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ATOMIC ENERGY
OF CANADA LIMITED

L'ÉNERGIE ATOMIQUE
DU CANADA LIMITÉE

EXAMINATION OF GARTER SPRINGS FROM CANDU REACTORS

L'examen des jarretières à ressort des réacteurs CANDU

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Chalk River, Ontario

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Résumé

L'espace annulaire entre les tubes de force et les tubes de cuve dans les reacteurs CANDU est maintenu par des jarretières à ressort autour des tubes de force. Ces jarretières à ressort sont habituellement fait de Zr-2.5% Nb-05.% Cu trempé et âgé. Les jarretières à ressort enlevées des réacteurs de Pickering-4 après 2 ans, Bruce-2 après 5 ans et Pickering-1, -2, -3 et -4 après 12 ans de service ont été examinées. L'examen a inclus: un examen visuel, métallurgique, essais de broyage, de fatigue et de tension, analyse d'hydrogène et de deutérium et mesure d'ovalité. Tout ceci a démontré qu'après 12 ans de service:

i) les ressorts ont demeuré indemne,

ii) l'hydrogène/deutérium a émigré aux points de contact là où les ressorts étaient en contact chargé avec les tubes de cuve,

iii) la ductilité et la puissance de broyage et de fatigue ont resté beaucoups plus qu'adéquat,

iv) la concentration d'hydrogène n'a pas changé depuis l'installation, et

v) le rapt de deutérium a été plus élevé aux bouts qu'au milieu d'un ressort correctement orienté et peut être jusqu'à 240 ppm (240 x 10^{-4} pd%).

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ABSTRACT

The annular space between pressure and calandria tubes in CANDU reactors is maintained by coil springs around the pressure tubes. These garter springs are usually Zr-2.5% Nb-0.5% Cu in a quenched and aged condition. Garter springs removed from Pickering-4 after 2 years, Bruce-2 after 5 years, and Pickering-1, -2, -3 and -4 reactors after 12 years' operation have been examined. The examination included: visual examination, metallography, crush tests, fatigue tests, tension tests, hydrogen and deuterium analysis and ovality measurement. This showed that after 12 years' service:

(i) the springs remained intact,

(ii) hydrogen/deuterium migrated to the contact areas where the springs were in loaded contact with the calandria tubes,

(iii) ductility, crush and fatigue strength remained much more than adequate,

(iv) hydrogen concentration was unchanged from installation, and

(v) deuterium pickup was much greater at the ends than the middle of correctly oriented springs and could be up to 240 ppm (240×10^{-4} wt%).

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1. INTRODUCTION

The fuel channels in CANDU-PHW* nuclear reactors are horizontal, and each consists of:

(i) a zirconium alloy pressure tube which contains the natural uranium fuel, and heavy water coolant at a pressure of about 10 MPa and a temperature of 525 to 585 K,

(ii) stainless steel end fittings which are attached to the pressure tube by rolled joints,

(iii) a Zircaloy-2 (except NPD) calandria tube outside the pressure tube which is in contact with the heavy water moderator and operates at 343 to 373 K.

(iv) garter spring spacers which are designed to retain the gas-filled gap between the pressure tube and the calandria tube.

A schematic diagram of a fuel channel is shown in Figure 1.1.

The gas filling the gap between the pressure tube and calandria tube is air for NPD and Douglas Point reactors, nitrogen for Pickering A reactors, and carbon dioxide for all subsequent reactors. The purpose of this annular gap is to insulate the hot pressure tube from the cold calandria tube and heavy water moderator. Many spacer designs were considered, and the following were important components in selecting spacers:

(a) Adequate strength to carry the loads imposed, and thus maintain the separation of the tubes.

(b) Low neutron capture cross-section.

(c) Allow axial movement between the pressure tube within the calandria tube (from differential thermal expansion).

(d) Allow the gas in the annulus to pass by freely.

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*<u>CAN</u>ada <u>D</u>euterium <u>U</u>ranium - <u>P</u>ressurized <u>H</u>eavy <u>W</u>ater.

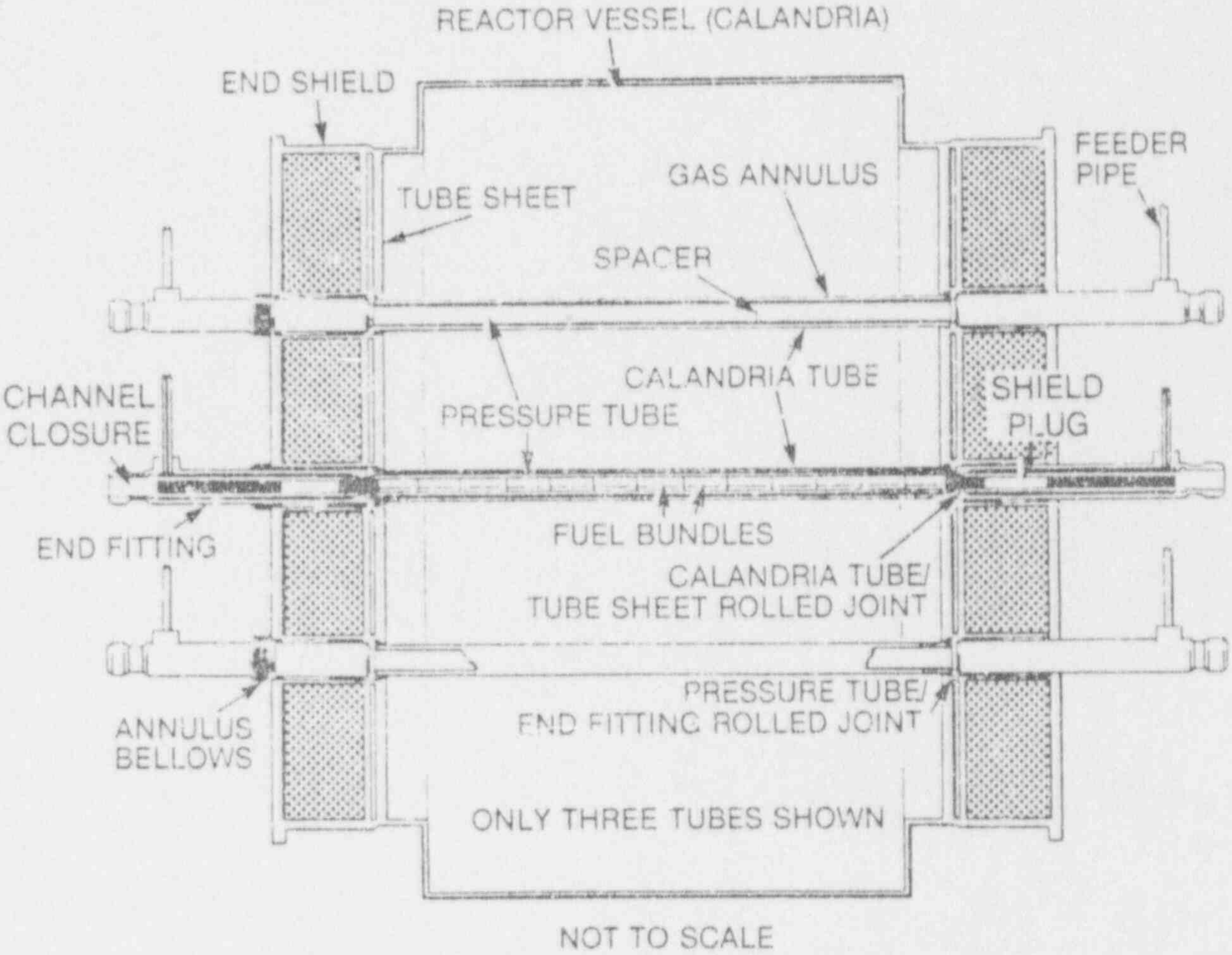


Figure 1.1 Schematic of CANDU Fuel Channels.
(Lengths of calandria: NPD - 4.57 m
Douglas Point - 5.08 m
Pickering - 5.94 m)

(e) Not corrode in the annulus environment.

(f) Minimum heat transfer from the coolant to the moderator.

(g) Allow the pressure tube to creep circumferentially.

(h) Not damage the pressure tube or calandria tube significantly by wear or fretting.

(i) Be easy to install.

More recent requirements for the spacers were that (i) in the event of a LOCA, there would be sufficient contact between the pressure tube and calandria tube (by sagging or bulging between the spacers) to enable the moderator to act as a heat sink, (ii) the spacer must not move out of position, and (iii) that the position of the spacer in the fuel channel could be verified.

Many concepts have been considered for spacers including pads, rings, indented calandria tubes, continuous strips, circumferential bellows and circumferential springs. The circumferential spring, called garter spring, has been used as the fuel channel spacer for all CANDU reactors (see Figures 2.1 and 2.2 in the next section).

2. HISTORICAL SUMMARY

2.1 NPD Reactor & KANUPP Reactors

The first CANDU reactor, NPD, had one garter spring in the centre of each channel separating the 91 mm OD cold-drawn Zircaloy-2 pressure tubes from the 102 mm ID aluminum alloy 57S (AA5052) calandria tubes. The garter springs were made from Inconel X750 (approximate composition, wt%, Ni 72, Cr 16, Fe 7, Ti 2.5, Al 0.7, Nb 1.0) and were hooked together at the ends to fit tightly around the pressure tubes, with the hooked ends at the top of the pressure tube (Figure 2.1). The Inconel X750 wire was supplied in the No.1 temper, i.e. 15 to 20% cold-worked. After coiling, the springs were heat-treated in a vacuum for 16 h at 1005 K and furnace-cooled.

The garter springs for the KANUPP reactor were similar to NPD.

2.2 Douglas Point to Bruce-7 Reactors

For all CANDU reactors from Douglas Point to Bruce-7, both the material and the design were changed. The material was changed to Zr-2.5 wt% Nb-0.5 wt% Cu. A zirconium alloy was chosen to reduce the thermal neutron capture cross-section. The Zr-2.5% Nb-0.5% Cu alloy was selected over Zircaloy-2 and Zr-2.5% Nb since, in the heat-treated condition, it had the best combination of strength, hydride orientation and resistance to corrosion in moist annulus gas. The springs were coiled with the material in an annealed condition and then heat-treated on a mandrel as follows:

1130 K for 15 min in a salt bath-water quench-age at 810 K for 6 h in a vacuum.

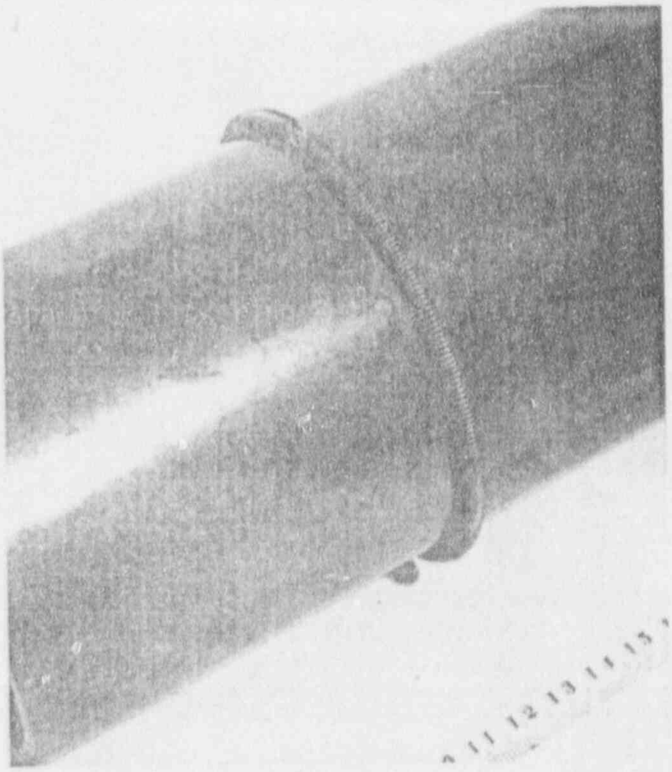


Figure 2.1 Photograph of an NPD garter spring on a section of pressure tube.

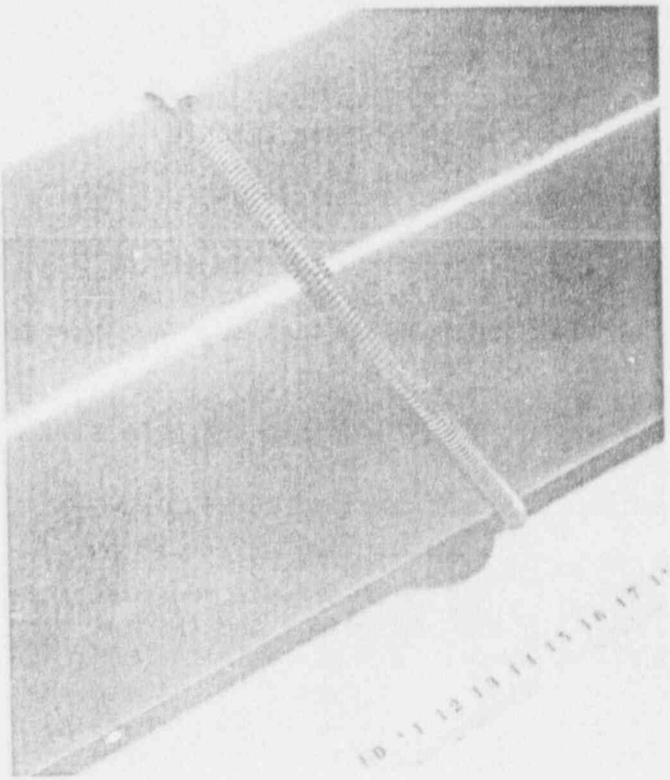


Figure 2.2 Photograph of a Pickering-A garter spring on a section of pressure tube.

The springs were then held in a circular shape with a girdle wire of annealed Zircaloy-2. This wire was spot-welded together at the ends which had been flattened (2 welds) (Figure 2.3). The resultant garter spring assemblies were a very loose fit over the pressure tubes, and an interference fit in the calandria tubes. The fit of these assemblies is illustrated in Figures 2.2 and 2.3. Douglas Point to Bruce-2 reactors had two garter springs per channel and later reactors had four per channel.

2.3 Bruce-8, Cernavoda and Darlington Reactors

A belated discovery was the susceptibility of the loose garter springs to moving along the channels away from their design positions, particularly during building and commissioning. The pressure tubes sag from the weight of the fuel and heavy water coolant, and rely on the garter springs to maintain a gap between the pressure tubes and calandria tubes. When a garter spring is significantly out of position, contact can occur after a period of operation, between the pressure and calandria tubes. This contact results in steep temperature gradients in the tubes which, if sufficient hydrogen/deuterium is present in the pressure tube, can cause hydrogen to migrate to the cold point of contact until solid hydride is formed at this point. This occurred in Pickering-2 channel G16 and a crack initiated at a brittle solid hydride, and caused a rupture of the pressure tube [1]. Solid hydrides have now been observed on Zircaloy-2 pressure tubes from Pickering-1 and -2 reactors where there has been contact between the pressure and calandria tubes. However, a Zr-2.5% Nb pressure tube removed from Pickering-3 reactor did not show any signs of hydrogen migration, even though contact had occurred with the calandria tube. This was because the hydrogen pickup was 25 to 50 times less, resulting in a much lower hydrogen/deuterium content. Contact may, therefore, not have the same consequences for Zr-2.5% Nb pressure tubes. Nevertheless, the hydrogen level may not remain low for the whole lifetime of a pressure tube, and garter springs should remain in their design position.

After it was realized that the loose garter spring design could move, the first reactor which could have a new spacer design was Bruce-8. Laboratory tests showed that a tightly-fitting spring with the ends hooked together (as used in NPD and KANUPP) did not move with any conceivable fuel channel vibration. There was concern that the hooked ends of a Zr-2.5% Nb-0.5% Cu spring would have radial hydrides because the hooks could not be made after the heat-treatment. Inconel X750 garter springs were chosen, but because of the time schedule, a very conservative design was chosen. A more optimum design, which was much less material, has been chosen for Cernavoda, Darlington and the new channels in Pickering-1 and -2 reactors. Unwelded Zircaloy-2 girdle wires are within these springs (1½ revolutions) to allow their position to be located by an eddy current method.

Table 2.1 summarizes the garter spring design data for CANDU reactors. Note that all Inconel X750 garter springs have the ends hooked together, and are a tight fit around the pressure tube; all Zr-Nb-Cu springs are a loose fit around the pressure tube.

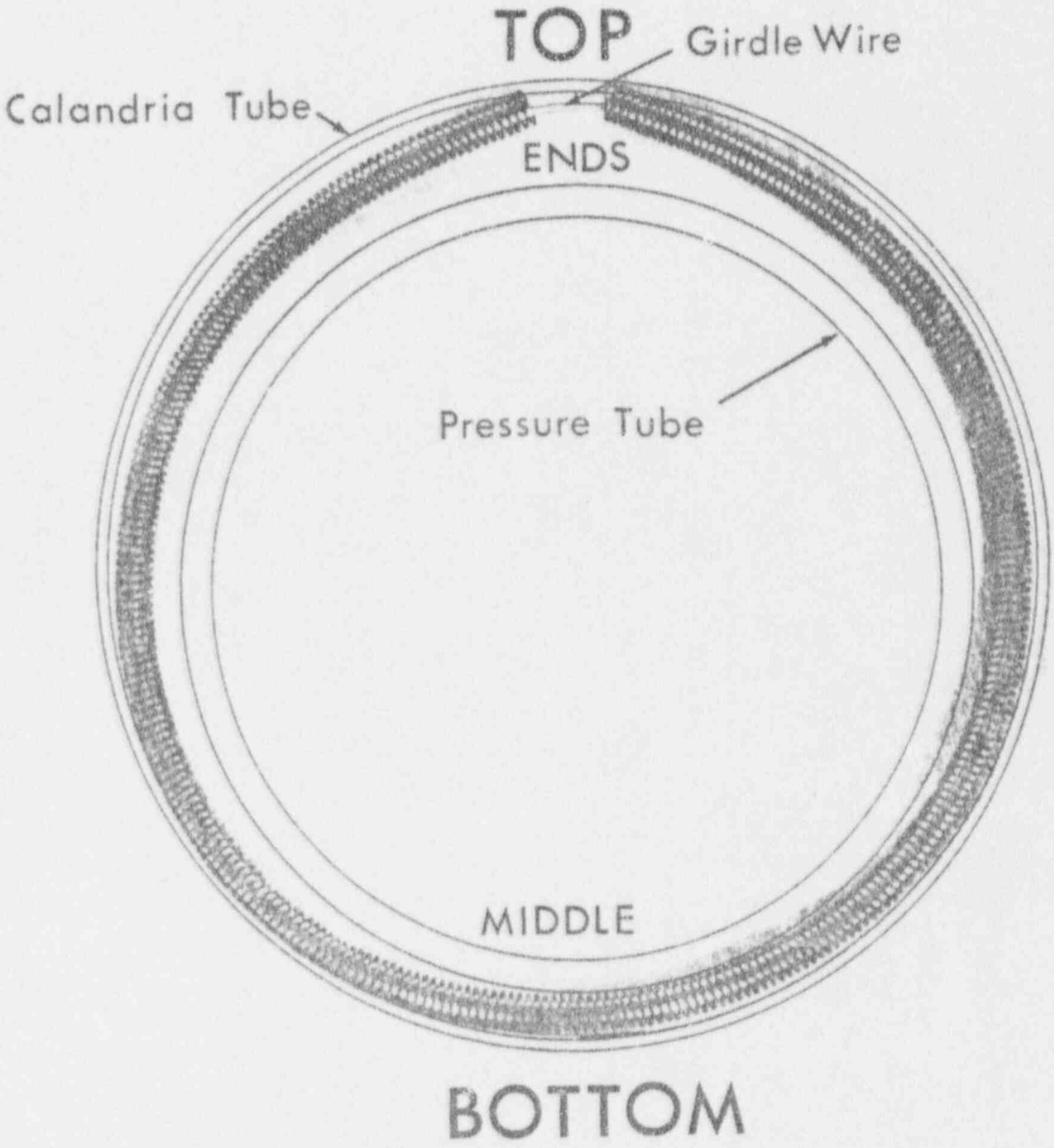


Figure 2.3 Cross-section of a Pickering Fuel Channel showing the fit of the garter spring between the pressure tube and the calandria tube.

TABLE 2.1 CANDU REACTOR GARTER SPRING INFORMATION

	PRESSURE TUBE		CALANDRIA TUBE		GARTER SPRINGS						GIRDLE WIRE	
REACTOR	Material	O.D. mm	Material	I.D. mm	No. per channel	Location from Reactor C/L m	Material	Wire Size Before Cooling Depth/Width mm	Coil O.D. mm	Coil Pitch mm	Dia. mm	Welded
NPD	C.W. Zircaloy-2	91.0	AA5052	101.9	1	0	Inconel X750	1.0/0.5	4.75	1.0	-	-
KANUPP	H.T. Zr-2.5% Nb	90.8	Zircaloy-2	101.0	2	0.63	Inconel X750	1.0/0.5	4.32	1.0	-	-
Douglas Pt. RAPP 1&2	C.W. Zircaloy-2	90.5	Zircaloy-2	107.7	2	0.60	Zr-2.5%Nb-0.5%Cu	1.9/1.0	7.52	1.3	1.2	yes
Gentilly 1	H.T. Zr-2.5% Nb	108.4	Zircaloy-2	118.3	1	0	Zr-2.5%Nb-0.5%Cu	1.7/1.0	6.81	1.3	1.2	yes
Pickering 1&2	C.W. Zircaloy-2	113.3	Zircaloy-2	130.8	2	0.95	Zr-2.5%Nb-0.5%Cu	1.7/1.0	6.81	1.3	1.2	yes
Pickering 3&4	C.W. Zr-2.5%Nb	111.5	Zircaloy-2	130.8	2	0.95	Zr-2.5%Nb-0.5%Cu	1.7/1.0	6.81	1.3	1.2	yes
Bruce 1&2	C.W. Zr-2.5% Nb	111.5	Zircaloy-2	129.0	2	0.91	Zr-2.5%Nb-0.5%Cu	1.7/1.0	6.81	1.3	1.2	yes
Bruce 3	C.W. Zr-2.5% Nb	111.5	Zircaloy-2	129.0	4	0.51,1.55	Zr-2.5%Nb-0.5%Cu	1.6/1.0	6.81	1.3	1.2	yes
Bruce 4	C.W. Zr-2.5% Nb	111.5	Zircaloy-2	129.0	4	0.51,1.55	Zr-2.5%Nb-0.5%Cu	1.6/1.0	5.59	1.3	0.9	yes
Gentilly-2 Embalse Pt. Lepreau Wolsung-1	C.W. Zr-2.5% Nb	111.8	Zircaloy-2	129.0	4	0.51,1.55	Zr-2.5%Nb-0.5%Cu	1.6/1.0	5.59	1.3	0.9	yes
Bruce 5,6,7	C.W. Zr-2.5% Nb	111.6	Zircaloy-2	129.0	4	0.51,1.55	Zr-2.5%Nb-0.5%Cu	1.6/1.0	5.59	1.3	0.9	yes
Bruce 8	C.W. Zr-2.5% Nb	111.6	Zircaloy-2	129.0	4	0.51,1.55	Inconel X750	1.0/1.0	4.83	1.2	0.9	no
Cernavoda	C.W. Zr-2.5% Nb	111.8	Zircaloy-2	129.0	4	0.51,1.55	Inconel X750	0.8/0.8	4.83	1.6	0.9	no
Darlington	C.W. Zr-2.5% Nb	111.8	Zircaloy-2	129.0	4	0.51,1.55	Inconel X750	0.8/0.8	4.83	1.6	0.9	no
Pickering 1&2 Retubed	C.W. Zr-2.5% Nb	111.8	Zircaloy-2	130.8	4	0.51,1.55	Inconel X750	0.8/0.8	4.83	1.6	0.9	no

3. DESIGN AND TESTING OF UNIRRADIATED PICKERING-A AND BRUCE-1&2 GARTER SPRINGS

3.1 Design

The designs of the Pickering-A and Bruce-1&2 garter springs were very similar with the same wire and coil dimensions, but slight differences in other dimensions because of the small difference in calandria tube diameter. Drawings for the two assemblies are shown in Figures 3.1 and 3.2. The design load for each spring was 1380 N for 2 springs per channel which is spread over a number of coils. (This was later raised to 1550 N.) The peak load per coil was estimated at 22 N.

3.2 Operating Temperature

A Douglas Point garter spring was electrically heated (to simulate gamma heating) and held between a hot section of pressure tube and a cold section of calandria tube. The temperature of the garter spring was estimated using indicating paints and miniature thermocouples. These experiments indicated that the temperature of garter springs was almost constant and about equal to the pressure tube temperature [2]. Thin sheets of mica were, however, used to electrically insulate the spring from both the pressure and calandria tubes, so it is unlikely that local cold spots, where coils contacted the calandria tube, would be produced.

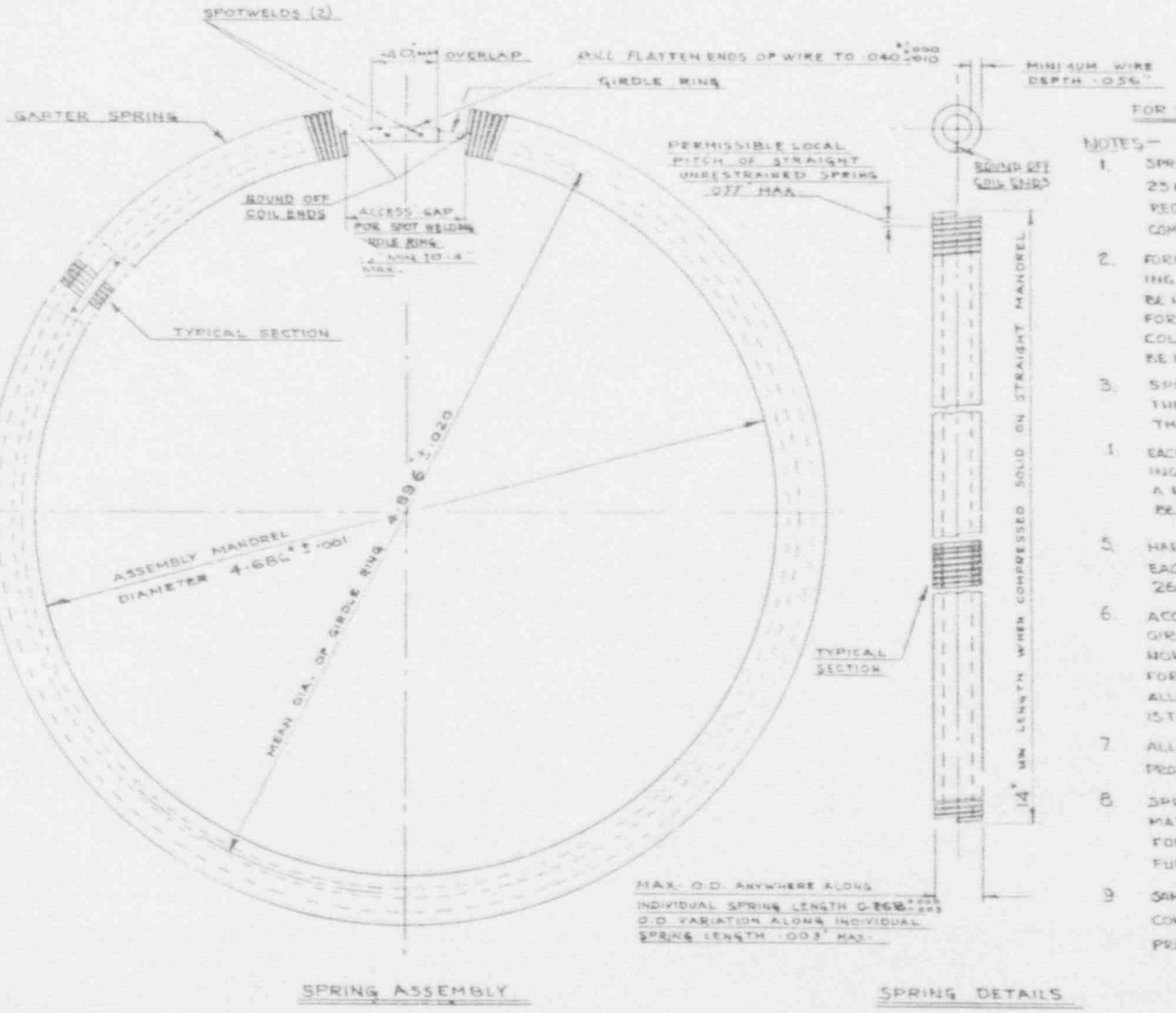
3.3 Zr-2.5% Nb-0.5% Cu Alloy Properties

The Zr-2.5% Nb-0.5% Cu alloy was examined to find a satisfactory treatment for strength and hydride orientation. The optimum mechanical properties are developed after water-quenching from about 40 K below the β-transus and aging at 810 K for 6 h. In this condition, it was found that straining the wire to make springs resulted in hydrides which were unfavourably (i.e. radially) oriented [3]. Thus, it was recommended that all heat treatment be done after making the springs. Tensile tests on heat treated specimens after irradiations up to 3×10^{24} n/(m^2.s) (> 1 MeV) showed the following effects of irradiation [4,5]·

(a) yield strength increased about 25%;
(b) reduction of area was not affected;
(c) uniform elongation was reduced.

3.4 Wear and Fatigue Tests

Garter springs were tested for fatigue and wear in rigs made up from sections of pressure tubes (at 565 K) and calandria tubes. The loads imposed on the garter springs were up to 4700 N, i.e. more than three times design load, and the pressure tube sections moved relative to the calandria tube by 12.5 mm for 1500 cycles [6]. Metallurgical examination of the garter springs showed no distortion, wear, or change in hardness with testing. Wear marks were apparent on the bottom half of both the pressure and calandria tube sections. The maximum depth of marks observed were 0.06 mm on the pressure tube, and 0.19 mm on the calandria tube, and the average depths from all the tests (regardless of load) were 0.04 mm and 0.07 mm, respectively.

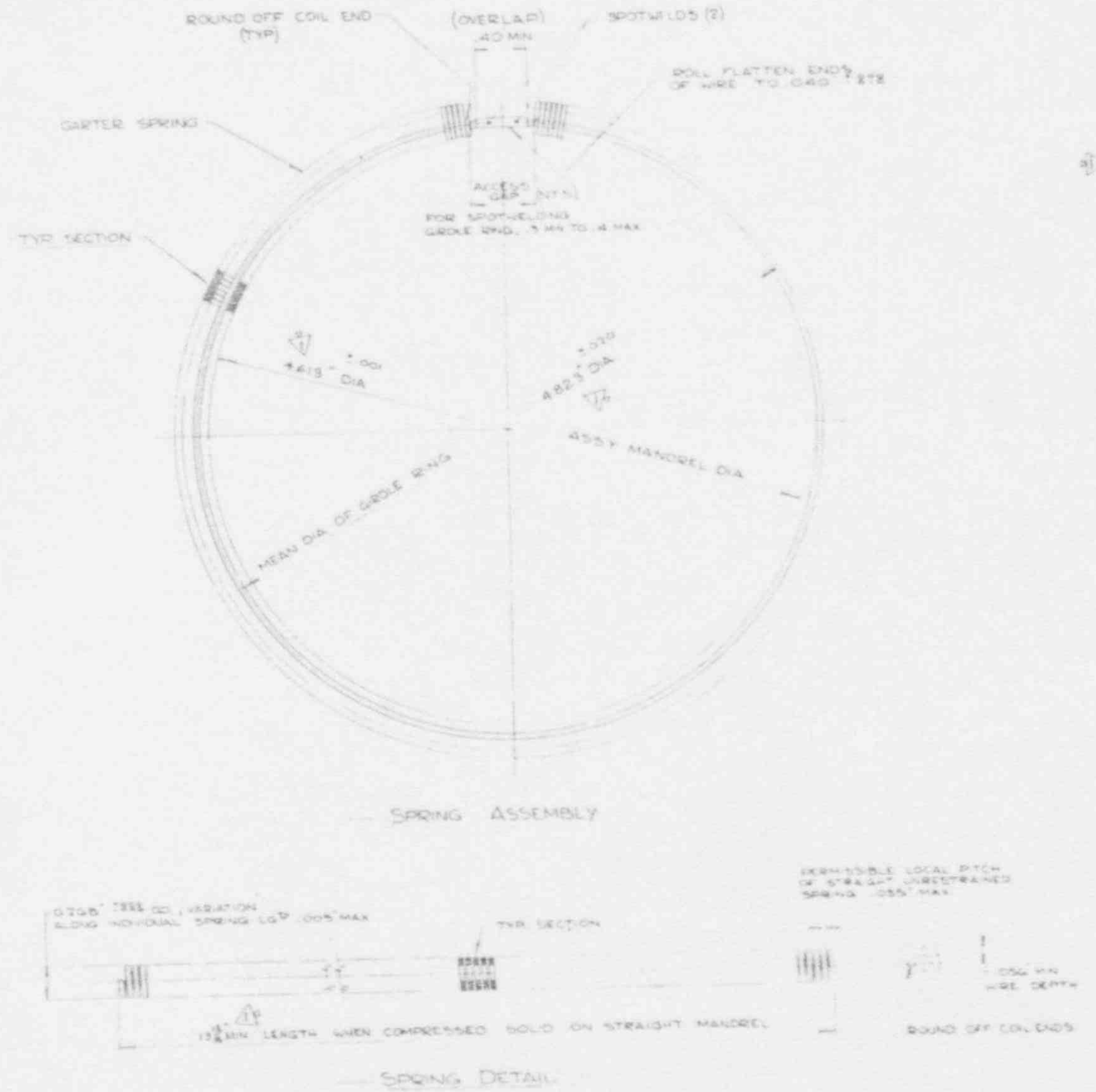


FOR NEXT ASSEMBLY SEE DWG NO GA-F-44-N 31100-12 13.14 & 16

NOTES—

1. SPRING SHALL BE MADE FROM ANNEALED ZIRCONIUM-2.5 NIOBIUM-0.5 COPPER ALLOY ·068 [illegible] X ·041 [illegible] (REF.) RECTANGULAR SECTION WIRE SUPPLIED BY THE COMMISSION TO A.E.C.L. SPECIFICATION NP-M-785.
2. FORMED SPRINGS SHALL BE LOADED ON TO A QUENCHING JIG AND DEGREASED. THE SPRINGS SHALL THEN BE HEAT TREATED AT A TEMPERATURE OF 1580° ± 10°F FOR A PERIOD OF 15 MINUTES AND QUENCHED IN COLD AGITATED WATER. HEAT TREATMENT SHALL BE IN A SALT BATH.
3. SPRINGS SHALL THEN BE PICKLED DEGREASED AND THEN AGED AT 1000° ± 10°F UNDER VACUUM NO GREATER THAN 1 MICRON OF MERCURY FOR 6 HOURS.
4. EACH STRAIGHT SPRING SHALL BE PROOF TESTED BY SUSPENDING AN 8 lb WEIGHT FROM ONE END. ANY SPRING SHOWING A RESIDUAL EXTENSION GREATER THAN 1/16" SHALL BE UNACCEPTABLE.
5. HARDNESS SHALL BE DETERMINED ON ONE END OF EACH SPRING. THE HARDNESS SHALL BE 260 ± 10 VPN
6. ACCEPTABLE SPRINGS SHALL BE ASSEMBLED ON TO GIRDLE WIRES. THE GIRDLE WIRE SHALL BE ·047 IN NOMINAL DIA AND SHALL MEET THE REQUIREMENTS FOR COLD FINISHED REACTOR GRADE ZIRCONIUM ALLOY WIRE TO A.S.T.M. B351 GRADE RA-1 (THIS IS TO BE SUPPLIED BY THE COMPANY)
7. ALL FABRICATING, HEAT TREATMENT AND INSPECTION PROCEDURES ARE SUBJECT TO APPROVAL BY THE COMMISSION
8. SPRINGS SHALL BE CLEAN, FREE FROM PARTICULATE MATTER AND INDIVIDUALLY PACKAGED READY FOR INSTALLATION IN THE REACTOR WITHOUT FURTHER CLEANING.
9. SAMPLE SPRING WILL BE SUBMITTED TO THE COMMISSION FOR APPROVAL BEFORE FABRICATION OF PRODUCTION SPRINGS.

Figure 3.1 Drawing of the garter springs for Pickering-A reactors.



NOTES:

1. SPRING SHALL BE MADE FROM ANNEALED ZIRCONIUM-2.5 NIOBIUM-0.5 COPPER ALLOY .048 [illegible] X .041 [illegible] (REF) RECTANGULAR SECTION WIRE TO AECL SPEC NP-M-1082.
2. FORMED SPRINGS SHALL BE LOADED ON TO A QUENCHING JIG AND DEGREASED. THE SPRINGS SHALL THEN BE HEAT TREATED AT A TEMP OF 1580° ±10° F FOR A PERIOD OF 15 MIN ±1 MIN AND QUENCHED IN COLD AGITATED WATER. HEAT TREATMENT SHALL BE IN A SALT BATH.
3. SPRINGS SHALL THEN BE PICKLED, DEGREASED AND THEN AGED AT 1000° ±10° F UNDER VACUUM WITH ABS PRESSURE NO GREATER THAN 1 MICRON OF MERCURY FOR 6 HRS ±5 MIN.
4. EACH STRAIGHT SPRING SHALL BE PROOF TESTED BY SUSPENDING AN 8 LB WEIGHT FROM ONE END. ANY SPRING SHOWING A RESIDUAL EXTENSION GREATER THAN 1/16" SHALL BE UNACCEPTABLE.
5. HARDNESS SHALL BE DETERMINED ON ONE END OF EACH SPRING. THE HARDNESS SHALL BE 260 ±10 VPN.
6. ACCEPTABLE SPRINGS SHALL BE ASSEMBLED ON TO GIRDLE WIRES. THE GIRDLE WIRE SHALL BE .047 NOM DIA AND SHALL MEET THE REQUIREMENTS FOR COLD FINISHED REACTOR GRADE ZIRCONIUM ALLOY WIRE TO ASTM B-351 GRADE RA-1.
7. ALL FABRICATING, HEAT TREATMENT, INSPECTION, PACKING, PACKAGING AND SHIPPING PROCEDURES ARE SUBJECT TO THE APPROVAL OF THE COMMISSION.
8. SPRINGS SHALL BE CLEAN, FREE FROM PARTICULATE MATTER AND INDIVIDUALLY PACKAGED READY FOR INSTALLATION IN THE REACTOR WITHOUT FURTHER CLEANING.
9. THREE (3) SAMPLE SPRGS WILL BE SUBMITTED TO THE COMMISSION FOR APPROVAL BEFORE FABRICATION OF PRODUCTION SPRINGS.

Figure 3.2 Drawing of the garter springs for Bruce 1 to 3 reactors.

Rolling wear tests on broken Douglas Point garter springs showed that they still performed satisfactorily [7].

3.5 Crushing Tests

Sections of garter spring, 90 mm long, were crushed at room temperature between mandrels that had the same curvatures as the inside of a calandria tube and the outside of a pressure tube [8]. The tests showed that these sections became unstable at loads greater than about 45 000 N (although maximum loads of up to 110 000 N were achieved) with the coils starting to tilt sideways (operating loads are up to a maximum of 1550 N).

3.6 Hydrogen Migration

Pieces of garter springs were placed between Zr-2.5% Nb plates, one at about 610 K and the other at about 345 K. After only 9 days' exposure, a solid hydride was seen at the point of coils where they touched the cold plate [9]. There was no simulation of gamma heating in the coils, so that the temperature gradients were not the same as in a garter spring in service.

Some similar tests on Douglas Point garter springs placed springs which had been hydrided up to 500 ppm† between Zircaloy-2 faces at 566 K and 333 K at loads of up to 270 N per coil for up to 2 months [7]. Some of these springs with the highest hydrogen and loads failed during exposure after 150 to 200 h. However, springs with 100 ppm hydrogen and loaded at 180 N per coil were intact after 1500 h; crush testing these springs showed the failure load had only decreased 15%.

4. EXAMINATION OF GARTER SPRINGS FROM PICKERING-A AND BRUCE-2 REACTORS

Garter springs have been examined which were removed when pressure tubes were changed in Pickering-3 and -4 reactors after 2 years' operation, Bruce-2 after 5 years' operation, and Pickering-1,-2,-3 and -4 after about 12 years' operation. The operating times are listed in Table 4.1 below.

TABLE 4.1 OPERATING TIMES FOR GARTER SPRINGS EXAMINED.

Reactor	Removal Date	Operating Time (EFPH*)
Pickering-3	1974 August	12850
Pickering-4	1975 May	15140
Bruce-2	1982 October	40535**
Pickering-1	[illegible] November	88900
Pickering-2	[illegible] August	86885
Pickering-3	1984 April	83758
Pickering-4	1984 September	82670

*effective full power hours; **full power taken as 2515 MW (i.e. design).

†500 x 10^{-4} wt%

A diagram for Pickering fuel channel lattice positions is shown in Figure 4.1.

(a) **Visual Examination:** Garter springs were examined visually with a Questar telescope in NRU bays and with the Kollmorgan periscope and stereo macroscope in Building 375 active cells. The examinations were for general integrity, deformation, surface discoloration and deposits, and fracture surface examination.

(b) **Neutron Radiography:** Neutron radiography was tried on an unirradiated garter spring, with solid hydride present, to see if it was a suitable method for identifying gross segregation of hydride.

(c) **Metallographic Examination:** Sections were cut from springs, especially in the contact area in the middle of the springs, to look for hydride distribution and oxide thickness. Girdle wires were examined for microstructure, hydride and porosity, especially near the welds. Hardness tests were also taken with the microhardness tester, but some comparison tests with out-of-cell measurements on unirradiated specimens showed them to be unreliable. Sections were also cut at garter spring marks on pressure and calandria tube to measure depth of marks, and look for signs of deformation or hydrides.

(d) **Crush tests:** Sections of garter springs were crush tested at room temperature between anvils with the same curvatures as pressure and calandria tubes (56 mm and 66 mm radius, respectively) using the Tinius Olsen test machine, except for one test which was between flat plates.

(e) **Fatigue tests:** Sections of garter springs were fatigue tested at room temperature between flat plates, with crushing loads, on the MTS test machine in-cell.

(f) **Tension tests:** Sections of garter spring were tension tested by inserting hooks between the coils and pulling. Girdle wires were tension tested to establish strength and ductility. Girdle wires were also bent in a vice to get further information on ductility.

(g) **Hydrogen and Deuterium Analysis:** Hydrogen concentration was measured in a few of the springs and girdle wires. Deuterium was measured at the middle and ends of most springs and in more positions in selected springs.

(h) **Ovality:** This was measured with a gauge micrometer to an accuracy of about 0.025 mm.

4.1 Examination of a Pickering-4 Garter Spring After Two Years' Operation

Pressure tubes were removed from Pickering-3 and -4 reactors in 1974 August and 1975 May after 13850 and 15140 EFPH (577 and 631 EFPD) operation, respectively. Several unidentified garter springs, that were retrieved from dismantled fuel channels from Pickering-4, were visually examined. All were intact and did not show any signs of damage or excessive oxidation.

Metallographic examinations of longitudinal and transverse sections from the middle of one spring showed the hydride distribution to be homogeneous and

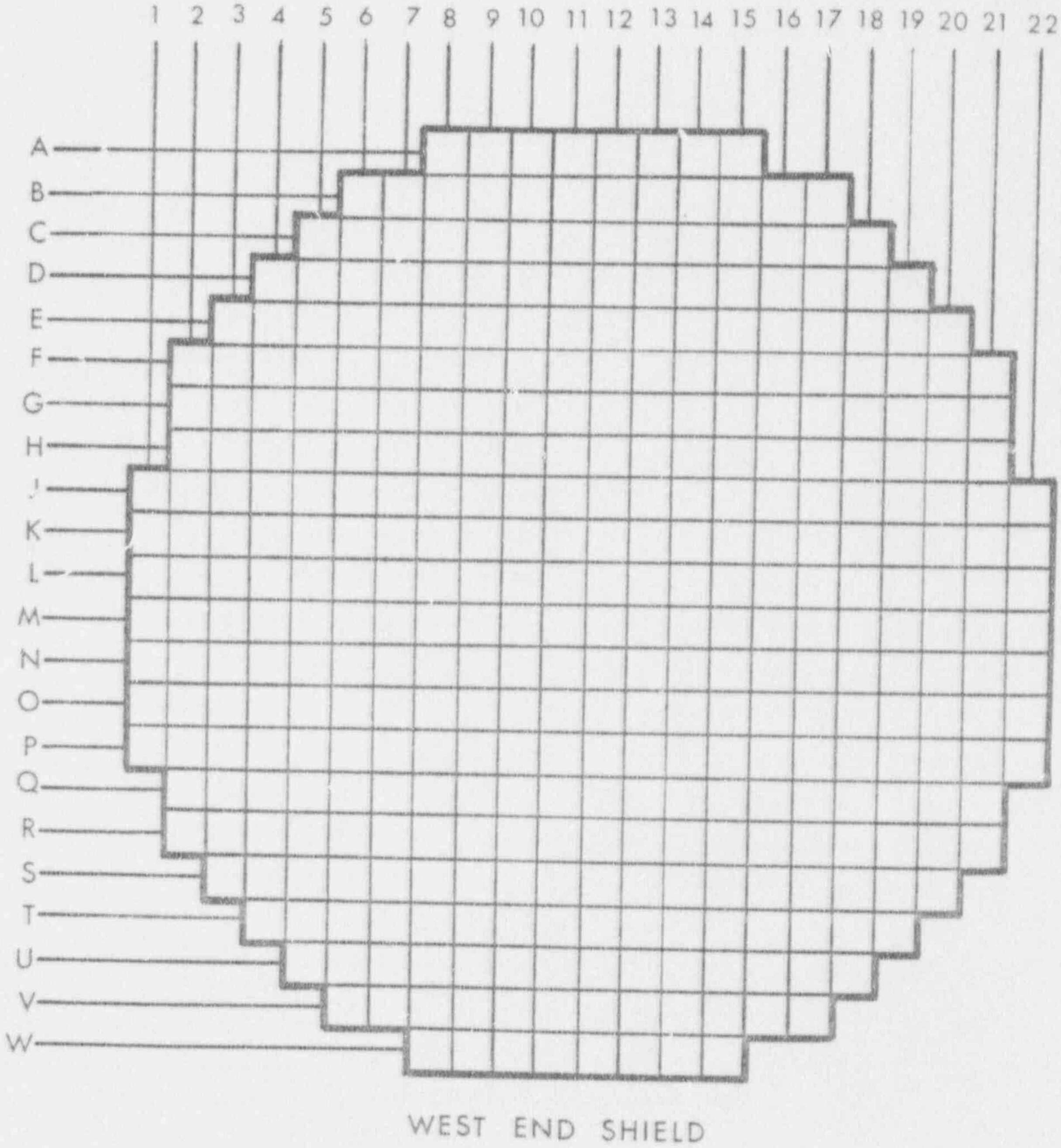


FIGURE 4.1 PICKERING REACTOR LATTICE

that the oxide thickness was less than 1 μm. Figure 4.2 shows typical grain structure and hydride distribution.

Sections from an unidentified garter spring and a spring from channel P4-J22 were crush tested between curved mandrels. The results are summarized in Table 4.2.

TABLE 4.2 CRUSH STRENGTH AT ROOM TEMPERATURE OF P4 GARTER SPRINGS AFTER 15140 EFPH OPERATION.

Spring Identification	Section Length (mm)	Maximum Load (kN)	Approx. Load Per Coil kN	Remarks
P4 Unidentified	60	94.1	2.0	Rig broke
	50	65.3	1.6	Collapsed sideways
	50	69.4	1.7	Collapsed sideways
P4-J22*	45	57.4	1.6	Collapsed sideways
	41	44.7	1.4	Collapsed sideways

*Note that this is an outer channel where the fast neutron fluence is only about 60% that for a central channel.

Visual examination of the garter spring sections after testing did not show any obvious signs of deformation. The loads per coil at instability are slightly higher than for the unirradiated tests which gave 1.1 to 1.6 kN per coil [8]. This may be due to some irradiation hardening but is more likely to be due to the different lengths of sections tested and differences in the test rigs.

Deuterium and hydrogen were analyzed on sections cut from about 80 and 100 mm from each end of an unidentified spring. The deuterium concentration was about 2 ppm and the hydrogen 35 to 45 ppm. This indicates very little pick-up in service since as-installed measured hydrogen contents were 35 to 45 ppm.

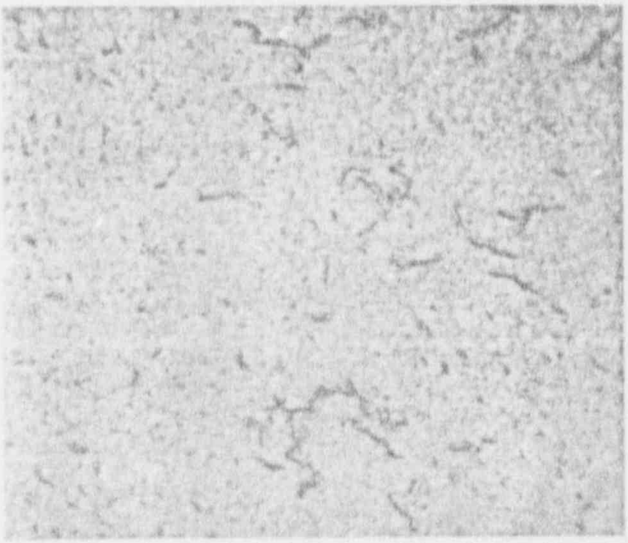
No ovality could be measured on coils from the centre of the garter spring within the accuracy of measurement of the measuring jig, i.e. < 0.025 mm.

4.2 Examination of Bruce-2 Garter Springs After Five Years' Operation and Pickering-A Garter Springs After Twelve Years' Operation

Most of the garter springs were received with, but not on, their pressure tube and therefore, while the channel could be identified, the positions of the springs in the channel were unknown. The exceptions to this were the Bruce-2 A14 and Pickering-4 N16 garter springs, where the east garter springs were still

H20 A-1 Transverse X500

(a) Grain structure



H20 A-2 Transverse X200

(b) Hydride Distribution

Figure 4.2 Grain structure and hydride distribution for a Zr-Nb-Cu garter spring removed from Pickering-4 after 2 years' operation.

on the pressure tubes, Pickering-2 J15, where the garter springs were supposed to be correctly identified, and Pickering-1 P14 garter springs, where the garter springs were received with end fittings. Thus, except for these four channels, garter springs have been numbered 1 and 2 for identification. The garter springs from the channel P2-G16 were received in many broken and deformed pieces. Most of this damage was believed to have occurred from the rupture of the pressure tube but further damage may have occurred when removing the pressure tube.

4.2.1 Visual Examination

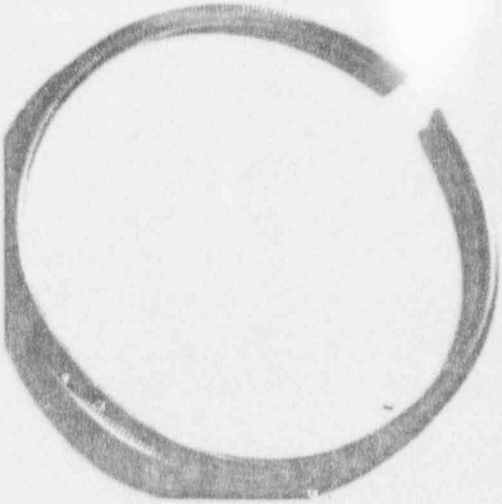
Most of the garter springs received (~ 70%) were completely intact, i.e. unbroken and undeformed. Some garter springs were deformed and a few were broken and deformed. We believe that all the deformation and breakages were due to handling and shipping damage after service in the reactors (except for P2-G16). Most of the garter springs were shipped in the same cavity in the shipping flask as the pressure tube pieces, and one spring, P1-G16 [2], was jammed on the end of a pressure tube section; it was deformed but not broken. Figure 4.3 shows photographs of an undamaged spring, a deformed spring and a broken and deformed spring. A summary of the condition of the springs is given in Table 4.3. No hydride blisters were visible on any of the springs, and oxide appeared to be thin with different interference colours. The spring from B2-A14 showed the least signs of deformation at its fractures and photographs are shown in Figure 4.4. All other fractured springs showed much more deformation close to the fractures.

4.2.2 Neutron Radiography

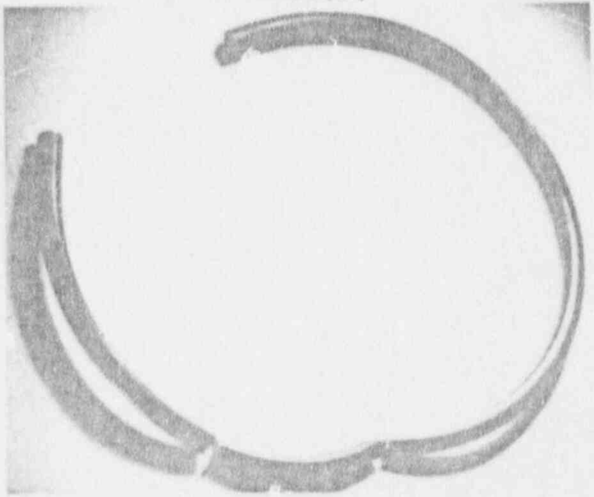
Neutron radiography was tried on an unirradiated garter spring which had had a temperature gradient imposed to give solid hydride on the surface. This technique proved to be unsuitable for detection of hydrides in garter springs, because the resolution was insufficient to detect solid surface hydrides of the size which have been observed.

4.2.3 Metallographic Examination

(a) Garter Springs: Most sections of coils from the middle of springs showed migration of hydride to the outside of the coil where there had been contact with the calandria tube. In the few springs where this migration was not observed, the deuterium concentration in the spring usually suggested that the spring had not operated with the middle at the bottom (see Section 4.2.8). The garter springs in P1-P14 operated very near the ends of the channel and probably did not have any portion squeezed between the pressure and calandria tubes; the observed absence of solid hydrides would therefore be expected. Figure 4.5 shows examples of solid surface hydrides of different sizes. Table 4.4 summarizes the dimensions of observed solid surface hydrides; note that the size range is unlikely to be real because we probably did not section through the largest hydride all the time. Note that garter springs P1-G20(1) and P3-J09(2) showed more than one solid hydride on a middle coil, which indicates that the contact points between these garter springs and the calandria



P1K18(2)



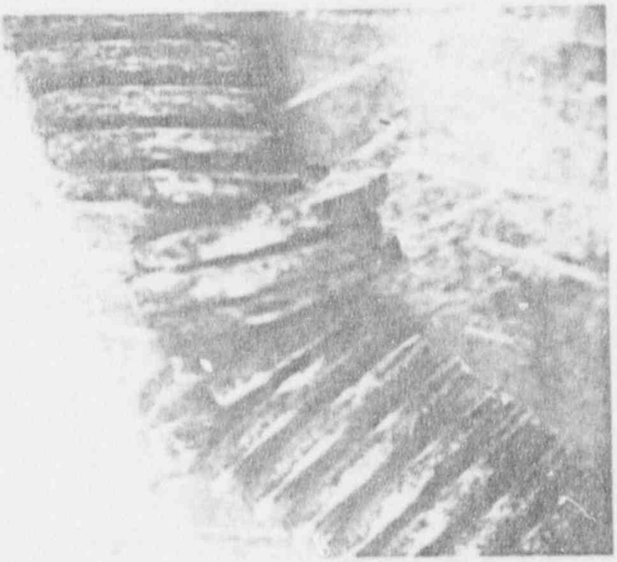
P1G16(2)

P2K13(1)

Figure 4.3 Examples of the different conditions that Pickering-A garter springs were received in at CRNL (12 years' operation).

TABLE 4.3 SUMMARY OF VISUAL EXAMINATIONS OF PICKERING A AND BRUCE-2 GARTER SPRINGS

Spring Identification	Garter Spring and Girdle Wire Condition
B2 A14(E) (outlet)	Spring broken near middle (5 fractures), deformed elsewhere/girdle wire intact
B2 A14(W)	Spring/girdle wire intact
P1 G14(1)	Spring/girdle wire intact
P1 G14(2)	Spring broken and deformed/girdle wire broken
P1 G16(1)	Spring intact/girdle wire broken
P1 G16(2)	Spring intact but deformed/girdle wire broken
P1 G20(1)	Spring intact/girdle wire broken
P1 G20(2)	Spring intact/girdle wire broken
P1 K05(1)	Spring/girdle wire intact
P1 K05(2)	Spring intact but deformed/girdle wire intact
P1 K18(1)	Spring/girdle wire intact
P1 K18(2)	Spring/girdle wire intact
P1 P14(E) (outlet)	Spring/girdle wire intact
P1 P14(W)	Spring/girdle wire intact
P2 G07(1)	Spring intact but deformed/girdle wire broken
P2 G07(2)	Spring broken and deformed/girdle wire broken
P2 J15(E)	Spring/girdle wire intact
P2 J15(W) (outlet)	Spring/girdle wire intact
P2 K11(1)	Spring/girdle wire intact
P2 K11(2)	Spring/girdle wire intact
P2 K13(1)	Spring broken in 2 places and deformed/girdle wire broken
P2 K13(2)	Spring/girdle wire intact
P2 G16	Spring/girdle wire broken into many pieces and deformed
P2 V09(1)	Spring/girdle wire intact
P2 V09(2)	Spring/girdle wire intact
P3 J09(1)	Spring/girdle wire intact
P3 J09(2)	Spring/girdle wire intact
P4 N16(E) (outlet)	Spring/girdle wire intact
P4 N16(W)	Spring broken in 2 places and deformed/girdle wire broken



RE-414-A X5

Figure 4.4 Fractured region of the Zr-Nb-Cu garter spring from Bruce-2 A14(E) (5 years' operation).

TABLE 4.4 HYDRIDE OBSERVATIONS IN THE MIDDLE OF GARTER SPRINGS AT THE OUTSIDE OF THE COILS

Spring Identification	Surface Solid Hydride Dimensions, depth x width, mm
B2 A14(E)	0.15 x 0.80
B2 A14(W)	No solid hydride
P1 G14(1)	0.06 x 1.05
P1 G14(2)	0.06 x 0.38
P1 G16(1)	0.03 x 1.80
P1 G16(2)	0.11 x 1.35
P1 G20(1)	0.03 x 0.40 + 0.03 x 0.30
P1 G20(2)	Not sectioned
P1 K05(1)	0.04 x 0.90
P1 K05(2)	Not sectioned
P1 K18(1)	0.10 x 2.30
P1 K18(2)	0.10 x 1.25
P1 P14(E)	No solid hydride
P1 P14(W)	No solid hydride
P2 G07(1)	0.05 x 1.45
P2 G07(2)	0.10 x 1.50
P2 J15(E)	0.03 x 1.20
P2 J15(W)	0.05 x 1.70
P2 K11(1)	No solid hydride, some concentration
P2 K11(2)	0.10 x ? (width not known - at fracture)
P2 K13(1)	No solid hydride, some concentration
P2 K13(2)	No solid hydride in middle, 0.10 x 1.3 at end
P2 G16	Unable to determine middle on pieces retrieved
P2 V09(1)	0.02 x >0.95
P2 V09(2)	0.06 x 0.50
P3 J09(1)	0.05 x 0.95
P3 J09(2)	0.05 x 0.80 + 0.03 x 0.60 + 0.02 x 1.10
P4 N16(E)	No solid hydride
P4 N16(W)	No solid hydride

C48B1-3 X100

Garter spring P1K18(1) showing large surface hydride layers.

C48F1 x100

Garter spring P1G20(1) showing small surface hydride layer.

Figure 4.5 Examples of surface hydride layers on garter springs where they have been in contact with the cold calandria tube.

tubes changed slightly during service. Garter spring P2-K13(2) which showed no solid hydride in the middle, and deuterium concentrations at the middle and ends opposite to the usual, showed a solid surface hydride at one end; this confirms that the spring operated upside down.

The oxide thickness on all springs was about 1 μm.

(b) Girdle Wires: Girdle wires from garter springs B2-A14E, P2-J15E, P2-J15W, P3-J09(1), P3-J09(2) and P4-N16(E) have been metallographically examined.

The general structure of the wires was equiaxed α grains about 0.04 mm across, with some voids within the wire (Figure 4.6(a)). All the welds appeared to be in good condition, but with more voids in this region (Figure 4.6(b)).

The oxide thicknesses on the specimens from girdle wires are summarized below:

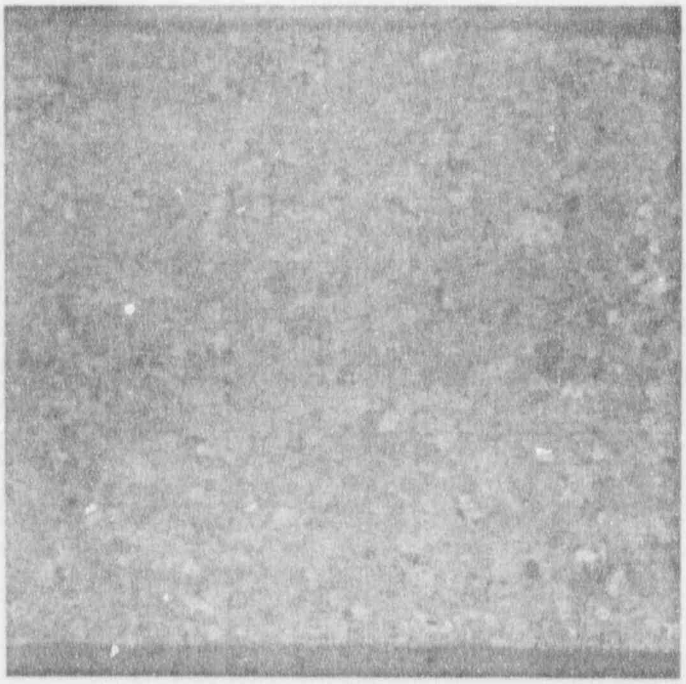
		OXIDE THICKNESS, μm	
		Weld Area	Away from Weld
Bruce-2	A14(E)	½ to 3	½ to 2
Pickering-2	J15(E)	½ to 2	½ to 3
	J15(W)	½ to 3	½ to 2
Pickering-3	J09(1)	-	10 to 30
	J09(2)	-	8 to 24
Pickering-4	N16(E)	1 to 2	8 to 14
	N16(W)	1 to 2	7 to 11

(c) Pressure Tube: A section was cut through the pressure tube from channel P2-J15 at the west (outlet side) garter spring mark (note that the garter springs in this channel were in the design position during operation). The mark had a maximum depth of 16 μm and showed a deformed layer under the mark and some twinning in the surrounding matrix (see Figure 4.7). There was no sign of hydride migration to the garter spring mark. The garter spring marks on the pressure tube from P3-J09 appear to be a little different than previously observed. The oxide on the pressure tube appeared to have worn away. However, metallography of the west (outlet) mark showed oxide throughout the mark which was thicker than on the rest of the surface, with no hydride associated with the mark; the depth of the mark was very small and could not really be separated from normal surface variations on the microsection.

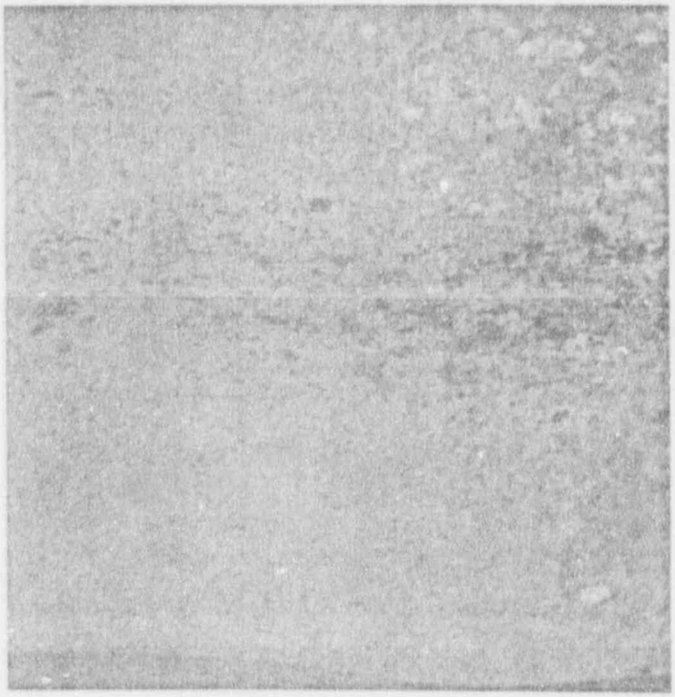
(d) Calandria Tube: A section was cut through the calandria tube from channel P2-G16 at the west (inlet side) garter spring mark. The west garter spring was in the design position in this channel, but the east one was over one metre inboard. The load on the west garter spring would, therefore, be less than if both springs had been in the correct position. Figure 4.8 shows the profile of the mark which has a maximum depth of 2 μm. There was no hydride concentration near the mark.

4.2.4 Crushing Tests

Sections 40-45 mm long from the ends and middles of springs were crush tested at room temperature, mostly between curved mandrels. The crosshead speed was about 4 μm/s. The results are summarized as follows:



C36I1 typical structure of girdle wires. 100X

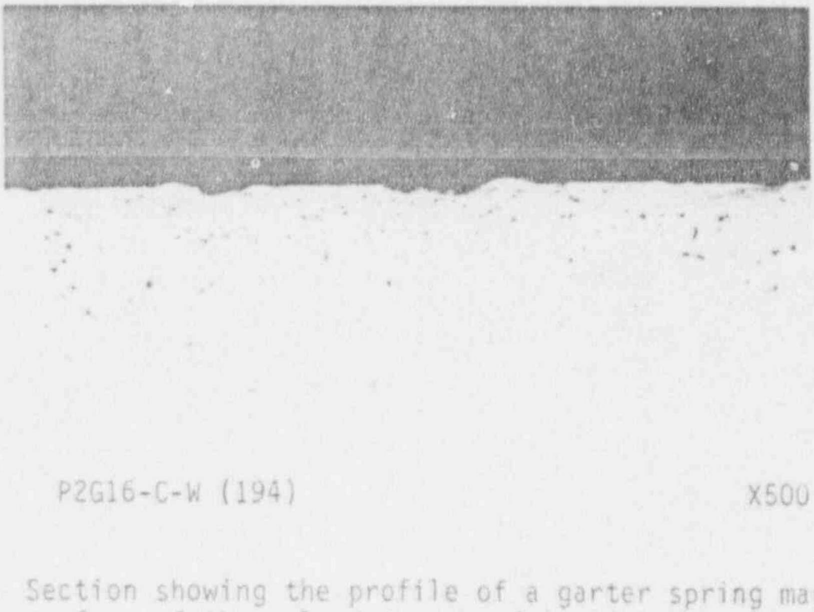


C36I2 typical structure at weld area of girdle wires (showing voids) 100X

Figure 4.6 Typical metallurgical structure in girdle wires both away from the weld and in the weld area (P2J15).

P2 J-15-P-W (170) garter spring mark 16 μm max depth X500

Figure 4.7 Section showing the profile of a garter spring mark on the outer surface of the pressure tube from Pickering-2 J15.



P2G16-C-W (194) X500

Figure 4.8 Section showing the profile of a garter spring mark on the inner surface of the calandria tube from Pickering-2 G16.

Bruce-2 Garter Springs: 40535 EFPH (at 0.88 of rated power)

A14 West-end, section length 45 mm
Inflection in loading curve at 59 kN; curve continued to 120 kN and unloaded and inspected - broken into pieces; maximum load per coil ~ 3.4 kN.

A14 West-middle, section length 42 mm
Load drop when load reached 29.7 kN - visually examined and found to be intact but with a kink; reloaded to 44 kN where loading curve flattened - visually examined and found part of the section squashed and a few coils broken off one end; maximum load per coil ~ 1.3 kN.

A14 East-end, section length 41 mm (some sideways deformation before testing)
Load drop when load reached 31.4 kN - visually examined and found to be intact; reloaded to 40.7 kN where loading curve flattened - visually examined and still intact except for some flattening of coils at one end; maximum load per coil ~ 1.3 kN.

A14 East-middle, section length 42 mm. (This test was between flat plates so that the maximum bending stress was on the section of coil with solid hydride on the outside surface.)
Load up to 34.9 kN with no marked flattening in the curve but with a change in slope at 28.4 kN - visual inspection showed fracture at one end which probably occurred at 28.4 kN; maximum load per coil ~0.9 kN at fracture.

Pickering-2 Garter Springs: 86885 EFPH

J15 West-end, section length 40 mm
Load drop when load reached 31.0 kN - visually examined and found to be intact; maximum load per coil ~ 1.0 kN (no fracture).

J15 West-middle, section length 40 mm
Load drop when load reached 26.4 kN - visually examined and found to be intact; reloaded to 46.2 kN before load drop - visual examination showed several pieces broken off; maximum load per coil ~ 1.5 kN.

J15 East-end, section length 45 mm
Load drop when load reached 18.0 kN - visually examined and found to be intact but with some surface flattening; reloaded to 44.7 kN - visually examined and still intact; maximum load per coil ~ 1.3 kN (no fracture).

J15 East-middle, section length 44 mm
Load deviation when load reached 54.0 kN but reached 57.8 kW before unloading - visual examination showed some surface flattening and some pieces broken off, probably at 54.0 kN; maximum load per coil ~ 1.6 kN.

J15 East-near middle, section length 45 mm
Loaded to 58.2 kN before load drop - visually examined and section had flattened and broken into many pieces; maximum load per coil ~ 1.6 kN.

The crushing load sustained in all these tests was much greater than the design load of 22 N/coil.

The elastic deflection on loading these 40-45 mm garter spring sections was typically linear to at least 25 kN and deflects 2.5 mm at this load.

4.2.5 Crush Fatigue Tests

Sections 40 mm long (about 30 coils) were cut from Pickering-2 garter springs G07(1) and G07(2) from the middle regions. All these sectons had some solid hydride on the outside of the coils. The curvature of the spring put the outside of the coil with solid hydride at 90° to the compressive stress. The results are summarized in Table 4.5.

TABLE 4.5 CRUSH FATIGUE TESTS ON 40 mm LONG GARTER SPRING SECTIONS IN SERVICE FOR 86885 EFPH: TESTS AT ROOM TEMPERATURE AT 10 Hz.

Spring	Section No.	Load Range, N	No. of Cycles	Garter Spring Condition
P2-G07(1)	1	100-500 (16*)	10000	Intact
		100-1000 (33*)	+10000	Intact
		100-2000 (66*)	+10000	Intact
		100-5000 (166*)	+10000	Intact
		200-10000 (333*)	+ 3600	Some coils broken off
		TOTAL	43600	
P2-G07(1)	2	200-10000 (333*)	9000	Broken into many pieces
P2-G07(2)	1	200-10000 (333*)	2900	Broke into two pieces
P2-G07(2)	2**	400-8000 (266*)	10000	Broken (may have broken at 6200 cycles)

*approximate load per coil. **section kinked at the start of the test.

The results show that the fatigue strength, even with solid hydride in the middle of the garter springs, greatly exceeds the maximum expected static load of 22 N per coil; lifetime cycles in reactor service are expected to be 1000 to 2000, mostly at less than the maximum load.

4.2.6 Tension Tests

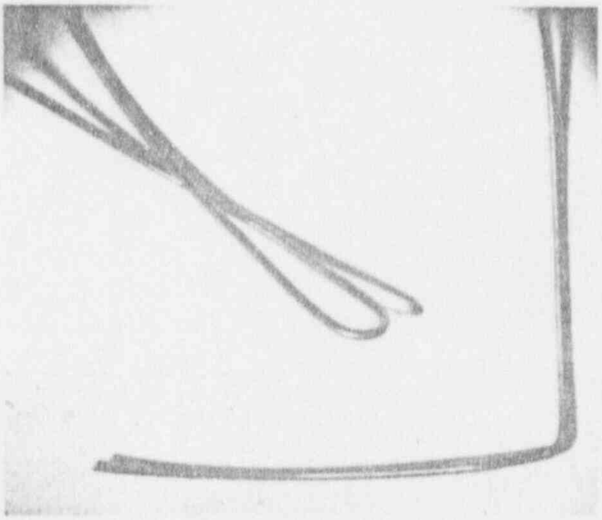
(a) Garter Springs: Tension tests were performed on two pieces retrieved from channel P2-G16, one piece without any obvious permanent stretch and one piece which was stretched by a factor of about four. A section from the middle of spring P1-G14(1) was also tension tested. The results are given in Table 4.6.

(b) Girdle Wires: Two tension tests were performed at room temperature on sections from Zircaloy-2 girdle wire P2-J15 East. The breaking loads for the two tests were 935 N and 985 N, with a reduction of area of 22%. The diameter of the wire was 1.19 mm which gives breaking stresses of 840 and 885 MPa.

TABLE 4.6 TENSION TEST RESULTS FOR GARTER SPRING SECTIONS - ROOM TEMPERATURE.

Spring Identification	Length Tested mm	Maximum Load N	Spring Stretch %	Remarks
P2-G16 (not deformed)	25	165	190	Broke where hooked
P2-G16 (deformed)	50	173	12	Broke where hooked
P1-G14(1)	100	170	110	Did not break - later shown to contain solid surface hydrides

Three bend tests were performed on sections of Zircaloy-2 girdle wire from P2-V09(1). In the first test, a section of wire was bent through 180° using manipulators in the cells. This section of wire remained intact, Figure 4.9. Two more sections were bent using a vice in-cell. They were bent through a sharp 90° angle (Figure 4.9). Both were then bent through 180° to give a similar sharp 90° bend in the opposite direction. One then broke almost immediately on attempting to bend back again (the fracture was close to a weld) while the other bent about 45° before breaking.



P2 V09-GW (1)

Figure 4.9 Bend tests on Zircaloy-2 girdle wire from garter spring P2V09(1).

These tests showed that the girdle wires are retaining excellent ductility and strength.

4.2.7 Hydrogen Analysis

Hydrogen concentration was measured for a few of the springs in various positions. The concentration did not vary significantly around springs or from spring to spring and is similar to the level observed in unirradiated springs. The results are summarized in Table 4.7.

TABLE 4.7 HYDROGEN CONCENTRATIONS OF GARTER SPRINGS FROM PICKERING AND BRUCE REACTORS

Spring Identification	Hydrogen Concentration, ppm Weight, in Different Positions				
	End 1	¼ Position	Middle	¾ Position	End 2
B2-A14(E)	41	29	42	-	-
(W)	35	34	32	-	-
P2-J15(E)	31	33	38	36	68?
(W)	40	36	32	37	33
P2-G16		44, 33, 41 unknown locations			

Average hydrogen concentration = 36 ppm S.D. ± 4 (does not include P2-J15(E) end 2)

Hydrogen concentration was measured on some girdle wires. These values are shown on Table 4.8.

TABLE 4.8 HYDROGEN CONCENTRATION OF GIRDLE WIRES FROM PICKERING AND BRUCE REACTORS.

Identification	Hydrogen Concentration, ppm Weight	
	Near Weld	Away from Weld
B2-A14(E)		20,21
(W)		17,31
P2-J15(E)	23,29	32,41,69,32
(W)	21,28	37,29,26,22
P3-J09(1)		23,21
(2)		25,29
P4-N16(E)		14
(W)		22,33

TABLE 4.9 DEUTERIUM CONCENTRATIONS OF GARTER SPRINGS FROM PICKERING AND BRUCE REACTORS.

Spring Identification	Deuterium Concentration, ppm weight, in different positions								
	End 1	1/8	1/4	3/8	Middle	5/8	3/4	7/8	End 2
B2 A14(E)	8	-	5	-	2	-	-	-	9
B2 A14(W)	3	-	2	-	1	-	-	-	-
B2 Average	6				2				
P1 G14(1)	35	-	-	-	11	-	-	-	-
P1 G14(2)	36	-	-	-	38	-	-	-	-
P1 G16(1)	20	-	4	-	0.5	-	-	-	-
P1 G16(2)	105	-	31	-	3	-	-	-	-
P1 G20(1)	114	-	48	-	8	-	-	-	-
P1 G20(2)	not measured								
P1 K05(1)	192	-	4	-	4	-	-	-	-
P1 K05(2)	not measured								
P1 K18(1)	52	-	15	-	3	-	-	-	-
P1 K18(2)	117	77	21	5	3	4	28	73	240
P1 P14(E)	23	-	-	-	1	-	-	-	-
P1 P14(W)	22	-	-	-	2	-	-	-	-
P1 Average	87				7				
P2 G07(1)	37	-	-	-	6	-	-	-	-
P2 G07(2)	48	-	-	-	5	-	-	-	-
P2 J15(E)	70*	-	36	-	39	48	74	-	66*
P2 J15(W)	-	19	11	-	10	12	17	-	57*
P2 K11(1)	85	-	-	-	40	-	-	-	-
P2 K11(2)	36	-	-	-	5	-	-	-	-
P2 K13(1)	49	-	-	-	18	-	-	-	-
P2 K13(2)	63	-	-	-	117	-	-	-	39
P2 V09(1)	64	-	-	-	9	-	-	-	-
P2 V09(2)	160	-	-	-	20	-	-	-	-
P2 Average	68				17				
P3 J09(1)	62	16	17	5	3	-	-	-	-
P3 J09(2)	64	-	20	-	3				
P4 N16(E)	41	-	-	-	2				
P4 N16(W)	50	-	-	-	33				
P3/4 Average	54				10				

*not true ends and not included in averages. †not included in averages.

4.2.8 Deuterium Analysis

The results of deuterium analyses from different positions around the garter springs are summarized in Table 4.9. The results show that, with two exceptions, the deuterium concentrations are higher at the ends of springs than in the middle. The only exception with a much larger deuterium concentration in the middle than the ends (P2-K13(2)), showed solid hydride at the end, rather than the middle during the metallographic examination (4.2.3).

The deuterium concentrations of the Bruce-2 springs are much lower than for the Pickering A springs, which is probably due to both carbon dioxide in the annulus in Bruce compared to nitrogen in Pickering A, and to the shorter operating time.

The difference in deuterium concentration between the middle and ends was less in Pickering-2 springs than for other Pickering-A springs. This may indicate that the annulus gas was less stagnant in Pickering-2 than the others, thus not allowing deuterium to segregate as much to the top of the channels.

Deuterium concentration was measured for the girdle wires from some channels. The results are summarized in Table 4.10.

TABLE 4.10 DEUTERIUM CONCENTRATIONS FOR GIRDLE WIRES

	Deuterium Concentration, ppm weight, in different positions	
	Near Weld	Away from Weld
B2-A14(E)	-	24,23
(W)	-	17,14
P2-J15(E)	15,15	31,52,25,25
(W)	18,18	25,27,26,25
P3-J09(1)	-	55,56
(2)	-	81,78
P4-N16(E)	-	47,36,370?
(W)	-	48,42

4.2.9 Ovality

The diameter of the coils in the middle of springs B2-A14E, B2-A14W, P1-J15E and P2-J15W were measured with a micrometer to an accuracy of about 0.025 mm. No ovality could be detected.

5. SUMMARY

(1) The garter springs were probably all intact after service up to 12 years in-reactor; any broken springs showing signs of heavy deformation indicated handling damage, either when removing from the reactor or during shipping.

(2) All garter springs, which operated with the ends at the top, showed solid surface hydride on the outside coils in the middle of the springs (where they contacted the cold calandria tube).

(3) Crush, crush fatigue and stretch tests show that the garter springs retain strength, fatigue resistance and ductility after 12 years operation that is much greater than is required in service, even with solid surface hydride present.

(4) Hydrogen concentrations are unchanged by in-reactor service.

(5) Deuterium concentrations of up to 240 ppm were observed on springs from Pickering A. The deuterium was much greater at the ends of the springs than the middle. The concentrations were much lower for the Bruce-2 springs than Pickering-A.

(6) Oxide thickness on the garter springs was about 1 μm.

(7) The Zircaloy-2 girdle wires retained excellent strength and ductility after reactor service.

(8) Oxide thicknesses of up to 30 μm were observed on girdle wires.

6. CONCLUSIONS

The garter springs from Pickering-A and Bruce-2 showed good strength and ductility, despite some solid surface hydrides, and show negligible corrosion after up to 12 years' service.

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8. REFERENCES

[1] G.J. Field, J.T. Dunn and B.A. Cheadle, "Analysis of the Pressure Tube Failure at Pickering NGS 'A' Unit 2", Atomic Energy of Canada Limited, Report AECL-8335, 1984 June.

[2] D.G. Dalrymple, Unpublished work CRNL, 1962 December.

[3] G.W. Parry, "Strain-Induced Directionality of Zirconium Hydride Precipitates in Zr-2.5% Nb-0.5% Cu Alloy", Atomic Energy of Canada Limited, Report AECL-1888, 1963 December.

[4] C.E. Ells and A. Sawatzky, "The Effect of Neutron Irradiation and Hydrogen Concentration on Tensile Properties of the CANDU Coolant Tube Spacer Alloy", Atomic Energy of Canada Limited, Report AECL-2272, 1965 June.

[5] C.E. Ells and A. Sawatzky, "The Effect of Neutron Irradiation on the Tensile Properties of Zr-2.5% Nb 0.5% Cu Alloy", Trans. Met. Soc. AIME, <u>233</u> (1965) p.2041.

[6] L. Fallis, unpublished data AECL Toronto, 1973.

[7] D.G. Dalrymple and W.A. Crago, Unpublished work CRNL 1962-1964.

[8] E.G. Price, unpublished work, AECL Toronto, 1974 May.

[9] G.D. Moan, unpublished work, AECL Toronto, 1983.

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