrosion cracking. In this case, the stress-corrosion cracking typically results in I.D.-initiated axial cracks in the roll transition region. If no remedial action is taken, these cracks can eventually lead to leakage of the primary coolant.

Nondestructive examinations using eddy current technology are employed on a periodic basis to inspect these tubes and to repair or remove from service (by plugging) tubes that have cracks exceeding predetermined criteria. However, if remedial action is not taken to mitigate the cracking, there would be so many tubes plugged that the power output of the plant would have to be reduced.

SHOT PEENING PROCESS

One method that has been developed to prevent or mitigate the effects of stress-corrosion cracking is shot peening. Shot peening is a process that uses a stream of dry air to project tiny metal balls ("shot") against the inside circumference of the steam generator tubes. By shot peening the tubes in the roll transition region, the tensile stress on the I.D. surface of the tube is changed to a compressive stress, thereby removing one of the three factors which (in combination) are required to produce stress-corrosion cracking.

Extensive process testing and qualification were performed to select the correct variables for the shot peening process as applied to nuclear steam generator tubing. Mockups were prepared simulating all of the tube roll transition geometry variables. These tubes were shot peened with varying process parameters. Control samples that were not shot peened were also included in the testing. The samples were subjected to corrosion tests to confirm that the final process variables selected resulted in an effective shot peening process.

An important concern in the development of this process was the intensity. While it was important to have a sufficient intensity to provide a compressive layer on the tube I.D. that would resist cracking, it was also important to not have so high an intensity that there would be significant increases in the tensile stress on the O.D. of the tube, which could result in future problems in that region.

SHOT PEENING SYSTEM

Once the process parameters were established, a number of special considerations had to be addressed to effectively apply the process in the radioactive nuclear environment. An important consideration was that the system function as a reliable, automated system with operation by personnel from a remote control trailer outside of the reactor building approximately 500 feet away from the steam generators. The object here is to keep personnel away from the radioactive area near the steam generators and reduce radiation exposure to personnel as much as possible (Fig. 3).

The various components of the system had to be designed to be compact and modular so that they could be carried by one or two people into the close confines of the work areas outside of the steam generators. The shot media in this application consists of metallic balls that are smaller than 0.010-inch in diameter. The shot media becomes radioactively contaminated after it is applied to the inside of the nuclear steam generator tubing, and thus it was extremely important that the system be designed as a closed system. All of the "shot" and the radioactive contamination it picked up during the peening process had to be contained within the system and recycled continuously. This closed system was important not only to reduce the spread of radioactive contamination, but also to minimize the potential for the shot media to mechanically damage critical bearing surfaces and other areas with close clearances.

PROCESS CONTROL

The basic shot peening technology and equipment were provided by the Metal Improvement Company (MIC). Through a teaming agreement, MIC worked very closely with B&W Nuclear Service Company on the process development, equipment preparation and process implementation.

In this shot peening system, shot is stored in a pressure vessel. From this vessel, shot is metered out with an auger into a stream of compressed air flowing through a flexible hose. The shot is carried to a nozzle that is stroked back and forth across the area to be peened by a device that alternately pushes and pulls the shot hose and nozzle. A vacuum system is part of the tool head and removes shot from the steam generator tube. This shot is cycled through a return line to a cyclone separator that removes the dust and broken pieces of shot through a filter and collector system and returns the good shot back to the pressure vessel to be recycled to the next tube. After each cycle is completed, the shot hose and nozzle are moved to the next tube by a robotic arm developed by B&W Nuclear Service Company.

Another important aspect of performing successful shot peening is to ensure a supply of clean dry air. "Dry air" is not normally available in the very humid environment inside a nuclear power plant, and therefore, we bring our own air compressors with drying towers to supply peening air for the system. The entire operation is controlled by a two-man control station; one individual operates the remote manipulator; the other, operates the peening control system.

It was very important in the design of the system to be able to maintain tight control over the essential process variables to assure that the process was correctly applied. If the intensity of the shot was too low or the coverage incomplete (that is, less than 100% coverage), it would still be possible for stress-corrosion cracks to initiate on the

I.D. surface of the tube. If the shot intensity were too great, too much stress would be generated on the O.D. of the tube. Therefore, B&W Nuclear Service Company developed a microprocessor-based automated control system that continuously monitors all process variables and initiates an automatic system abort when any of the key process variables moves outside of a preselected range.

The three essential variables we control to assure that the correct process is being applied are: the nozzle speed (i.e., the speed at which the shot peen nozzle traverses up and down the inside of the steam generator tube); the air pressure (which determines the velocity at which the shot media is impacting the inside of the steam generator tube); and the shot flow (quantity of shot passing through the nozzle in a given time). These parameters are monitored continuously by the automated control system, and if any of the parameters moves outside of its preselected range, the process is automatically aborted and the process variables are printed out for the operator, so that corrective action can be initiated. Other variables are also monitored by the operator on a continuing basis. A hard copy printout of the actual parameters used to peen each tube is provided to the plant owner as part of the permanent Quality Assurance record of the work performed.

Additional in-process checks of intensity and coverage are performed at periodic intervals by removing the shot peening nozzle and toolhead from the steam generator and peening a test strip made from Inconel material. This test strip is very similar to the almen strip used in the shot peening industry except that the material used is the same as that of the steam generator tubing.

PROCESS IMPLEMENTATION

In a typical shot peening operation, we will perform work on four steam generators in parallel (i.e., four systems operating concurrently) and approximately 250 tubes per day per system will be peened. Including setup and teardown time, it normally takes about three to four weeks to perform such an operation on a large nuclear power plant. When all support personnel are considered, the total crew size is approximately 90 - 100 people, based on two, 12-hour shifts per day, seven days per week.

Since the initial application of this process to nuclear steam generators in the United States in early 1986, B&W Nuclear Service Company and Metal Improvement Company have shot peened more than 260,000 tube ends in ten nuclear power plants. Note, that both ends of each tube must be shot peened. The general consensus based on inspection data one or two years following shot peening is that shot peening has been effective as a remedial measure to mitigate the effects of stress-corrosion cracking when it was applied early enough in plant life. On some occasions, the shot peening process may have been applied after very small cracks had already initiated in the tubing and the shot peening process was less effective in these plants.

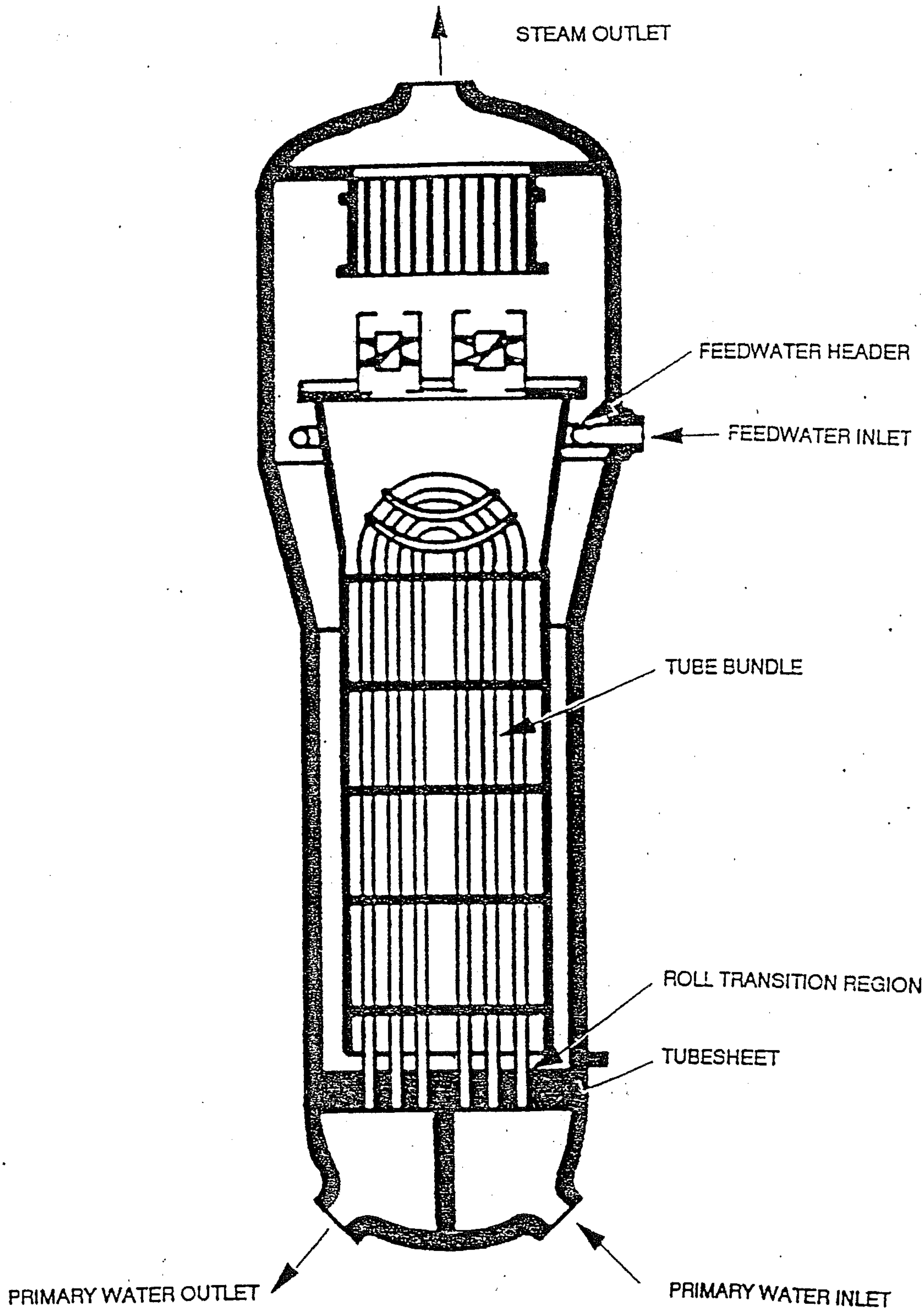

Fig. 1 Steam Generator Cutaway

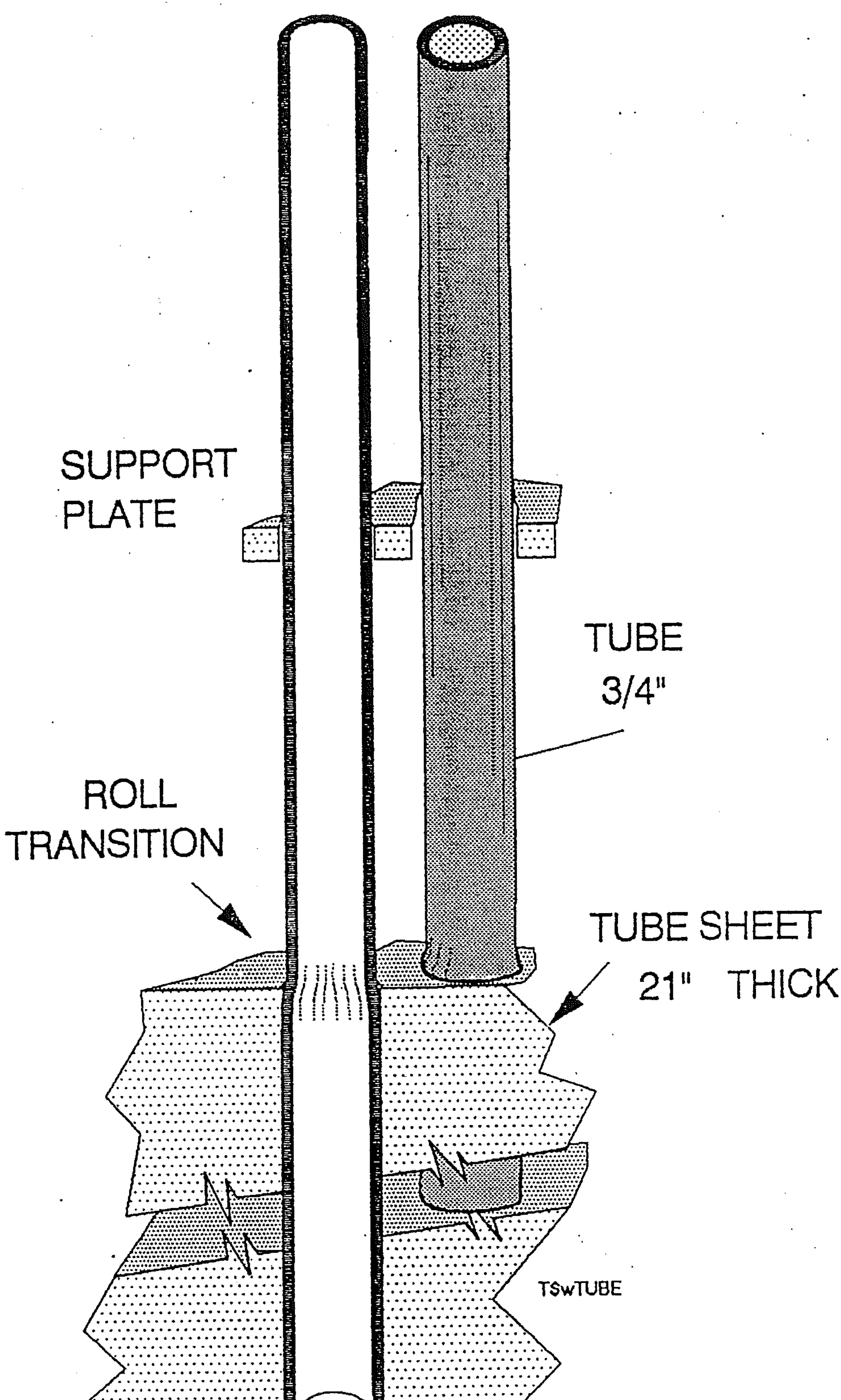

Fig. 2 Roll Transition Area

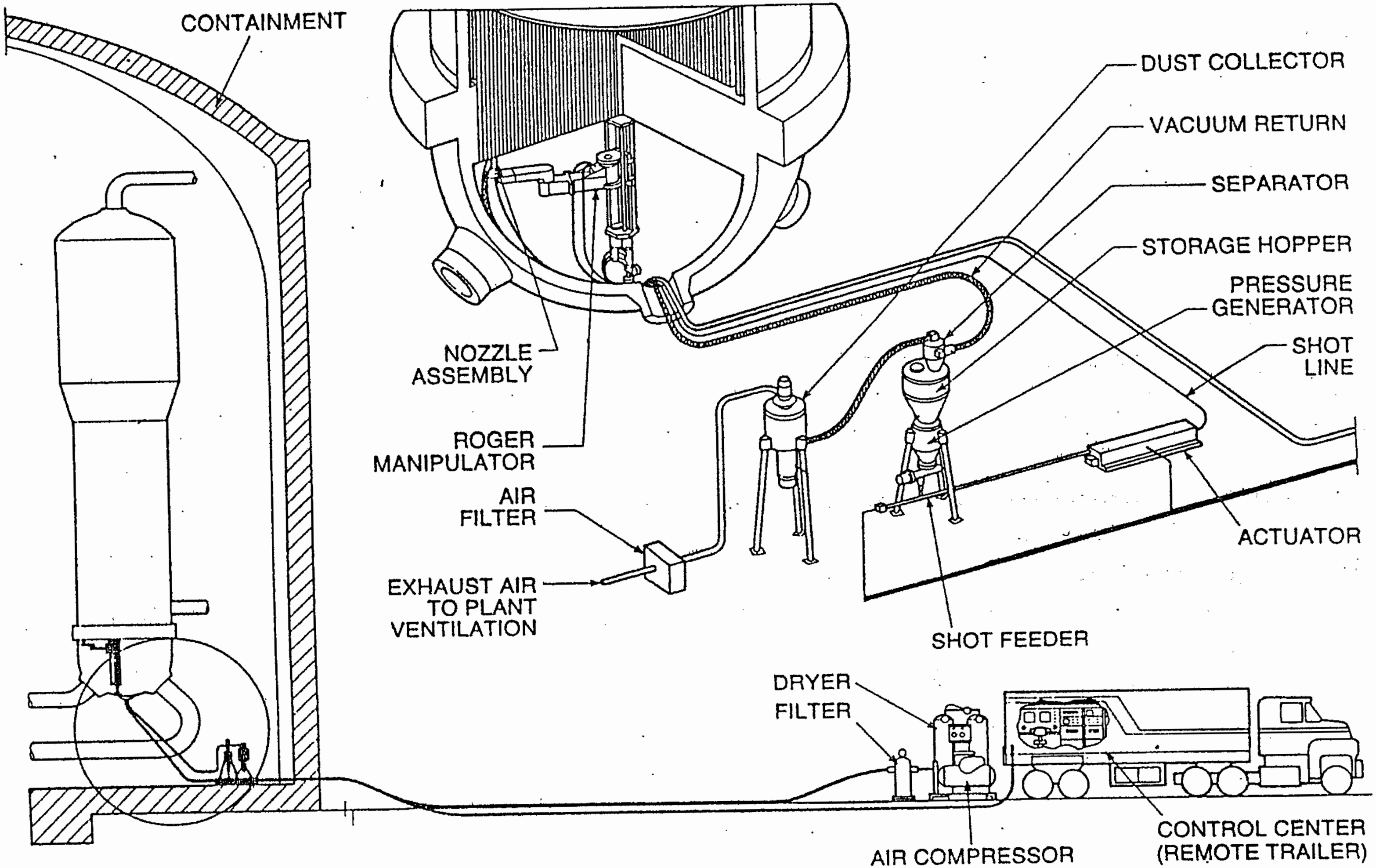

Fig. 3 BWNS/MIC Shot Peening System