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# CANDU STEAM GENERATOR TUBING MATERIAL SERVICE EXPERIENCE AND ALLIED DEVELOPMENT

by

A.E. HART and J.E. LESURF

Colloquium paper A1/01 presented at NUCLEX 75, International Nuclear Industries Fair and Technical Meetings, October 7 to 11, 1975, Basel, Switzerland.

Chalk River Nuclear Laboratories
Chalk River, Ontario

January 1976

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ABSTRACT

This paper covers the following aspects for the tube materials in CANDU-PHW steam generators: inservice performance with respect to tube leaks and coolant activity attributable to boiler tube corrosion, selection of tube materials for use with non-boiling and boiling primary coolants, supporting development on corrosion, vibration, fretting wear, tube inspection, leak detection and plugging of defective tubes.

RESUME

Le présent rapport concerne les aspects suivants des matériaux constituant les tubes des générateurs de vapeur CANDU-PHW: performance en service quant aux fuites des tubes et à la radio-activité du caloporteur imputable à la corrosion des tubes de chaudière; sélection des matériaux pour les tubes destinés à des caloporteurs primaires bouillants et non bouillants; développements de soutien ayant trait à la corrosion, aux vibrations, à l'usure par frottement, à l'inspection des tubes, à la détection des fuites et à l'obturation des tubes défectueux.

ZUSAMMENFASSUNG

Dieser Bericht befaßt sich mit folgenden Aspekten des Rohrmaterials für Dampferzeuger in CANDU-Druck-Schwerwasserreaktoren: Verhalten während des Reaktorbetriebs in Hinsicht auf Rohrlecks, die auf Korrosion der Dampfkesselrohre zurückzuführen sind; Auswahl des Rohrmaterials für nichtsiedende und siedende Primärkühlmittel; zusätzliche Entwicklungsarbeiten uber Korrosion, Vibration, Reibungsverschleiß, Rohrinspektion, Lecksuche und Absperrung schadhafter Rohre.

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## INTRODUCTION

Canada's experience with nuclear steam generators has been very good. The operating experience covers eight reactors, beginning with the commissioning of NPD in 1962 followed by: Douglas Point in 1967, KANUPP in 1971, RAPP-1 in 1972 and the four Pickering reactors 1971 to 1973. Two tube materials, Monel-400* and Inconel-600* have been used with the above reactors. In addition, Incoloy-800* tubing is being used for some CANDU reactors currently under construction or in the design stage. Table 1 gives the pertinent data for the steam generators used in CANDU-PHW reactors.

A centralized reactor design team, concentrating on the CANDU-PHW type of reactor, has achieved very close cooperation between Research and Development, design, manufacturing and utility groups. This has resulted in highly reliable CANDU-PHW systems and, in particular, highly reliable steam generators.[1]

Data on the performance of CANDU steam generators and the support activities for existing units and to further improve steam generator technology are presented below.

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* MONEL, INCONEL, and INCOLOY are trademarks of the International Nickel Co. and are used here because of general familiarity. In this paper they are used to designate alloys of the following composition:

| | Nominal Composition - wt% | | | |
|---|---|---|---|---|
| | Ni | Cr | Fe | Cu |
| MONEL alloy 400 | 63-70 | - | 2.50 max. | Balance (~30) |
| INCOLOY alloy 800 | 32-35 | 19-23 | Balance (~48) | - |
| INCONEL alloy 600 | 72 min. | 14-17 | 6-10 | - |

The use of trade names does not imply that the materials tested or used were supplied by the International Nickel Co.

CORROSION

No leaks attributable to corrosion have occurred in any boiler tubes in any CANDU-PHW reactors.

Primary Side Tube Corrosion

In all water cooled reactors corrosion products from the boiler tubing are transported by the primary coolant to the core where they become radioactive. They later are transported out of the core and re-deposit on out-reactor surfaces. The resulting radiation fields complicate maintenance and repair of out-reactor equipment.

The aqueous corrosion of Monel-400 increases markedly if oxygen is present. In the Douglas Point reactor, which has Monel-400 alloy boiler tubes, radiation fields rose rapidly due to the presence of oxygenated coolant during the commissioning and early operation of the reactor. A series of chemical cycling techniques[2] reduced the boiler room radiation fields by about an order of magnitude, and the rate of growth of fields is now very much less than before, due to the rigorous suppression of radiolytic oxygen in the coolant by dissolved hydrogen (deuterium). The radiation fields from activated corrosion products around the four Pickering reactors which also have Monel-400 boiler tubes, are very much less than at Douglas Point because of chemical control of the coolant and layout of the equipment. The current rate of growth is slow and very similar at all five Canadian reactors which have Monel-400 boiler tubes (see Figure 10 of Reference 1). Four more reactors are being built at Pickering. Based on the satisfactory performance of the existing reactors, Monel-400 is again specified for boiler tubing but a maximum limit of 0.01 wt% is placed on the cobalt impurity in the alloy to reduce fields even further at a very low cost penalty. A full system decontamination of Douglas Point reactor is planned in the fall of 1975. The main requirement is to reduce the radiation fields from the carbon steel piping in the feeder cabinets, but a significant reduction in boiler room radiation fields should also be achieved.

In the 750 MWe reactors at the Bruce station and all subsequent CANDU-PHW reactors the primary coolant is allowed to boil in the fuel channels. Under these two-phase conditions in-core it is much more difficult to suppress the radiolytic production of oxygen or oxidizing free-radicals. Because of the experience with Monel-400 and oxidizing coolant at Douglas Point, Inconel-600 which has better corrosion resistance in the presence of oxygen was used for boiler tubing. The NPD reactor which has boiler tubing of Inconel-600 and has operated satisfactorily since initial start-up in 1962 has also operated for 30 months with boiling coolant, giving confidence in the performance of Inconel-600 in primary coolant.

A potential hazard with Inconel-600 is intergranular corrosion in high purity water.[3] Alloys such as Incoloy-800 with nickel concentrations between about 30 wt% and 65 wt% retain the excellent resistance to transgranular chloride stress corrosion cracking of Inconel-600 but do not exhibit that alloy's sensitivity to intergranular attack in high purity water.[4] The lower nickel concentration also results in less Co-58 activity (derived from Ni-58). AECL have recommended Incoloy-800 (or alloys of similar composition, such as Sanicro-30) for steam generator tubing in future CANDU-PHW reactors with boiling primary coolant.

## Secondary Side Corrosion

The major consideration from the secondary side is to avoid the alkaline or acid modes of attack which have led to so many failures in PWRs over the past few years.[5,6,7]

Monel-400 appears to be more resistant to caustic attack than either Inconel-600 or Incoloy-800 (see, for example, Table 2). There is probably little significant difference between Inconel-600 and Incoloy-800 in their resistance to caustic corrosion and acid phosphate attack.

NPD has operated since start-up with a mixture of volatile (morpholine and hydrozine) and non-volatile (sodium phosphate) water treatment additives. No corrosion problems have been encountered. For our new reactors, normal operation will be with all-volatile water treatment.

For CANDU-PHW reactors cooled with brackish water or sea water, sodium phosphate will be injected on detection of a condenser leak. A network of sodium specific ion electrodes should allow condenser leaks to be detected rapidly, and the appropriate half-condenser isolated for repair. A maximum phosphate concentration of 10 ppm in the boiler blowdown is specified. Following isolation of the leak, which should normally be accomplished within one eight-hour shift, phosphate additions will be stopped but maximum blow-down will be maintained to remove the residual phosphate (and precipitated sea-water impurities) from the boiler.

A scheme for automatic analysis and computer control of boilerwater and feedwater is being developed. If development trials are satisfactory, it is intended to install the system on a 600 MWe CANDU-PHW reactor currently being built.

## VIBRATION AND FRETTING

To date we have experienced only three boiler tube leaks; one tube at NPD in 1969, one tube at Douglas Point in 1971 and one tube at Pickering in 1974. In NPD, a tube opposite a downcomer nozzle fretted at a support plate. The Douglas Point fretting failure occurred in a tube with an abnormally large unsupported length. The single tube leak in Pickering occurred near the tube sheet. Based on eddy current data, we believe it is damage that occurred during manufacture.

### Flow Induced Vibration

Development work on flow induced vibration of tubes by AECL and their associates has produced a computer program which predicts the tube vibrations caused by secondary side flow in boilers and in non-boiling heat exchangers. The predictions have been verified by full-scale field trials.

CANDU-PHW boiler specifications now require the manufacturer to provide a vibration assessment of the proposed boiler showing that tube vibration will not cause tube failures within the design life (thirty to forty years). AECL judges the validity of the assessment.

The vibration mechanisms examined are: fluid elastic instability, periodic excitation and random excitation. The vibration amplitude and frequency response to each of these excitations is calculated. The total effect for each tube span and support point investigated is obtained by summing the squares of the separate motions and forces. From the derived tube vibration amplitudes the maximum bending stress in the tube is calculated. This stress, combined with pressure and thermal stresses, provides a maximum cyclic stress. To be acceptable, this must be below the fatigue limit stress for the tube material.

Fretting

The calculated reaction forces at the tube support plates are used to assess the fretting rate. A tube wall thickness of approximately 1 mm and a 30 year design life gives a "through wall" fretting rate of $3.8 \times 10^{-6}$ mm/hr. Therefore with a reasonable safety margin the maximum acceptable fretting rate is $1 \times 10^{-6}$ mm/hr. Because of this extremely small figure the gathering of experimental data is slow and must be done with extreme care. AECL's current program on fretting started in 1970 and is now yielding valuable data.

Two parallel activities are in progress. In the first, fretting in water at room temperature is studied on tube specimens which pass through tube support plate samples. Variable speed motors, which rotate out-of-balance weights, impart motion to the tubes. The selected motor speeds and out-of-balance weights vary the frequency, impact forces and motion over the range of interest. Both the impact forces and the type of motion are important. With the orthogonal force ratio near unity far more fretting damage occurs than if the forces are not equal, i.e., if one force is doubled, less fretting damage occurs. This is due to a change in the tube motion. With equal forces the tube tends to rub fairly uniformly around the support hole. This removes more material than occurs with unbalanced forces where the motion changes and while the impact forces may be larger, less material is removed because very little rubbing occurs.

In the second series, fretting tests are conducted in autoclaves where the values of pressure, temperature and water chemistry are simiiar to those in the secondary side of a boiler. Sequential testing with samples in water and then in steam will cover the range of conditions from preheater to steam separator. Dismantling to measure wear rates would be slow and would disrupt the environment; therefore a method of wear measurement has been developed which correlates wear with the number of sample contacts in which the contact resistance is less than 10 ohms. Special eddy current probes have been developed which can detect material loss from the outside surface equivalent to a uniform 5 μm wear. This eddy current method looks very promising and will probably become the standard method of measurement in these tests.

The low temperature fretting tests are simpler and a greater throughput of samples is possible. These tests provided an insight into fretting mechanisms. Data generated on these rigs is directly applicable to non-boiling heat exchangers, of which there are many in both nuclear power plants and heavy water production plants. Critical parameters from the low temperature tests are being investigated in the high temperature apparatus to establish correlations so that low temperature results can be used for boilers also.

FIELD SERVICES

Leak Detection and Tube Plugging

Detailed procedures for boiler tube leak detection and tube plugging were developed for Pickering, using a mockup of the boiler inlet head and surrounding area.

The boiler manufacturer, under contract to AECL and Ontario Hydro, has trained teams to quickly locate and plug leaking tubes. A team was used in January of 1974 to locate and plug the single tube leak that occurred at Pickering. Ontario Hydro have estimated that in this one operation $800,000 was saved by having procedures, equipment and trained repair crews available. Similar procedures and equipment for Bruce are near completion, and on Gentilly-2 (a CANDU-PHW 600 reactor) provision of tube plugging equipment was included in the boiler supply contract.

In-Service Inspection

An in-service boiler inspection capability has been developed for Pickering. The temperature of transition from magnetic to non-magnetic properties (Curie temperature) occurs near room temperature for Monel-400 and is a gradual transition. The varying magnetic permeability between tubes complicates eddy current inspection, and masks defect signals. Development of permanent magnet single coil probes which magnetically saturate the tube area under inspection has greatly improved the sensitivity of inspection of Monel-400[8].

The Curie temperature is sensitive to alloy composition. Monel-400 tubing for Pickering B (four 540 MWe CANDU-PHW reactors) was specified with a controlled composition still within the appropriate ASTM specification, which ensures that the Curie temperature is well below the ambient temperature.[8]

We are currently developing an automated eddy current system which includes automatic defect recognition.

## SUMMARY

Current steam generators in CANDU-PHW reactors have an enviable record of reliability. They are different from other nuclear steam generators in design, materials of construction, fabrication methods and operating characteristics. A continuing program of research and development in all of these areas plus inspection and repair techniques should ensure a similar reliability in future units of more advanced design.

## ACKNOWLEDGEMENTS

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| | NPD* | Douglas Point and RAPP 1 | KANUPP | Pickering A + B | Bruce*** A + B | 600 MWe Series |
|---|---|---|---|---|---|---|
| Number of boilers | 1 | 8 + 8 | 6 | 48 + (48) | (32)+(32) | 4/reactor |
| Elect. output per boiler MWe | 25 | 27.[illegible] | 22 | 4[illegible] | 99 | 16[illegible] |
| Avge. heat flux (boiling) $kW/m^2$ | 150** | 80 | 74 | 73 | 105 | 150 |
| Tubing - material | Inconel 600 | Monel 400 | Monel 400 | Monel 400 | Inconel 600 | Incoloy 800 |
| - outer diameter mm | 12.7 | 12.7 | 12.7 | 12.7 | 12.7 | 15.9 |
| - wall thickness mm | 1.25 | 1.25 | 1.25 | 1.25 | 1.2[illegible] | 1.25 |
| - number of tubes | 2099 | 1950 | 1755 | 2600 | 4200 | 3550 |
| - boiling area $m^2$ | 594 | 8[illegible] | 782 | 1590 | 242[illegible] | 262[illegible] |
| - heat transfer length m | 14900 | 24900 | 22500 | 46600 | 59300 | 63700 |
| Heavy water - flow kg/s | 6[illegible] | 18[illegible] | 319 | 694 | 1[illegible] | 18[illegible] |
| (Prim. side) - inlet temp. °C | 277 | 293 | 293 | 293 | 299 | 309 |
| - inlet quality % | 0 | [illegible] | [illegible] | 0 | [illegible] | [illegible].4 |
| - inlet pressure $MN/m^2$ | 7.34 | 8.52 | 8.52 | 8.26 | 8.56 | 9.89 |
| - outlet temp. °C | 250 | 249 | 247 | 249 | 26[illegible] | 26[illegible] |
| Steam - flow kg/s | 41.7 | 40.3 | 33.6 | 67.8 | 151 | 238 |
| (secondary side) - temperature °C | 232 | 251 | 250 | 252 | 25[illegible] | 259 |
| - pressure $MN/m^2$ | 2.91 | 4.02 | 4.00 | 4.09 | 4.48 | [illegible].62 |

* Feedwater supplied to steam drum

** Includes 25 $kW/m^2$ due to feedwater subcooling

*** Separate preheater

Figures in brackets are for committed units not yet operating

TABLE 1 CANDU-PHW STEAM GENERATOR DESIGN DATA

| Material/Stress | Conc'n of NaOH (Normality N) | Heat Treatment 1 | 2 | 3 | Test Time h |
|---|---|---|---|---|---|
| Inconel-600 48 MPa (7,000 psi) | 2.5 | 0/5 | 0/5 | 0/5 | 5016(162) 1220(3) |
| Inconel-600 170 MPa (25,000 psi) | 5 | 5/5 | 4/4 | 4/5 | |
| | 2.5 | 3/5 | 3/4 | 5/5 | 3700 |
| | 1 | 0/5 | 0/5 | 0/5 | |
| Incoloy-800 48 MPa (7,000 psi) | 2.5 | 0/5 | 0/5 | - | 5016 |
| Incoloy-800 170 MPa (25,000 psi) | 5 | 0/5 | 0/5 | 0/5 | |
| | 2.5 | 1/5 | 2/5 | 4/5 | 1650 |
| | 1 | 1/5 | 1/5 | 5/5 | |
| Monel-400 170 MPa (25,000 psi) | 5 | 0/5 | 0/2 | - | |
| | 2.5 | 2/5 | 0/4 | - | 3350(1) |
| | 1 | 1/5 | 0/2 | - | 2840(2) |

Heat Treatment 1: Mill annealed and machined.
Heat Treatment 2: Mill annealed, machined, heated at 600°C, 5.5 h, air cooled.
Heat Treatment 3: Mill annealed, machined, heated at 870°C, 1 h, air cooled.

Where the number tested is less than 5, then one or more capsules have leaked at the end cap weld.

TABLE 2 CAUSTIC CRACKING TESTS ON PRESSURIZED CAPSULES AT 30[illegible]
(number failed/number tested)

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