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# STEAM GENERATOR TUBE FAILURES:

# EXPERIENCE WITH WATER-COOLED NUCLEAR POWER REACTORS DURING 1976

by

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# Défaillance des tubes de générateurs de vapeur

Expérience acquise en 1976 dans des centrales
nucléaires ayant un ou plusieurs réacteurs refroidis par eau

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## Résumé

Une étude a été effectuée au sujet de l'expérience acquise en 1976 avec les tubes de générateurs de vapeur de centrales nucléaires. Sur les 68 réacteurs refroidis par eau ayant été étudiés, 25 ont eu des défaillances de tubes de chaudière. On décrit ces défaillances ainsi que les méthodes conçues pour les détecter et les réparer. Les données recueillies ont permis de constater que la corrosion a été la principale cause des défaillances de tubes de chaudière en 1976. Des améliorations doivent être apportées à la conception des générateurs de vapeur, à l'intégrité des condenseurs et au contrôle chimique de l'eau secondaire.

L'Energie Atomique du Canada, Limitée
Laboratoires Nucléaires de Chalk River
Chalk River, Ontario

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## ABSTRACT

A survey was conducted of experience with steam generator tubes at nuclear power stations during 1976. Failures were reported at 25 out of 68 water-cooled reactors. The causes of these failures and the repair and inspection procedures designed to cope with them are summarized. Examination of the data indicates that corrosion was the major cause of steam generator tube failures. Improvements are needed in steam generator design, condenser integrity and secondary water chemistry control.

Atomic Energy of Canada Limited
Chalk River Nuclear Laboratories
Chalk River, Ontario
February 1978

AECL-6095

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## INTRODUCTION

The performance of steam generator tubes at water-cooled nuclear power plants during 1976 has been reviewed. Data on tube failures, their causes and repair are presented as in previous surveys by Atomic Energy of Canada Limited (1-5). This survey does not include data from reactors in the USSR and Eastern Europe. Nor does it include reactors rated at 50 MW(e) or less except for NPD*. Otherwise, all water-cooled power reactors with steam generators with more than 85 effective full power days (EFPD) at 31 December 1976, were included.

The 68 reactors in this study were of the following types:

- 52 pressurized water reactors (PWR)
- 10 pressurized heavy water reactors (PHWR)
- 5 boiling water reactors (BWR)
- 1 water-cooled graphite-moderated reactor

Eight of the PHWR's were of the CANDU-PHW** design.

Steam generator tubes were plugged at 24 reactors because of failures and at four reactors where tubes were removed for laboratory investigation. A number of tubes were known to be leaking at Garigliano but were not plugged during the reporting period.

More than 60% of steam generator tubes plugged during 1976 had tube constriction at tube support plates (denting). A further 26% of tubes plugged had sustained wall thinning in excess of acceptable or regulatory limits. The thinning was due to corrosion by risidual phosphates (wastage) in the zone of accumulated sludge above the tube-sheet. Stress corrosion cracking (SCC),

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*NPD - Nuclear Power Demonstration Reactor, Rolphton, Ontario, 25 MW(e).
**CANDU-PHW - CANada Deuterium Uranium - Pressurized Heavy Water

fretting and fatigue also accounted for a significant number of tube failures.

Information for this review was obtained from the literature and from questionnaires mailed to operating personnel of the reactors involved. Approximately 95% of the questionnaires were returned to the authors.

## SURVEY OF 1976 FAILURES

Operations are described below for power reactors in which steam generator tube repair was performed during 1976. A summary of these operations is presented in Table 1.

### *BEZNAU-1, Switzerland*

Seven tubes were plugged in Beznau-1 steam generators during 1976. The failures were caused by caustic stress corrosion cracking. Cracks were located within the tubesheet crevice, distributed in a random pattern over the hot leg side. Fourteen tubes showed thinning greater than 20% of wall thickness from the secondary side. These were located on both inlet and outlet legs.

Automated eddy-current testing was performed on 1757 tubes to the first support plate and to the uppermost support plate on 339 tubes. An additional 106 tubes were inspected through the U-bend from the hot leg side. No dent indications were reported. Secondary water chemistry was maintained within specification; no condenser leaks occurred during the year.

### *BEZNAU-2, Switzerland*

Extensive wastage in Beznau-2 steam generators resulted in the plugging of 118 tubes. All defects were within the tubesheet sludge pile and were especially severe on the cold leg side.

More than 3000 tubes in each steam generator were subjected to eddy-current testing to the first support plate. An additional 860 tubes were tested to the top tube support and 174 tubes through the U-bend from the inlet side. No problems due to denting were reported for 1976. In both Beznau-1 and -2 repairs were made by explosive tube plugging techniques.

*BIBLIS-A, FRG*

The 900 mm tube sections were removed from Biblis-A steam generators for laboratory inspection. The sites were explosively plugged and seal-welded. Eddy-current testing was performed on an additional 1200 tubes.

*BORSSELE, Netherlands*

A tube was removed from one of the steam generators for laboratory examination; explosive plugs were fitted to 2 tubes because of problems encountered during the operation. Also as part of the testing program remote eddy-current inspection was performed on about 3% of hot leg tubes and 1% of cold leg tubes in each steam generator. No defects were reported.

Seven condenser leaks were repaired during 1976 but no secondary chemistry upsets were experienced. This station is cooled by sea water and secondary water chemistry control is achieved by phosphate addition. No dent indications were reported, but the tube support plates in Borssele steam generators are stainless rather than carbon steel.

Table 1 - SUMMARY OF STEAM GENERATOR TUBES PLUGGED DURING 1976.

| REACTOR | TUBES PLUGGED | FAILURE CAUSE | FAILURE LOCATION | SECONDARY CHEMISTRY CONTROL | CONDENSER COOLING WATER | CONDENSER LEAKS | COMMENTS |
|---|---|---|---|---|---|---|---|
| Beznau-1 | 7 | SCC | TS crevice | AVT | Fresh | No | |
| Beznau-2 | 118 | W | few in HL many in CL | AVT | Fresh | No | |
| Biblis A | 2 | -- | -- | $PO_4$ | Fresh | Yes | removed for inspection |
| Borssele | 2 | -- | -- | $PO_4$ | Sea | Yes | 1 removed for inspection, 1 plugging error |
| Dresden-1 | 4 | UD | outer edge of tube bundle | NR | Fresh | | BWR |
| Garigliano | -- | -- | -- | NR | Fresh | Yes | SSG-A out of service due to leakage but not opened in 1976, BWR |
| Ginna | 56 | W, SCC | few cm above TS | AVT | Fresh | Yes | 3 tubes caustic cracking, 1 random leak |
| Haddam Neck (Conn. Yankee) | 4 | UD | >2.5 cm above TS | AVT | Fresh | Yes | |
| KRB Gundremmingen | 231 | corrosion | near divider plate at TS | NR | Fresh | Yes | BWR |
| KWO Obrigheim | 9 | SCC | HL near bundle centre above TS, U-bend | AVT | Fresh | Yes | |
| Mihama-1 | 2 | -- | -- | NR | Sea | No | removed for inspection, shut-down all 1976 |
| N-Reactor | 3 | UD | UD | AVT | Fresh | Yes | all leaks in stainless steel tubes. |
| Oconee-1 | 6 | fatigue | upper TS (on open inspection lane), 14th TSP (not on open lane) | AVT, CD | Fresh | Yes | OTSG |
| Oconee-2 | 3 | fatigue, fretting | upper TS (open lane), 15th TSP (open lane), 12th TSP (not open lane) | AVT, CD | Fresh | Yes | OTSG |
| Oconee-3 | 3 | fatigue | 15th TSP (open lane), weld at upper TS | AVT, CD | Fresh | Yes | OTSG |

TABLE 1 - cont'd

| REACTOR | TUBES PLUGGED | FAILURE CAUSE | FAILURE LOCATION | SECONDARY CHEMISTRY CONTROL | CONDENSER COOLING WATER | CONDENSER LEAKS | COMMENTS |
|---|---|---|---|---|---|---|---|
| Palisades | 711 | W | 3rd & 4th TSP | AVT | Fresh | Yes | cooling towers |
| Point Beach-2 | 6 | W,SCC | above TS | AVT | Fresh | Yes | |
| Robinson-2 | 12 | W | 1st & 2nd TSP | $PO_4$ | Fresh | Yes | dent indications in one SG |
| San Onofre | 104 | W, fretting | above TS, AVB | $PO_4$ | Sea | Yes | 3 removed for U-bend inspection at AVB, hour-glassing at lower 2 TSP in 2 SG |
| Sena(Chooz) | 4 | fretting | AVB | AVT | Fresh | Yes | |
| Surry-1 | 968 | D,SCC | near tube lane and peripheral wedge areas | AVT | Brackish | Yes | |
| Surry-2 | 797 | D,SCC | near tube lane and peripheral wedge areas | AVT | Brackish | Yes | |
| Takahama-2 | 1 | -- | -- | AVT | Sea | No | removed for inspection |
| Tarapur-1 | 1 | UD | UD | NR | Sea | Yes | BWR |
| Tarapur-2 | 80 | UD | UD | NR | Sea | Yes | BWR |
| Three Mile Island-1 | 8 | fretting | 15th TSP | AVT,CD | Fresh | Yes | OTSG |
| Turkey Point-3 | 275 | D,SCC,W | above TS in HL, between 1st and 6th TSP, U-bend | AVT | Sea | Yes | |
| Turkey Point-4 | 351 | W,D,SCC | above TS in HL, HL between 1st and 6th TSP, U-bend | AVT | Sea | Yes | 6 tubes removed for U-bend inspection |
| Yankee Rowe | 2 | W suspected | within 10 cm above TS | AVT | Fresh | No | |

D = denting
SCC = stress corrosion cracking
W = wastage
AVB = anti-vibration bar
TS = tube sheet
TSP = tube support plate
HL = hot leg
CL = cold leg
UD = undetermined

AVT = all-volatile treatment
CD = condensate demineralization
$PO_4$ = phosphate treatment
BWR = boiling water reactor
OTSG = once through steam generator
SG = steam generator
SSG = secondary steam generator
NR = not reported

*DRESDEN-1, USA*

Four defects of unknown cause were plugged near the tube bundle outer edge in secondary steam generator C. Leaking tubes were detected by hydrostatic testing. Due to installation of new sampling equipment, piping and coolers, secondary steam generator chemistry was not monitored during 1976. There was no secondary water treatment for that year.

*GARIGLIANO, Italy*

Many tube defects occurred in secondary steam generator A and it was removed from service. However, neither steam generator was opened during 1976. The defects were believed to be caused by stress corrosion cracking (6).

*GINNA, USA*

One failed tube was plugged during January, 1976. A further 39 tubes were plugged on the inlet side of steam generator A and two tubes on the B inlet. It was suspected that three of the defects in A were caused by caustic cracking. The remainder were plugged because the 40% wall-thinning criterion had been exceeded. During April, primary to secondary leak indications were observed on B steam generator. The leaking tube was identified by eddy-current techniques. Fourteen tubes were plugged. The defects were caused by tube-wall thinning.

During the shutdown early in 1976, an extensive inspection of tubes in both steam generators was performed to evaluate the effect of conversion to all-volatile treatment (AVT) and to verify tube integrity for continued operation.

Eddy-current testing at a frequency of 400 kHz was conducted on all inlet and outlet tubes to the first support plate. In addition, about 200 tubes were examined through the U-bend and large numbers in both steam generators were tested for denting. Sludge height was profiled with low frequency (25 kHz) eddy-current testing. Test results showed that no denting had occurred in Ginna steam generators up to this time. In-line condensate demineralizers were installed during an outage (7,8).

*HADDAM NECK, USA*

Four tubes were explosively plugged during 1976. The defects were 2.5 cm above the tubesheet or higher. The cause of failure is not known.

Automated remote eddy-current inspection was performed on a large number of tubes to satisfy the regulatory authority. About 1500 tubes were tested at the U-bend, more than 1400 to the first tube support plate, 98 to the fourth support and almost 500 around the U-bend. Phosphate concentrations of 10-20 mg $PO_4$/kg water were observed in the secondary water at low power and during shutdown.

*KRB GUNDREMMINGEN, FRG*

The steam generators at Gundremmingen are tubes with stainless steel. During the period of this survey 231 defected tubes were explosively plugged. Although the failure mechanism has not been extablished with certainty, it is believed to be corrosion related. All defects were located at the tubesheet, bundle centre, near the divider plate. Leaking tubes were identified by a hydrostatic test.

*KWO OBRIGHEIM, FRG*

Eight tubes were plugged in steam generator I and one tube in steam generator II. Defects in steam generator I were caused by intergranular stress corrosion cracking from the secondary side just above the tubesheet. The defects were located near the centre of the tube bundle in the hot leg. In steam generator II, the failure occurred at the U-bend in the inner tube row where bend radius is smallest. Repairs were made by explosive plugging. Eddy-current testing was performed on 1000 hot leg tubes in steam generator I and 95 hot leg tubes in II.

*MIHAMA-1, Japan*

Mihama-1 remained out of service during 1976. The steam generators were flushed with hot water from February to May in an effort to remove residual phosphates. Sections of two tubes were pulled to establish the effectiveness of flushing and to ensure that no further degradation had taken place. The tube sites were blocked by manually welded plugs. Also as part of the testing program, all unplugged tubes in both steam generators were subjected to eddy-current testing throughout their full length. It was established that tube deterioration had not propagated since the last inspection. Steam generators in Mihama-2 were also subjected to 100% eddy-current testing to check for changes following conversion to all-volatile treatment of secondary water. No changes were reported.

*N-REACTOR, USA*

Three tubes defected in one of the two remaining steam generators that are tubed with 304 stainless steel. The leaking tubes were fitted with manually welded plugs. Although not determined with certainty, the defects were thought to be caused by stress corrosion. The failure pattern followed that of previous years; only stainless steel tubes have failed at N-Reactor. Remote eddy-current inspection was performed on 206 tubes, 150 in the hot leg, of steam generator 6A, which has Inconel tubes. No defect indications were observed.

*OCONEE-1, USA*

Six tubes were fitted with explosive plugs in Oconee-1 steam generators during 1976. The defects were evenly divided between the upper tubesheet and the 14th tube support plate. Two tubes that leaked were found to have circumferential cracks, believed to be caused by fatigue. During the shutdowns for tube repair, 435 tubes were inspected by automated eddy-current testing; a further 1015 were inspected during the annual outage. Fibre optics techniques were used on the open inspection lane and the inside bore of failed tubes.

*OCONEE-2, USA*

Three tubes failed in unit-2 steam generators and were removed for further examination. One tube showed circumferential cracking to be transgranular. The second tube was pulled to investigate wear at the top support plate and the third to investigate an eddy-current indication at the 12th tube support. About 1000 tubes were inspected during the scheduled shutdown and 134 during the leak outage. Inspection techniques were the same as those used at the other two Oconee units.

*OCONEE-3, USA*

Tube failures in Oconee-3 consisted of one due to cracking at the uppermost tube support plate and two caused by physical damage at the upper tubesheet. It is believed that defects in all three units are due to mechanical rather than chemical processes.

*PALISADES, USA*

During the annual outage early in 1976, 102 and 609 tubes were plugged in Palisades A and B steam generators, respectively. Defects were caused by excessive wall thinning at the third and fourth support plates. Tapered interference-fit plugs with an integral consumable lip were secured by TIG welding. Eddy-current inspection was conducted on 100% of inlet tubes and 7% of outlet tubes in both boilers. Denting, present in both steam generators, did not appear to have propagated since the last inspection.

In cooperation with the manufacturer, Consumers Power initiated a tube sleeving experiment which, if successful, could prolong tube life at least until full penetration of the original tube occurred. Ten selected tubes in B steam generator were sleeved with little difficulty during the refuelling outage and development work to establish feasibility of large-scale sleeving at the next outage was initiated (9).

*POINT BEACH-2, USA*

Six tubes were fitted with explosive plugs in the two steam generators at Point Beach-2. One of two defective tubes in A steam generator inlet had a through-wall penetration caused by caustic corrosion, the rest had thinning in excess of predetermined limits. Eddy-current inspection was conducted on 726 tubes to the first support and 330 around the U-bend on the inlet side of A steam generator and 221 to the first support and 37 to the sixth support on the outlet side. More than 1100 tubes were inspected to the first tube support and 227 around the U-bend in B steam generator inlet. The tubesheets were also photographed to provide an accurate record of plugged tubes. As with other reactors with a previous history of phosphate treatment, phosphates were detected in the boilers during shutdown.

*H.B. ROBINSON-2, USA*

Extensive eddy-current inspection showed that 12 tubes had wall thinning greater than 50% at the first and second support plates. These were sealed with explosive plugs. Dent indications and defects in tube support plates were found in one steam generator. At Robinson-2 secondary water is treated by the congruent phosphate method, holding the sodium to phosphate molar ratio between 2.3 and 2.6. Denting was less extensive compared to plants using all-volatile treatment.

*SAN ONOFRE, USA*

At the beginning of the reporting period, San Onofre was shut down for refuelling and modifications. The principle cause of tube degradation was wear at the anti-vibration bars which had exceeded limits in 88 tubes. Three of these tubes were removed for further inspection. Anti-vibration bars with square cross section, installed as part of the modification program, are expected to reduce or eliminate thinning in the U-bend region. Tube thinning at the tubesheet exceeded 50% of wall thickness in 12 tubes. In all, explosive plugs were inserted into 104 tubes. More than 5300 tubes were subjected to eddy-current inspection at 400 kHz around the U-bend from the inlet side and 1427 were similarly inspected at 100 kHz. Although further propagation of dents was not reported, hour-glassing was observed in the bottom two of four support plates in two of the three steam generators. Secondary water continued to be treated with low phosphate.

During July a primary-to-secondary leak was detected. The leaking tube was identified by hydrostatic test and explosively plugged (10,11).

*SENA (CHOOZ), France*

Four tubes were plugged because of wall thinning at the anti-vibration bar. Eddy-current inspection at 200 kHz was performed on tubes in the hot and cold legs of steam generator 1 and on the cold leg tubes of steam generators 2, 3 and 4. The purpose of the inspection was to observe tube condition at the anti-vibration bars.

*SURRY-1, USA*

Denting, stress corrosion cracking and U-bend straining resulted in 968 failed tubes in Surry-1 steam generators of which 17 were through-wall penetrations. Denting was more pronounced in peripheral areas with cracking at some dents. Cracks in the U-bend region were generally located at the inner tube rows where radius of curvature is smallest.

A variety of techniques including eddy-current and tube-diameter gauging were employed through the U-bend of several thousand tubes in an effort to map out the condition of the tube bundle. Explosive plugs were used to effect repairs.

*SURRY-2, USA*

Nine leaking tubes and 788 others were plugged in unit-2 steam generators. Failures were similar in location and type to those experienced in unit-1.

During removal of a wedge-shaped section of the seventh tube support plate from one steam generator, small cracks and radial growth were detected on the periphery of the plate. It was found, that in spite of the cracks the tubes and support plates were firmly locked together (12).

*TAKAHAMA-2, Japan*

The reactor was shut down for its first annual outage in September, 1976 with resumption of operation scheduled for April 1977. All tubes in the three steam generators were inspected throughout their length by remote eddy-current techniques. In addition, one tube was removed for further examination. No defects were reported. No condenser leaks were experienced in either Takahama-1 or -2 during 1976.

*TARAPUR-1, India*

The secondary steam generators at Tarapur are tubed with stainless steel 304L. A leak in one tube, plugged in early 1975 was caused by a previous plug working loose. During July, 1975 a leak was detected in steam generator 1B; it was plugged early in 1976.

*TARAPUR-2, India*

Late in 1974, 21 tubes were plugged in secondary steam generator 2A and 42 tubes in 2B. Further leakage was detected during 1975 by radio-chemical analysis. Repair undertaken during the 1976 refuelling outage consisted of plugging 80 tubes. Although not well understood, the defect mechanism is thought to be corrosion resulting in pin hole perforations of the tube wall.

*THREE MILE ISLAND-1, USA*

Three Mile Island is equipped with once-through steam generators. Six tubes were plugged because of fretting wear at the top tube support plate. Two additional tubes were plugged because of wall thinning of uncertain origin at the seventh and eighth tube support plates, the region of nucleate boiling. Both welded and explosive plugs were used.

*TURKEY POINT-3, USA*

At the nuclear units at Turkey Point, steam generator tube denting was experienced on a scale surpassed only by Surry. In unit 3 steam generators, 136 tubes showed dent indications and were plugged. These were located at all tube support plates in the hot leg; nine were leaking. Cracking due to U-bend straining affected 88 tubes sufficiently that these too were plugged. An additional 51 tubes were plugged because of excessive phosphate thinning above the tubesheet on the inlet side. Explosive plugs were used to make these repairs. An extensive eddy-current testing program, similar in scope and purpose to that performed at Surry, was conducted.

*TURKEY POINT-4, USA*

Similar experience was obtained with unit 4 as with unit 3 except that phosphate thinning was much less evident and cracking at the U-bend was much more pronounced. Two dented tubes and 31 U-bends were removed for further examination and another 19 showed leakage. In all, 351 tubes were plugged, 52 due to denting, 294 due to U-bend defects and 5 because of phosphate thinning. Inspection similar in scope to that of unit 3 steam generators, but even more extensive, was performed using eddy-current techniques.

*YANKEE ROWE, USA*

Two leaking tubes, each in a different steam generator, were plugged during 1976. Both defects were located just above the tubesheet and were attributed to the use of phosphates for secondary chemistry control during the early years of operation. No scheduled inspections were performed.

## LOCATION AND CAUSE OF TUBE FAILURES

The location of tube failures in 1976 is summarized in Table 2.

TABLE 2 - LOCATION OF 1976 FAILURES

| Location | Reactor | Tubes Plugged |
|---|---|---|
| Tubesheet | Beznau-1 | 7 |
| | Beznau-2 | 118 |
| | Dresden-1 | 4 |
| | Ginna | 55 |
| | Haddam Neck | 4 |
| | KRB Gundremmingen | 231 |
| | KWO Obrigheim | 8 |
| | Oconee-1 | 3 |
| | Oconee-2 | 1 |
| | Oconee-3 | 2 |
| | Point Beach-2 | 6 |
| | San Onofre | 12 |
| | Turkey Point-3 | 51 |
| | Turkey Point-4 | 5 |
| | Yankee Rowe | 2 |
| Support Plates | Oconee-1 | 3 |
| | Oconee-2 | 2 |
| | Oconee-3 | 1 |
| | Palisades | 711 |
| | Robinson-2 | 12 |
| | Surry-1 | 968 |
| | Surry-2 | 797 |
| | Three Mile Island-1 | 8 |
| | Turkey Point-3 | 136 |
| | Turkey Point-4 | 52 |
| U-bend | KWO Obrigheim | 1 |
| | San Onofre | 88 |
| | SENA | 4 |
| | Turkey Point-3 | 88 |
| | Turkey Point-4 | 294 |
| Other or Unknown | Ginna | 1 |
| | N-Reactor | 3 |
| | San Onofre | 4 |
| | Tarapur-1 | 1 |
| | Tarapur-2 | 80 |

As in previous years, the defects occurred frequently near the tubesheet and at the tube support plates and less frequently at the U-bends.

The causes of tube failures in 1976 and the number of tubes plugged for each cause are shown in Table 3.

*DENTING*

Denting is circumferential constriction of tubes by tube support plates. It was the leading cause of tube failures in 1976. Denting was caused by compressive stresses exerted on the tubes by the rapid growth of corrosion products (magnetite) formed on the inner surfaces of the carbon steel support plate holes (13). The problem affected only certain designs of tube support plates. It was most acute at stations using brackish or sea water for condenser cooling, although minor denting has also been observed in stations with fresh-water cooling. Extensive denting was observed in steam generators which changed from phosphate to all-volatile treatment (Surry-1, -2, Turkey Point-3, -4). However, recently (1977) denting was observed in steam generators which have operated only on AVT and used sea water for condenser cooling (Ringhals-2, Maine Yankee, Millstone-2) (14). To a lesser extent denting also occurred in San Onofre which was always operated on phosphate treatment and uses sea-water cooling (5). Sea water can enter a steam generator through condenser leaks. Non-volatile impurities in the sea water can concentrate in the steam generator crevices and form concentrated acidic chloride solutions which can cause rapid corrosion of carbon steel (13). The corrosion product so produced is voluminous and has little protective effect.

## TABLE 3

### CAUSE OF 1976 FAILURES

| Cause | Number of Tubes Plugged | % of Tubes Plugged |
|---|---|---|
| Denting | 2281 | 60.4 |
| Wastage | 968 | 25.7 |
| SCC* | 74 | 2.0 |
| Other or Unknown (SCC?)** | 336 | 8.9 |
| Fretting | 99 | 2.6 |
| Fatigue | 5 | 0.1 |

* This includes both tubes which cracked from the secondary side and those shown to have cracked from the primary side.

** Includes a large number of tubes in BWR secondary steam generators which are suspected to have failed bv SCC.

The use of additives to inhibit rapid corrosion of carbon steel in existing steam generators is being evaluated. One manufacturer is proposing to use redesigned type 405 stainless steel tube support plates to prevent denting in future units (15).

*WASTAGE*

Wastage or tube thinning because of residual phosphates was observed in 1976 in some (but not all) steam generators which had converted from phosphate treatment to all-volatile treatment in 1974-75. Wastage occurred mainly in the sludge zone just above the tubesheet in both hot and cold legs. The change to AVT, and the cleaning of steam generators by lancing and hot flushing decreased the incidence of wastage but did not eliminate it entirely. This suggests that removal of phosphate deposits and sludge from a steam generator is rather difficult in practice.

*STRESS CORROSION CRACKING*

Stress corrosion cracking (SCC) of Inconel-600 steam generator tubes initiating from secondary (shell) side occurred in Beznau-1, Ginna, KWO Obrigheim and Point Beach-2. In the N-Reactor SCC occurred in steam generators tubed with type 304 stainless steel but not in those tubed with Inconel-600. Most cracks occurred in the hot leg just above the tubesheet. KWO Obrigheim and N-Reactor have always operated on AVT whereas the other stations changed from phosphate to AVT in 1974. It is believed that SCC is caused by free hydroxide (caustic) which may be produced by in-leakage of alkali-forming condenser cooling water or by too high a molar ratio (> 2.85) of sodium to phosphate ions in the steam generator water (16). It is noteworthy that SCC from secondary side occurred in stations using fresh-water cooling. Fresh waters are usually alkali-forming whereas sea waters are acid-forming (17,18).

In some reactors (Surry-1, -2, Turkey Point-3, -4) the deformation produced by denting resulted in intergranular SCC of Inconel-600 tubes from the primary (tube) side. Leaks occurred within the dented region at tube support plates and at the innermost U-bends. Straining of the small radius U-bends was caused by the inward movement of tube legs because of distortion of the tube support plates.

Leaks at innermost U-bends also occurred in KWO Obrigheim; however, it is not known whether the attack initiated from the primary or secondary side. Schenk has reported that the tube-to-tubesheet rolled joints in KWO Obrigheim showed intergranular SCC initiating from the primary side. The cracks did not penetrate the tube wall (19). Primary side intergranular SCC of Monel-400 tubes has also been observed in the secondary steam generators of Garigliano BWR (6).

The cause of failure of 9% of the tubes was unknown. Many of these failures occurred in the stainless steel tubes of the secondary steam generators of various BWR's. It is possible that the failures were caused by SCC.

*FATIGUE*

Circumferential cracking attributed to high-cycle fatigue resulted in tube leaks in the once-through steam generators (OTSG) at Oconee-1, -2, -3. Most of the cracks were in tubes adjacent to an open inspection lane near the upper tubesheet or the uppermost plate. It is believed that steam flow up the open lane caused excessive vibrations in the adjacent tubes and initiated the fatigue cracks. The mode of cracking was transgranular. Units currently under construction do not have this open lane.

*FRETTING*

Fretting wear of tubes was observed in Three Mile Island, SENA and San Onofre. Fretting in San Onofre occurred at the anti-vibration bars in the U-bend region. Previous reports in this series show that fretting in the U-bend region has been a persistent problem in San Onofre steam generators. Additional anti-vibration bars of different design were installed to overcome this problem.

## HISTORY OF TUBE FAILURES

Table 4 shows the historical trend of steam generator tube failures. In the last three annual surveys nearly 40% of the reactors in the survey reported steam generator tube failures. Table 5 shows that the number of reactors with tube failures increased with increasing effective full power days of operation. Whereas none of the reactors with less than 200 EFPD reported tube failures, 81% of the reactors with more than 1000 EFPD had tube failures. A similar trend was shown in previous surveys. This effect of operating time on tube failures is understandable since most failures were caused by time-dependent phenomena such as corrosion, fretting and fatigue. There were only five reactors which exceeded 1000 EFPD with no tube failures. These were KKS Stade (Incoloy-800 tubes, low phosphate treatment), MZFR, Trino Vercellese (Stainless Steel Tubes, AVT) and Pickering-1 and -3 (Monel-400 tubes, AVT).

TABLE 4

ANNUAL TUBE FAILURES VS. YEAR

| Year | Number of Reactors in Survey | Number of Reactors With Failures | % of Reactors with Failures |
|---|---|---|---|
| 1971* | 34 | 19 | 56 |
| 1972 | 41 | 13 | 32 |
| 1973 | 49 | 11 | 22 |
| 1974 | 59 | 25 | 42 |
| 1975 | 62 | 22 | 35 |
| 1976 | 68 | 25 | 37 |

* Data for 1971 is cumulative to the end of 1971.

## TABLE 5

## CUMULATIVE TUBE FAILURES VS. EFPD*
## TO 31 DECEMBER 1976

| EFPD | Number of Reactors | Number With Failures | % With Failures |
|---|---|---|---|
| < 200 | 5 | 0 | 0 |
| 200 to 500 | 11 | 1 | 9 |
| 500 to 1000 | 25 | 13 | 52 |
| > 1000 | 27 | 22 | 81 |

* EFPD - Effective Full Power Days

The Inconel-600 tubed steam generators in the N-Reactor (AVT) were also in this category although the stainless steel tubed steam generators in the same reactor have suffered many tube failures. All these reactors use fresh water for condenser cooling. It is possible that corrosion due to adverse chemistry conditions has not occurred in these units because of good design and chemical control. In any case the reasons for the excellent reliability of steam generators in these reactors need further analysis. Information from such a study may be useful in improving the design and reliability of future units.

## INSPECTION AND REPAIR PROCEDURES

Most of the operators inspected some of their steam generator tubes during 1976. In general the hot legs of the U-bend steam generators were inspected more extensively than the cold legs. The most common method of inspection was remote-automatic eddy-current technique. Tube diameter gauging was used to monitor denting. Fibre optics was also used to examine tubes in some reactors (Oconee-1, -2, -3).

The tubes were repaired by explosive plugging in many reactors. Manually welded plugs were used in some reactors such as Dresden-1, Mihama-1, Takahama-2, N-Reactor and Palisades. Most operators carried out preventative plugging of tubes with partial wall defects and hence the number of plugged tubes was considerably more than the number of leakers. The plugging criterion varied from reactor to reactor. In the United States most operators plugged tubes with defects exceeding 40% of the tube wall thickness.

SECONDARY WATER CHEMISTRY CONTROL

As indicated in Table 6 a majority of the operators used the all-volatile treatment (AVT) for control of secondary-side water chemistry. In this treatment the pH of the feedwater is maintained between 8.8 and 9.2 if there are copper alloys in the condenser and feedwater heaters (20). If there are no copper alloys in the feed train then a pH of 9.2 to 9.5 is maintained to minimize the corrosion of carbon steel in the system. The pH is controlled by addition of ammonia or morpholine, and oxygen is removed by addition of hydrazine. Full-flow condensate demineralizers are used in all reactors with once-through steam generators. They are also available for use during chemistry upsets in some reactors with recirculating steam generators.

Seven reactors still use the congruent phosphate treatment. Four of these operate with 2-6 mg $PO_4$/kg water, a sodium to phosphate molar ratio of 2.0 - 2.6 and have not encountered any tube failures. The other three use 5 - 10 mg $PO_4$/kg water after having operated with higher phosphate concentrations between 1972 and 1974. Although tube thinning has been observed in some of these reactors it is not a serious problem and therefore phosphate treatment will be continued in these units. One reactor (Trino Vercellese) used all-volatile treatment during normal operation but switched to phosphate treatment during a condenser leak. The phosphate concentration was 12 mg/kg water and the sodium to phosphate molar ratio was 2.4 to 2.6. This reactor is cooled by fresh water.

Many of the reactors surveyed reported condenser leaks during the year. Table 1 indicates that corrosion-induced tube failures were often associated with condenser leaks. Therefore it is essential to improve the reliability of condensers in order to increase the reliability of steam generators. Reactor vendors and

TABLE 6

SECONDARY WATER CHEMISTRY CONTROL

| Reactor | Method | Remarks |
|---|---|---|
| Atucha<br>Biblis A<br>Borssele<br>KKS Stade | Phosphate treatment | 2 to 6 mg $PO_4$/kg water |
| Jose Cabrera (Zorita)<br>Robinson-2<br>San Onofre | Phosphate treatment | 5 to 10 mg $PO_4$/kg water |
| Arkansas-1<br>MZFR<br>Oconee-1,-2,-3<br>Rancho Seco<br>Three Mile Island | All Volatile treatment | With full-flow condensate demineralization |
| Calvert Cliffs<br>Doel-1,-2<br>Ginna<br>N-Reactor<br>Trojan | All Volatile treatment | Full-flow condensate demineralization available if required |
| Trino Vercellese | All Volatile treatment | Phosphate addition during condenser in-leakage |
| Other reactors in survey | All Volatile treatment | |

utilities are turning to more corrosion resistant tube materials such as titanium for condensers in sea-water service (21). Titanium tubing will be used in the new sea-water cooled CANDU reactors (22).

Steam generator manufacturers recommend either corrective action within limited time or a shut down, if the chemistry of feedwater or steam generator water goes out of specification. Limits are placed on pH, conductivity and free hydroxide concentration. A method of automatic control of secondary-side water chemistry is also under development (23).

## TUBE MATERIALS

The experience with various tube materials is summarized in Table 7. Type 304 stainless steel was used in early PWR's and in the secondary steam generators of BWR's. Stainless steel was superseded by Inconel-600 because of chloride stress corrosion cracking problems, although it has given satisfactory service in some reactors.

Inconel-600 is the most widely used tube material today; however, failures of this material have occurred by the various mechanisms indicated in Table 7. Some of the failure mechanisms (e.g. denting, fretting, fatigue) were related to design rather than material. Failures by stress corrosion cracking and wastage probably resulted from a complex interaction of design, material, and chemistry control. Thus tube material is just of the many factors which influence the tube failure rates shown in Table 8.

Monel-400 has been used in seven CANDU-PHW reactors and so far only two tubes, out of 164,130 tubes in service, have failed. However, many tubes of Monel-400 have failed in the secondary steam generators of Garigliano BWR.

## TABLE 7

## EXPERIENCE WITH TUBE MATERIALS TO 31 DECEMBER 1976

| Tube Material | Number of Reactors | Number of Tubes | Number of Tube Failures | Tube Failure Rate | Failure Mechanism |
|---|---|---|---|---|---|
| Type 304 SS | 10 | 55,303 | 894 | 1.6% | SCC, W |
| Inconel-600 | 41 | 520,852 | 11,726 | 2.2% | SCC, W, D, Fr, F |
| Monel-400 | 8 | 167,700 | 232 | 0.14% | SCC, Fr |
| Incoloy-800 | 4 | 35,840 | 0 | 0 | -- |

SCC: Stress Corrosion Cracking
W: Phosphate Wastage
D: Denting
Fr: Fretting
F: Fatigue

It has been reported that these failures were caused by intergranular SCC induced by high levels of dissolved oxygen in the coolant.

Although experience with Incoloy-800 is not as extensive as that with other materials, no steam generator tubes of Incoloy-800 have failed in service. One of the reactors with Incoloy-800 tubes (KKS Stade) has now accumulated ~ 1500 EFPD of operation without tube failures. Kraftwerk Union (KWU) have used Incoloy-800 tubes since 1972. Atomic Energy of Canada Limited will use this material in future steam generators.

## SUMMARY

The performance of steam generator tubing continues to be less than satisfactory. Denting has replaced wastage as the leading failure mechanism, although there is reason to believe that better control of secondary water chemistry should arrest this problem. An important part of the solution for future stations seems to be condensers of higher tube integrity, especially at sites using sea or brackish cooling water. Development of steam generator designs which minimize stagnant zones and on-line control of secondary-side water chemistry will also be necessary.

Inspection and repair techniques have been developed to a high degree of effectiveness. These techniques are coordinated with preventative plugging programs during scheduled shutdowns thereby minimizing forced outages.

## ACKNOWLEDGEMENTS

The authors acknowledge with gratitude the supportive response of station operating staff around the world, without whose assistance this survey would not be possible. It would be appreciated if any errors or omissions could be communicated to the authors.

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# APPENDIX I

Salient parameters and lifetime performance of steam generators are presented in this Appendix.

STEAM GENERATOR EXPERIENCE TO 31 DECEMBER 1976

| Reactor | MW(e) Net | # of SG | Tubes per SG | Material | Builder | Area per SG($m^2$) | Condenser Cooling Water | EFPD | Cumulated Defects | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| Arkansas-1 | 820 | 2 | 15531 | Inconel | BW | 12 304 | Fresh | 464 | 0 | OTSG |
| Atucha | 319 | 2 | ~4000 | Incoloy | GHH | 3 600 | Fresh | 750 | 0 | PHWR |
| Beznau-1 | 350 | 2 | 2604 | Inconel | W | 3 097 | Fresh | 1731 | 989 | |
| Beznau-2 | 350 | 2 | 2604 | Inconel | W | 3 097 | Fresh | 1513 | 226 | |
| Biblis A | 1146 | 4 | 4060 | Incoloy | KWU/DBW | 4 510 | Fresh | 512 | 2 | removed for examination |
| Borssele | 447 | 2 | 4234 | Incoloy | Balcke | 3 600 | Sea | 898 | 2 | removed for examination |
| Calvert Cliffs-1 | 850 | 2 | 8519 | Inconel | CE | | Brackish | 532 | 0 | |
| Cook-1 | 1054 | 4 | | Inconel | W | | Fresh | 462 | 0 | |
| Doel-1 | 392 | 2 | 3260 | Inconel | W | 4 130 | Brackish | 561 | 0 | |
| Doel-2 | 392 | 2 | 3260 | Inconel | W | 4 130 | Brackish | 339 | 0 | |
| Douglas Point | 208 | 8 x 10 | 195 x 10 | Monel | MLW | 97 x 10 | Fresh | 1612 | 1 | CANDU vertical hairpin |
| Dresden-1 | 200 | 4 | 1801 | SS | FW | 605 | Fresh | 2963 | 161 | |
| Fort Calhoun-1 | 457 | 2 | 4980 | Inconel | CE | | Fresh | 671 | 0 | |
| Garigliano | 150 | 2 | 1785 | Monel | KM | 560 | Fresh | 2995 | 230+ | BWR |
| Genkai-1 | 529 | 2 | | | MHI | | Sea | 433 | 1 | Due to foreign matter |
| Ginna | 490 | 2 | 3260 | Inconel | W | 4 129 | Fresh | 1530 | 134 | |
| GKN Neckar | 750 | 3 | | | Balcke/ GHH | | Fresh | 110 | 0 | |
| Haddam Neck | 575 | 4 | 3794 | Inconel | W | 2 573 | Fresh | 2492 | 30 | |

STEAM GENERATOR EXPERIENCE TO 31 DECEMBER 1976 - cont'd

| Reactor | MW(e) Net | # of SG | Tubes per SG | Material | Builder | Area per SG($m^2$) | Condenser Cooling Water | EFPD | Cumulated Defects | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| Indian Pt-2 | 864 | 4 | 3260 | Inconel | W | 4 129 | Brackish | 523 | 15 | |
| Indian Pt-3 | 965 | 4 | 3260 | Inconel | W | 4 129 | Brackish | 134 | 0 | |
| Jose Cabrera (Zorita) | 153 | 1 | 2604 | Inconel | W | 2 308 | Fresh | 2070 | 3 | |
| Kanupp | 126 | 6 | 1355 | Monel | B & W(Can) | 705 | Sea | 703 | 0 | CANDU |
| Kewaunee | 540 | 2 | 3388 | Inconel | W | 4 785 | Fresh | 680 | 0 | |
| KKS (Stade) | 630 | 4 | 2900 | Incoloy | DBW | 2 930 | Fresh | 1446 | 2 | Removed for examination |
| KRB Gundremmingen | 237 | 3 | 1929 | SS | VKW | 870 | Fresh | 2651 | 364 | BWR |
| KWL Lingen | 256 | 2 | 5000 | SS | GHH | 2 360 | Fresh | 1739 | 112 | BWR, amended total |
| KWO Obrigheim | 328 | 2 | 2605 | Inconel | GHH/Balcke | 2 750 | Fresh | 2356 | 202 | amended total |
| Maine Yankee | 790 | 3 | 5703 | Inconel | CE | 5 405 | Brackish | 945 | 0 | |
| Mihama-1 | 320 | 2 | 4426 | Inconel | CE | 3 381 | Sea | 646 | 2206 | |
| Mihama-2 | 470 | 2 | 3260 | Inconel | MHI | | Sea | 904 | 266 | |
| Mihama-3 | 780 | 3 | | Inconel | MHI | | Sea | 141 | 0 | |
| Millstone-2 | 796 | 2 | 8485 | Inconel | CE | | Sea | 250 | 0 | |
| MZFR | 52 | 2 | 2113 | SS | GHH/Balcke | 920 | Fresh | 2134 | 0 | PHWR |
| NPD | 22 | 1 | 2069 | Inconel | BW(Can) | 577 | Fresh | 3216 | 1 | CANDU, horizontal steam generator |
| N-Reactor | 790 | 10<br>2 | 1920 | Inconel<br>SS | CE | 1 486 | Fresh | 1762 | 0<br>27 | LGR |

STEAM GENERATOR EXPERIENCE TO 31 DECEMBER 1976- cont'd

| Reactor | MW(e) Net | # of SG | Tubes per SG | Material | Builder | Area per SG($m^2$) | Condenser Cooling Water | EFPD | Cumulated Defects | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| Oconee-1 | 871 | 2 | 15531 | Inconel | BW | 12 304 | Fresh | 750 | 8 | OTSG |
| Oconee-2 | 871 | 2 | 15531 | Inconel | BW | 12 304 | Fresh | 548 | 3 | OTSG |
| Oconee-3 | 871 | 2 | 15531 | Inconel | BW | 12 304 | Fresh | 504 | 3 | OTSG |
| Palisades | 700 | 2 | 8519 | Inconel | CE | | Fresh | 588 | 3657 | cooling towers |
| Pickering-1 | 514 | 12 | 2600 | Monel | BW(Can) | 1 858 | Fresh | 1594 | 0 | CANDU |
| Pickering-2 | 514 | 12 | 2600 | Monel | BW(Can) | 1 858 | Fresh | 1494 | 1 | CANDU |
| Pickering-3 | 514 | 12 | 2600 | Monel | BW(Can) | 1 858 | Fresh | 1130 | 0 | CANDU |
| Pickering-4 | 514 | 12 | 2600 | Monel | BW(Can) | 1 858 | Fresh | 885 | 0 | CANDU |
| Point Beach-1 | 497 | 2 | 3260 | Inconel | W | 4 129 | Fresh | 1558 | 362 | |
| Point Beach-2 | 497 | 2 | 3260 | Inconel | W | 4 129 | Fresh | 1164 | 16 | |
| Prairie Island-1 | 520 | 2 | 3388 | Inconel | W | 4 786 | Fresh | 672 | 0 | |
| Prairie Island-2 | 520 | 2 | 3388 | Inconel | W | 4 786 | Fresh | 467 | 0 | |
| Rancho Seco | 913 | 2 | 15457 | Inconel | BW | 12 245 | Fresh | 228 | 0 | OTSG |
| RAPP-1 | 207 | 8 x 10 | 195 x 10 | Monel | MLW | 97 x 10 | Fresh | 480 | 0 | CANDU, vertical hairpin |
| Ringhals-2 | 822 | 3 | | Inconel | W | | Sea | 168 | 0 | |
| Robinson-2 | 700 | 3 | 3260 | Inconel | W | 4 128 | Fresh | 1480 | 97 | |
| San Onofre-1 | 430 | 3 | 3794 | Inconel | W | 2 573 | Sea | 2394 | 182 | |
| SENA(Chooz) | 280 | 4 | 1662 | SS | CO | 1 385 | Fresh | 1956 | 20 | |
| Surry-1 | 788 | 3 | 3388 | Inconel | W | 4 784 | Brackish | 826 | 1408 | |
| Surry-2 | 788 | 3 | 3388 | Inconel | W | 4 784 | Brackish | 769 | 987 | |

STEAM GENERATOR EXPERIENCE TO 31 DECEMBER 1976 - cont'd

| Reactor | MW(e) Net | # of SG | Tubes per SG | Material | Builder | Area per SG($m^2$) | Condenser Cooling Water | EFPD | Cumulated Defects | Comments |
|---|---|---|---|---|---|---|---|---|---|---|
| Takahama-1 | 780 | 3 | 3388 | Inconel | W | 4 784 | Sea | 579 | 99 | |
| Takahama-2 | 780 | 3 | 3388 | Inconel | W | 4 784 | Sea | 371 | 1 | removed for examination |
| Tarapur-1 | 198 | 2 | 1600 | SS | FW | | Sea | 1317 | 2 | BWR, amended total |
| Tarapur-2 | 198 | 2 | 1600 | SS | FW | | Sea | 1304 | 143 | BWR, amended total |
| Three Mile Island-1 | 792 | 2 | 15531 | Inconel | BW | 12 304 | Fresh | 673 | 8 | OTSG |
| Tihange-1 | 880 | 3 | | | CO | | | 362 | 0 | |
| Trino | 242 | 4 | 1662 | SS | W | 1 384 | Fresh | 2428 | 0 | |
| Trojan | 1130 | 4 | | Inconel | W | | Brackish | 85 | 0 | |
| Turkey Point-3 | 693 | 3 | 3260 | Inconel | W | 4 128 | Sea | 950 | 309 | |
| Turkey Point-4 | 693 | 3 | 3260 | Inconel | W | 4 128 | Sea | 815 | 515 | |
| Yankee Rowe | 175 | 4 | 1620 | SS | W | 1 248 | Fresh | 4144 | 65 | |
| Zion-1 | 1050 | 4 | 3260 | Inconel | W | 4 128 | Fresh | 564 | 0 | |
| Zion-2 | 1050 | 4 | 3260 | Inconel | W | 4 128 | Fresh | 444 | 0 | |

ACRONYMS USED IN THE TABLE:

| | |
|---|---|
| BW | Babcock & Wilcox |
| BW(Can) | Babcock & Wilcox Canada |
| BWR | Boiling Water Reactor |
| CANDU | Canada Deuterium Uranium |
| CE | Combustion Engineering |
| CO | Cockerill-Ougree SA |
| DBW | Deutsche Babcock and Wilcox-Dampfkessel Werke AG |
| EFPD | Effective Full Power Days (calculated from Nucleonics Week 18(4)) |
| FW | Foster Wheeler |
| GHH | Gutehoffnungshütte Sterkrade AG |
| KM | Koninklijke Machinefabrik Stork |
| KWU | Kraftwerk Union AG |
| LGR | Water-Cooled Graphite Moderated Reactor |
| MHI | Mitsubishi Heavy Industries |
| MLW | Montreal Locomotive Works |
| OTSG | Once-Through Steam Generator |
| PHWR | Pressurized Heavy Water Reactor |
| SG | Steam Generator |
| SS | Stainless Steel |
| VKW | Vereinigte Kesselwerke AG |
| W | Westinghouse |

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