LEAK BEFORE BREAK EXPERIENCE IN CANDU REACTORS

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EXPÉRIENCE DES FUITES AVANT RUPTURE DANS LES REACTEURS CANDU

par

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Abstract

The paper describes how the requirements for Leak-Before-Break are met in CANDU reactors. The requirements are based on operational and laboratory experience. After the onset of leakage in a fuel channel from a delayed hydride crack, time is available to the operator to take action before the crack grows to an unstable length. The time available is calculated using different models which use crack growth data from small specimen tests. When the results from crack growth behaviour experiments, carried out on components removed from reactor are used in the model, the time available for operator response is about 100 hours.

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Résumé

L'exposé décrit comment les réacteurs CANDU répondent aux prescriptions des fuites avant rupture. Ces prescriptions sont fondées sur l'expérience d'exploitation et de laboratoire. Après le début des fuites dans un canal de combustible, lesquelles sont causées par une fissuration différée, l'opérateur a le temps d'intervenir avant qua la fissure n'atteigne une longueur instable. Le temps dont il dispose est calculé à l'aide de divers modèles utilisant des données sur la propagation des fissures dans de petites éprouvettes. Lorsque les résultats des expériences sur la tenue à la propagation des fissures, réalisées sur les composants retirés du réacteur, sont utilisés dans le modèle, le temps dont disposent les opérateurs pour intervenir est d'environ 100 heures.

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ABSTRACT

The paper describes how the requirements for Leak-Before-Break are met in CANDU reactors. The requirements are based on operational and laboratory experience. After the onset of leakage in a fuel channel from a delayed hydride crack, time is available to the operator to take action before the crack grows to an unstable length. The time available is calculated using different models which use crack growth data from small specimen tests. When the results from crack growth behaviour experiments, carried out on components removed from reactor are used in the model, the time available for operator response is about 100 hours.

INTRODUCTION

If a crack develops in a pressure vessel, penetrates the vessel wall, is detected and located by fluid leakage and action is taken before the crack becomes unstable, then Leak-Before-Break has been achieved. The key elements are the ability to detect the fluid and the time available to take action relative to the time taken to detect the leak. This paper will concentrate on the time available and show how the principles apply to the pressure tubes of the CANDU reactor.

THE CANDU REACTOR

Figure 1 depicts the main features of a CANDU reactor. A large tank (calandria) containing D_2O moderator at 70°C is penetrated by about 400 horizontal fuel channels. Each channel consists of a pressure tube of length 6m, containing the natural uranium fuel and heat transport D_2O at a pressure of 10MPa and at a temperature ranging from 250 to 300°C, surrounded, and insulated from the cold moderator, by a calandria tube (Figure 2). The space between the pressure tube and the calandria tube is filled with gas and is described as the gas annulus. The pressure tubes are made from cold worked Zr-2.5Nb, with a wall thickness of 4.2mm and inside diameter of 103mm, and the calandria tubes are made from annealed Zircaloy-2, with a wall thickness of 1.4mm and inside diameter of 129mm.

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The annulus gas system has been developed into a system sensitive to the presence of any moisture resulting from a breach of the primary heat transport pressure boundary that passes through the reactor core (and also leakage from the surrounding calandria and lattice tubes, although this type of leakage has not been significant).

The annulus gas system is a closed loop, with header and intermediate tubing connections, that ensures as uniform a flow as possible through each annulus. In recent reactors up to 11 annuli may be connected in series between sets of headers. In early reactors a parallel rather than a series connection limited the number of annuli to two in a series between headers.

Compressors recirculate CO_2 (or N_2) through the system which is operated at a pressure of 70 kPa(g) and a dewpoint range of -30°C to -18°C. The system is instrumented outside containment with dewpoint indicators, "beetles" (moisture detectors), sight glasses, and cold finger moisture traps (see Fig. 3). Testing and analysis of the system show the system dewpoint is sensitive to small ingresses of moisture. The response is a function of leak rate, leak location, initial system dewpoint and CO_2 flow rate. Beetle alarms indicate liquid water collection, and have a slower response than the dewpoint indicators. Cold finger traps are used to obtain samples of moisture to establish the source of the heavy water (water from the moderator contains more tritium than the primary heat transport water - thus they can be distinguished).

The pressure tubes are attached to end fittings at each end of the channel. The end fittings contain connections to the heat transport system and closures to enable fuelling to be done on power. The connection of the pressure tubes to the end fittings is a rolled joint. The rolled joint fabrication produces residual stresses in the pressure tube due to the wall thinning and tube expansion. In early power reactors an incorrect rolling procedure produced excessive tensile residual stresses in the pressure tube (Fig. 4). These stresses, particularly the hoop tensile, had a high value over a length of 10mm on the inside surface just inboard of the burnish mark representing the inboard limit of roll penetration. The high tensile hoop stress was the cause of crack initiation that led eventually to detectable leakage of the primary heat transport water into the channel annulus. A modified installation procedure has eliminated the high stresses in current reactors.

EXPERIENCE OF LEAK-BEFORE-BREAK

There have been 24 instances of pressure tubes that have leaked from rolled joint cracks and that were taken to a cold shut down condition without the crack becoming unstable. The leaking pressure tubes were readily removed, and replaced, and the reactor returned to full power. The examination of these cracks has shown that they were always associated with the maximum value of the tensile hoop residual stress.

The leaks were detected when the dewpoint in the annulus increased and were confirmed by the water indicators. The experience with the 24 pressure tubes has shown that Leak-Before-Break is a valid defence against unstable pressure tube fracture from this mode of cracking.

Examination of the pressure tubes after removal from reactor has shown that the crack initiation and growth occurred by delayed hydride cracking.

DELAYED HYDRIDE CRACKING

Delayed hydride cracking (DHC) requires hydrogen to diffuse up a stress gradient and accumulate at a stress concentration where hydrides precipitate. If the stress is large enough the hydrides crack. This sequence is then repeated and the crack progresses in a series of steps.

Clearly at some rolled joints in early reactors the residual stresses had been high enough for DHC. The mechanism and its characteristics are discussed in detail elsewhere (1); the principal features of the crack are shown in Figure 5.

For Leak-Before-Break the controlling characteristic of a propagating delayed hydride crack is its velocity V that has a temperature dependence described by an equation of the form shown in Figure 6:

$$V = A \exp{-B/T} \qquad \underline{\qquad\qquad} (1)$$

where A and B are constants
T is the Absolute Temperature

TIME AVAILABLE FOR ACTION

To assure Leak-Before-Break in pressure tubes it is required that:

- the crack length at wall penetration is less than the critical crack length (CCL) for unstable propagation.
- the leak is detected
- action is taken before the crack length exceeds the CCL.
- the leaking channel is identified under stable conditions

The important question that the reactor operators need answering is "How much time is available to detect the leak and to take action before the crack becomes unstable?"

The time available can be estimated using the simple model shown in Figure 7, which represents the fracture face. The tube wall thickness is W, the crack length at leakage is L and the CCL is C, assuming C>L. In cold-worked Zr-2.5Nb pressure tubes, cracks tend to grow about twice as fast axially as radially and if the crack is initiated almost at a point on the inside surface, then L=4W. If the crack continues to grow in both directions axially, the amount of crack growth available in each direction is 0.5(C-4W), and with a crack velocity V the time, t, available to detect the leak from first penetration to the attainment of the CCL is

$$t = \frac{C-4W}{2V} \qquad (2)$$

Thus to estimate t, we need to know C and V and whether the penetration length is 4W. As an example, near the inlet end of a fuel channel at 250° the CCL is 50mm (at the lower 95% confidence interval), the crack velocity for unirradiated material is 1.36 x 10^{-7} m/s (at the upper 95% confidence interval), then from equation (2), t = 35h. This time is clearly adequate for operator action.

In an operating rolled joint, the situation is more complicated. Some factors shorten the allowable action time while others can lengthen it. The former factors are:

- The crack may tunnel and the initial length of the crack at detection may be larger than 4W. For example, in one channel, although the crack penetrated the tube wall at L = 4W, leakage was not detected until L = 7W, Figure 8.

- The crack surface may be coated with a thick oxide that chokes the leak path, reduces the leak rate and makes leakage difficult to detect. For example, oxide coated cracks at two rolled joints were up to 28.5 mm long but together they allowed leakage of only 0.3 kg/h. This is surprisingly small for such long cracks.

- In a leaking crack, a temperature gradient is established in the metal by latent heat loss where the water flashes to steam across the crack face. Thus the temperature of the metal on the outside of the pressure tube is less than that at the inside. Consequences of the temperature gradient may be that more cracking continues towards the outside surface of the tube. The asymmetry of crack growth allows the crack to grow without the leak rate increasing.

- Current estimates of t are based on crack velocities measured on unirradiated material. Some measurements on cracked tubes removed from the reactors and in laboratory experiments suggest that V is slightly higher in irradiated material, while C has a lower value after irradiation.

Some features of the cracking at rolled joints render equation (2) conservative leading to underestimates of the time available:

- after a certain amount of crack growth, the outboard end of the crack is influenced by the compressive stress at the rolled joint and the crack growth slows down and may eventually stop. An example is seen in Figure 8, where the amount of crack growth in the later stages is much smaller at the outboard end than at the inboard end of the cracks. Once the crack is stopped at the rolled joint, it becomes single-ended and equation (2) requires modification to:

$$t = \frac{2C-4W-C_R}{2V} \quad \text{———————} (3)$$

- where C_R = length of crack when stopped at the rolled joint, as shown in Figure 9.

- delayed hydride crack velocities measured on irradiated pressure tubes removed from power reactors are lower when coolant is leaking through the crack than the results of small specimen tests would predict (Figure 6).

- although the residual stresses will be redistributed as the crack grows, their influence will decrease until at some point they are ineffective for driving the crack. Thus, if the fuel channels are depressurized, the crack will not grow.

- at a rolled joint the pressure tube picks up more hydrogen than in the body of the tube. The hydrogen concentration thus decreases from under the end fitting into the main body of the tube. A crack growing inboard in this hydrogen concentration gradient will stop when hydrides, required for DHC, are no longer present at the operating temperature. This was demonstrated in a laboratory experiment using a rolled joint from a power reactor.

- the cracks may branch as they grow. The crack is effectively blunted, which may slow it down but, more important, it may become more stable, so that the CCL is increased. The stress intensity factor is expected to be reduced by about $1/\sqrt{n}$ where n is the number of branches. Branching was observed in laboratory experiments and there was a suggestion of branching in the crack in one leaking tube.

In summary conservative calculations of the action time may be different from the 35 hours derived earlier. Using crack velocities twice that of unirradiated material, a crack length at leak detection of 7 times the wall thickness, and a value of C_R = 22mm, a time of 25h is obtained from equation (3). This appears to be an acceptable action time, but has now to be compared with the detection time.

LEAK RATES

Experiments have been carried out in the laboratory using rolled joints removed from power reactors containing throughwall cracks in the high stress region of the pressure tubes. These cracks, stressed by hot pressurized water, grew by delayed hydride cracking. The fluid leak rates through the cracks were measured under different conditions.

The following trends can be discerned:

a) at low pressure the leak rates appear to decrease with time probably because of clogging by debris

b) at higher pressures, similar to operating pressure the leak rate appears to increase slowly, probably because the crack is extending sufficiently to compensate for the clogging.

c) crack velocities measured on irradiated pressure tubes removed from reactor are lower when coolant is leaking than if the coolant is prevented from leaking (Figure 6); under these conditions the temperatures used for the comparison are the coolant temperatures. A direct consequence of the lower velocities is that the action time has been shown to be over 100 hours.

d) tests show that for a crack length greater than a threshold value, the leak rate has a rapid rise with increases in crack length. However, this threshold value is variable from tube to tube. Thus it is necessary in any analysis to use the maximum threshold value. For crack lengths greater than 7W the leak rate is always a strong function of crack length, (Figure 10).

In summary the leak rate experiments are showing that the action time is large and that cracks will develop a large leak rate at some length well below the CCL.

MOISTURE DETECTION

The dewpoint of a CO_2 system will show a normal rate of increase due to the production of moisture from the reactions

$$CO_2 + D_2 \longrightarrow D_2O + CO$$

$$\text{or } O_2 + 2D_2 \longrightarrow 2D_2O$$

The deuterium originates in the primary heat transport system and enters the gas annulus by diffusion through the end fittings. To remove this deuterium and water from the annulus, and to lower the dewpoint, the system is periodically purged. The rate of dewpoint increase after purging is characteristic of each system and of the dewpoint to which it is purged. Any increases in this rate trigger an operator response. The dewpoint of the system is sensitive to the presence of small quantities of moisture and leaks of the order of a few grams per hour cause an increase above the normal rate of dewpoint increase.

By contrast the beetle response, which indicates the presence of liquid water, is relatively slow except for very large leak rates (> 1kg/h). The difference in time between the dewpoint response and the beetle alarm is however an indication of the size of the leak.

OPERATOR ACTION

Typically the sequence of events that is followed when a leak occurs is outlined in Table 1. Experimental data shown in Figures 6 and 10 have been used to calculate the crack length increase and the leak rates at different times after crack penetration. These leak rates and the operator response to them give a margin of 1 day before a leak reaches critical size.

OTHER METHODS OF ANALYSIS

In the preceding sections the approach to Leak-Before-Break analysis has been deterministic. That is, the worst combination of parameters has been used to determine the minimum operator action time. To date this approach is giving satisfactory predictions for station use. However, we believe that the circumstances leading to an adverse combination of controlling parameters is a very low probability occurrence. There is no obvious reason why a relationship between properties such as DHC velocity, CCL and crack length at penetration should exist. Thus the analysis of action time may be amenable to a probabilistic approach. Current work is directed along these lines with preliminary work aimed at finding the distribution functions for the main variables.

CONCLUSION

Leak-before-break is an established methodology for pressure tube failure in CANDU reactors and is incorporated into the operating procedures for power reactors. It has demonstrated its effectiveness a number of times and improvements in detection methods, system operation and understanding promise to make it an even more effective tool in the future.

ACKNOWLEDGEMENTS

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REFERENCES

1. Delayed Hydride Cracking in Zr-2.5%Nb Alloy; C.E. Coleman and J.F.R. Ambler; Reviews of Coatings and Corrosion Vol. 3, 1979, pp105-157.

2. An Overview of the Development of Leak Detection Monitoring for Ontario Hydro Nuclear Stations; J.M. Kenchington, P.J. Ellis, D.G. Meranda. Proceedings 8th Annual Conference, Canadian Nuclear Society, 1987.

TABLE 1

EVENTS FOLLOWING THE START OF A PRESSURE TUBE LEAK

Time Since Penetration Hours	Calculated Leak Rate* kg/hr	Dew Point	Beetle Alarm	Events
0	0	--	--	Crack Penetration
.5	<1	rising	--	
1	~1	rising	--	
1.5	>1	alarm	--	Alarm confirmed
5	~6	alarm	--	
6	<10	alarm	alarm	
7	~10	alarm	alarm	Reactor shutdown by operator Reactor cooldown
8-10		alarm	alarm	Reactor cold depressurized

*Based on Figures 6 and 10

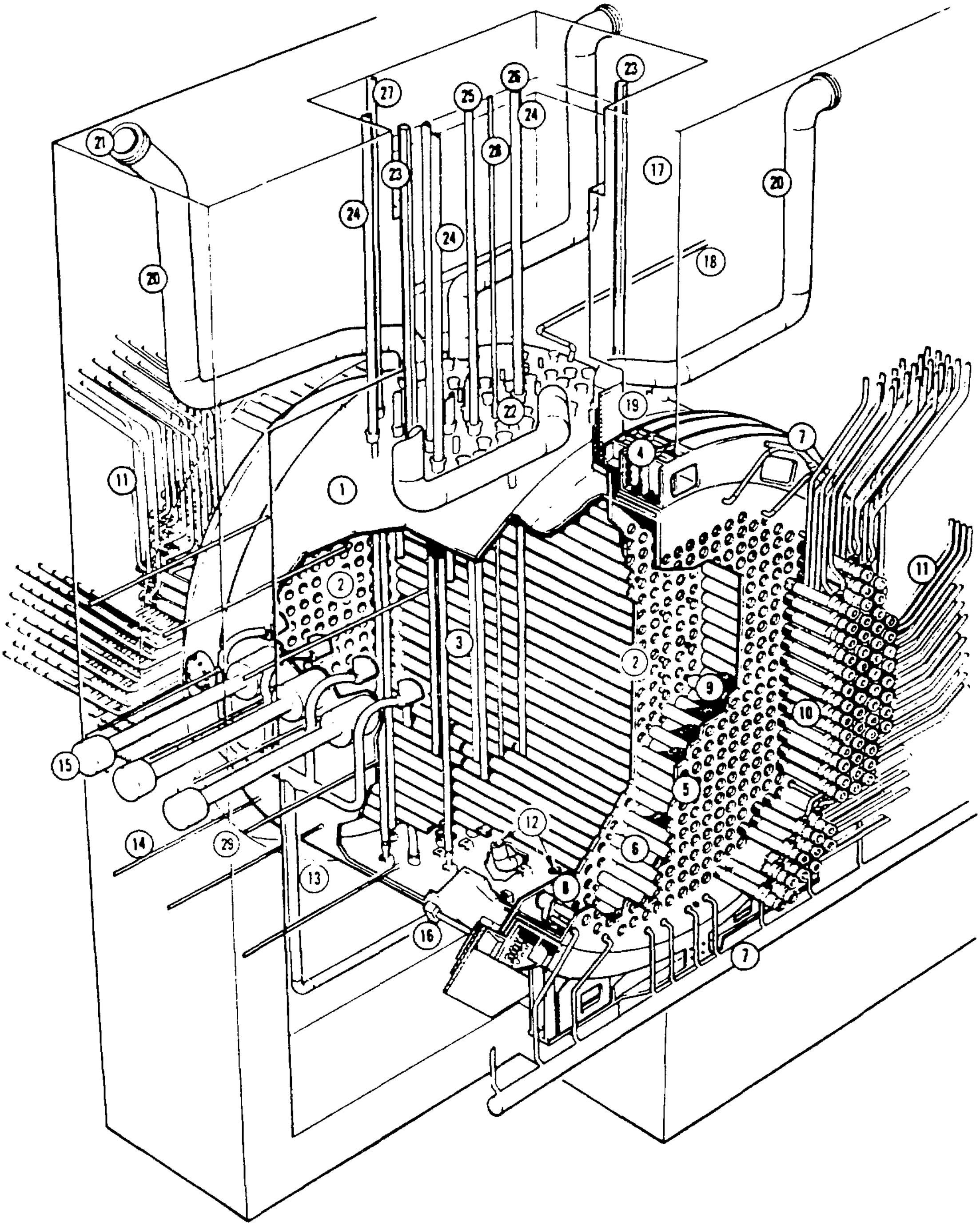


Figure 1 CANDU 600 MW reactor

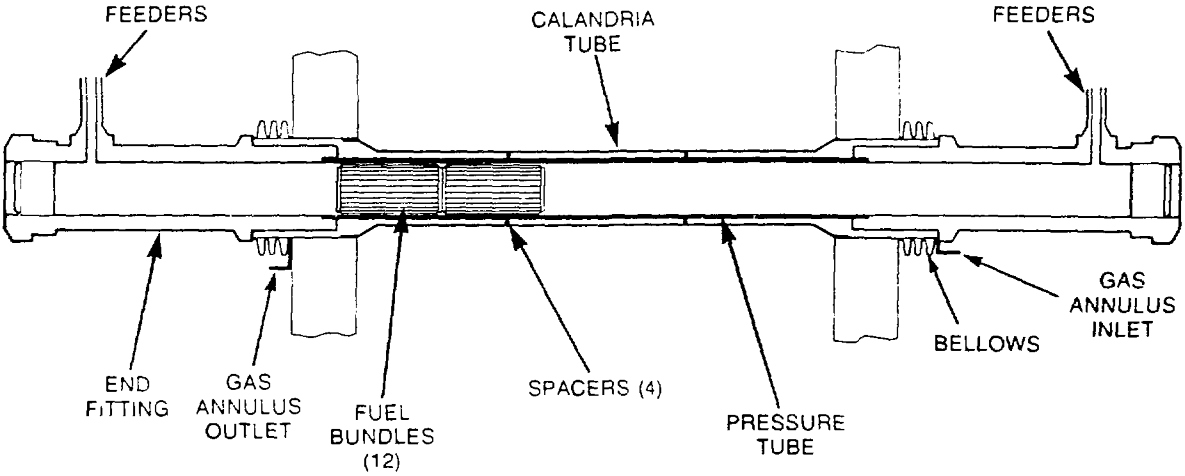


Figure 2 Simplified description of a Fuel Channel - Each fuel channel consists of a zirconium alloy pressure tube, sealed at each end with end fittings that have side port connections to the heat transport system. The gap, or annulus, between the pressure tube and the surrounding Zircaloy-2 calandria tube is filled with an insulating gas and contains four close-coiled helical spring spacers that provide physical separation between the two tubes and partial support for the pressure tube. The annulus is sealed at each end by bellows that accommodate relative axial movement between the fuel channel and the reactor end shields.

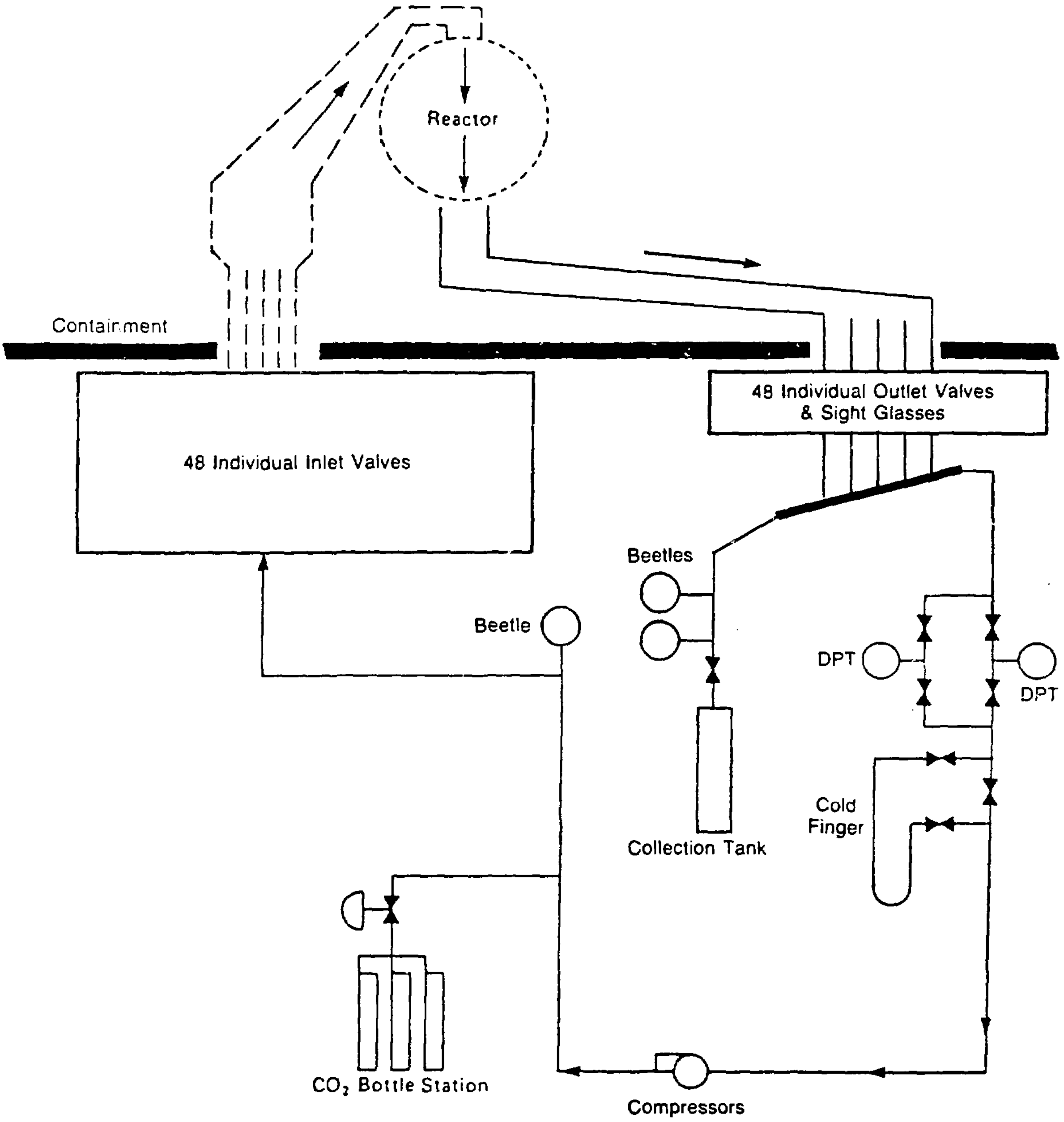


Figure 3 **Schematic diagram of gas flow in current Annulus Gas Systems**

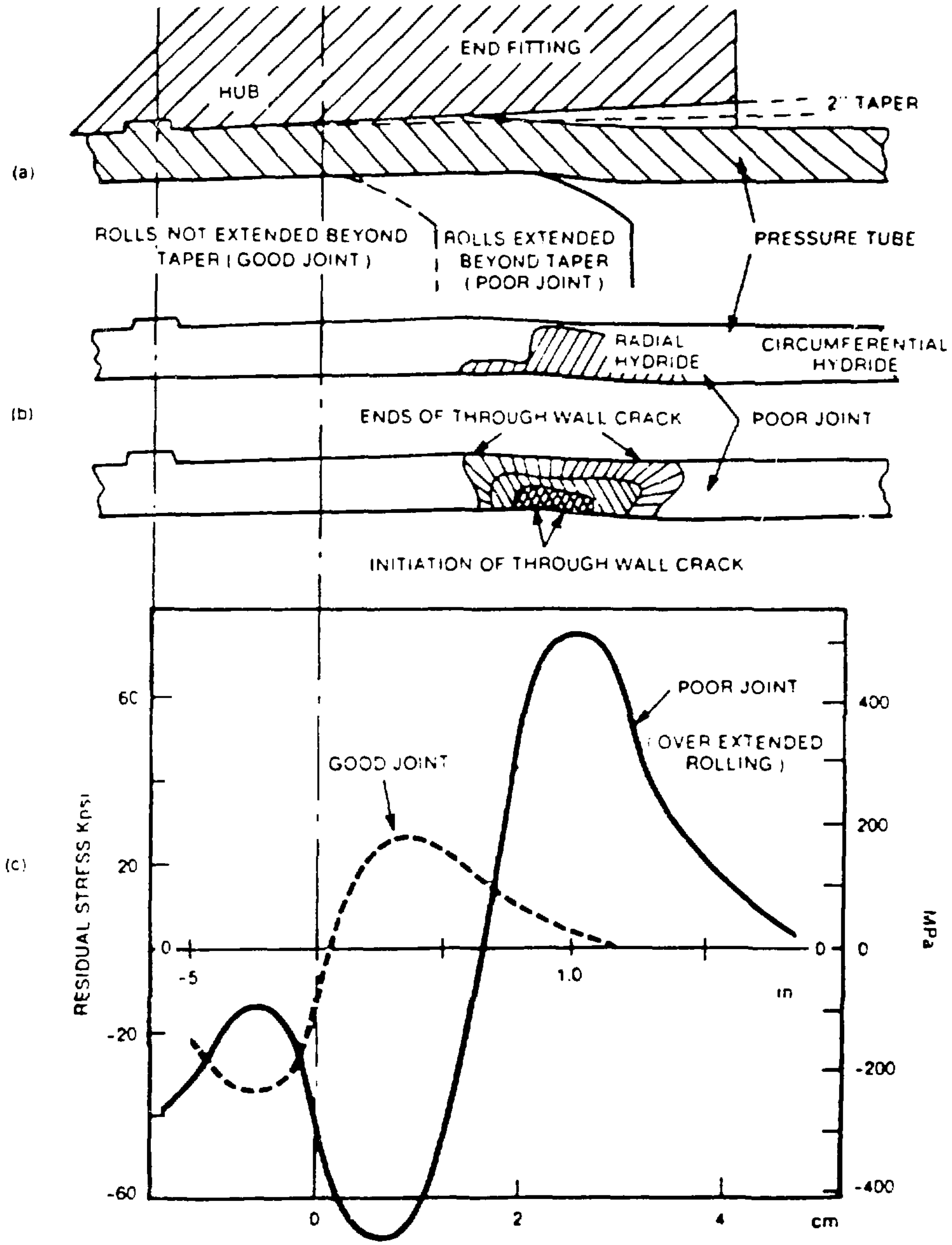


Figure 4 Effect of roll extension on residual hoop stresses in pressure tube

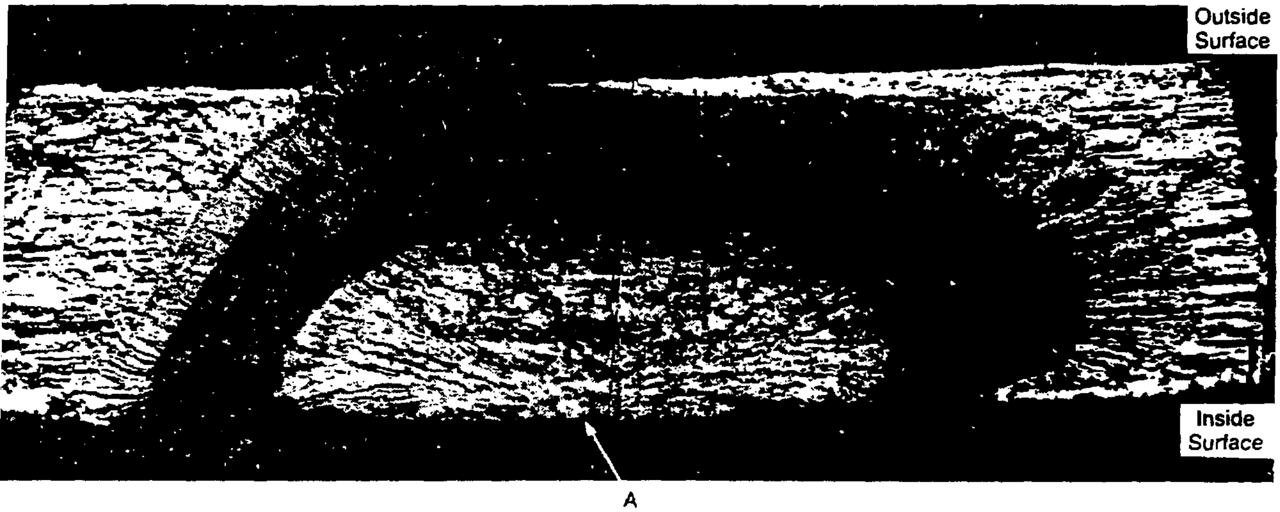


Figure 5 Composite macrograph showing the crack face in a leaking Zr-2.5 Nb pressure tube removed from Pickering. The crack nucleated at the inside surface at A and grew by delayed hydride cracking in the radial and axial directions. The different lines represent positions at which the crack had stopped. The wall thickness was 4 mm.

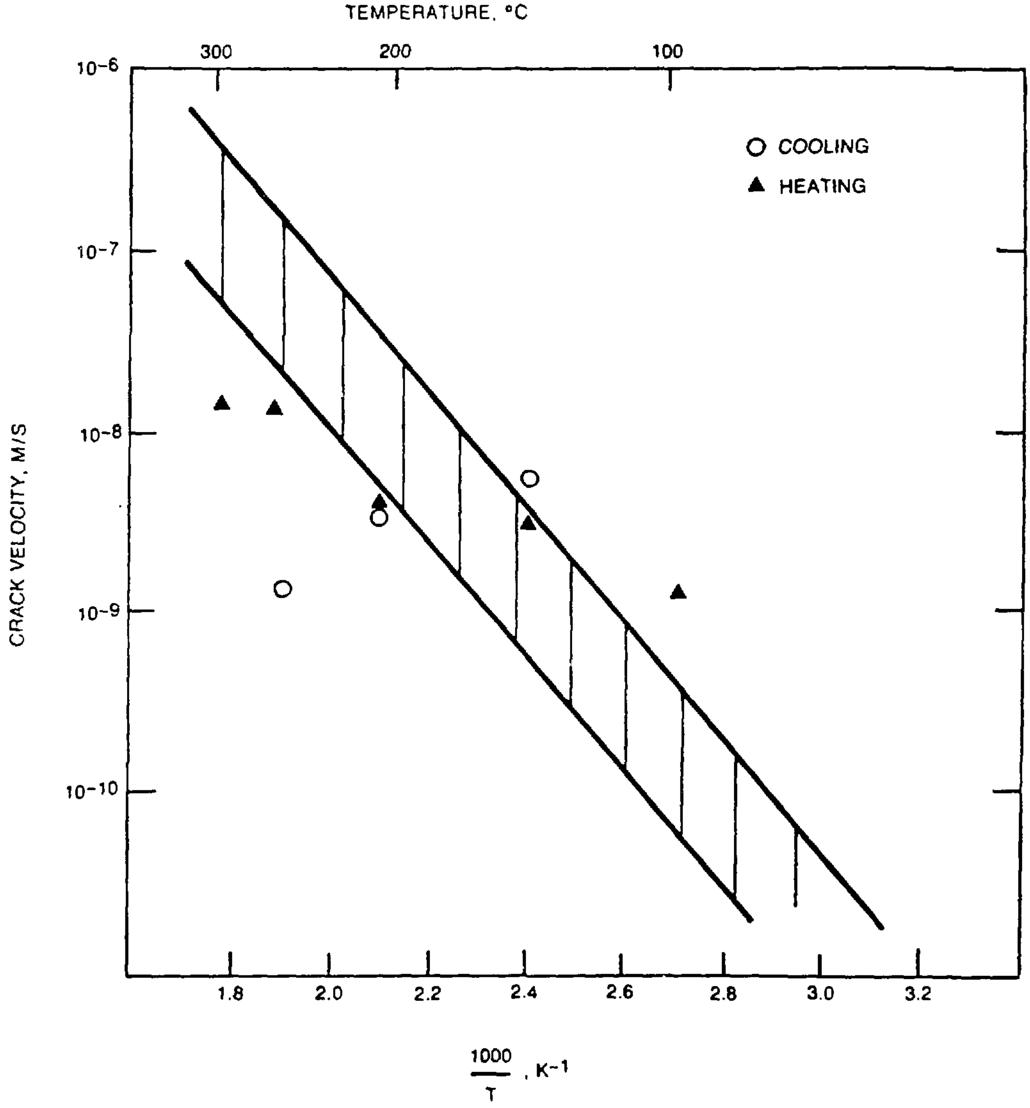


Figure 6 Graph showing the dependence of delayed hydride cracking velocity on temperature for Zr-2.5Nb. The band includes the scatter observed in tests carried out on small specimens. The other data were measured in tests on a leaking crack in a pressure tube during heating and cooling cycles when the crack length was 25-50 mm.

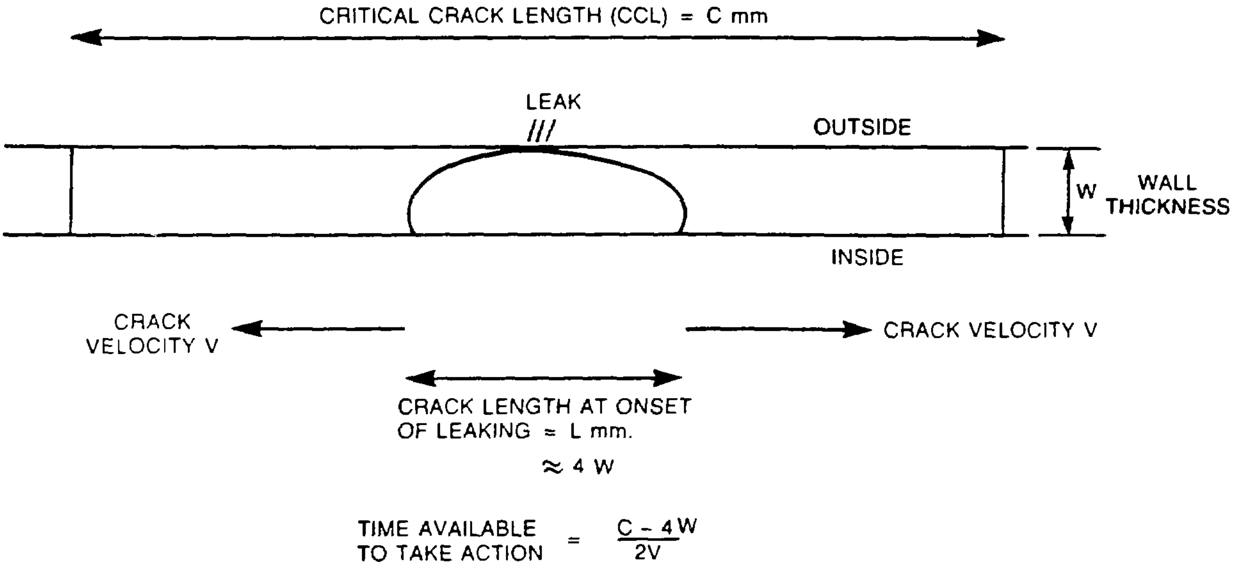


Figure 7 Schematic diagram to show crack dimensions at onset of leakage.

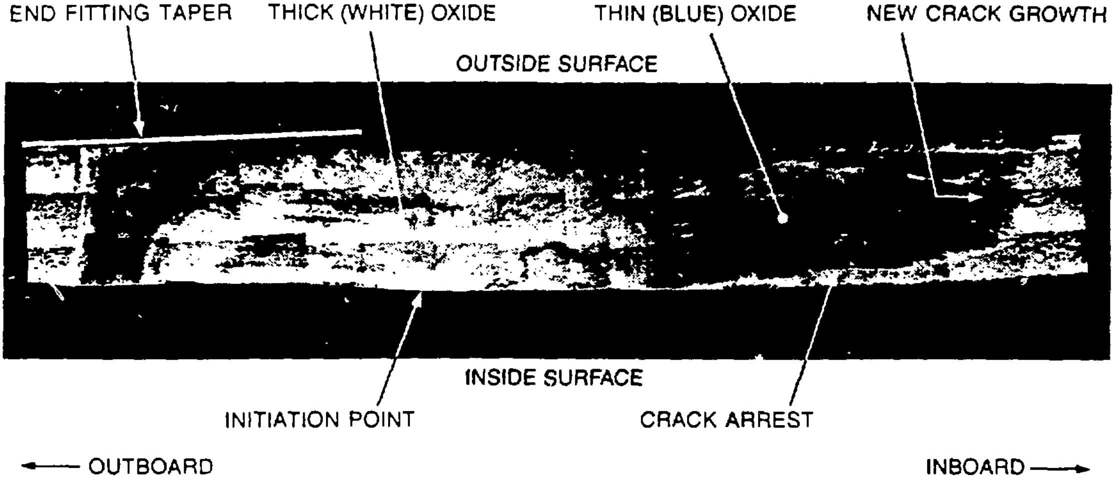
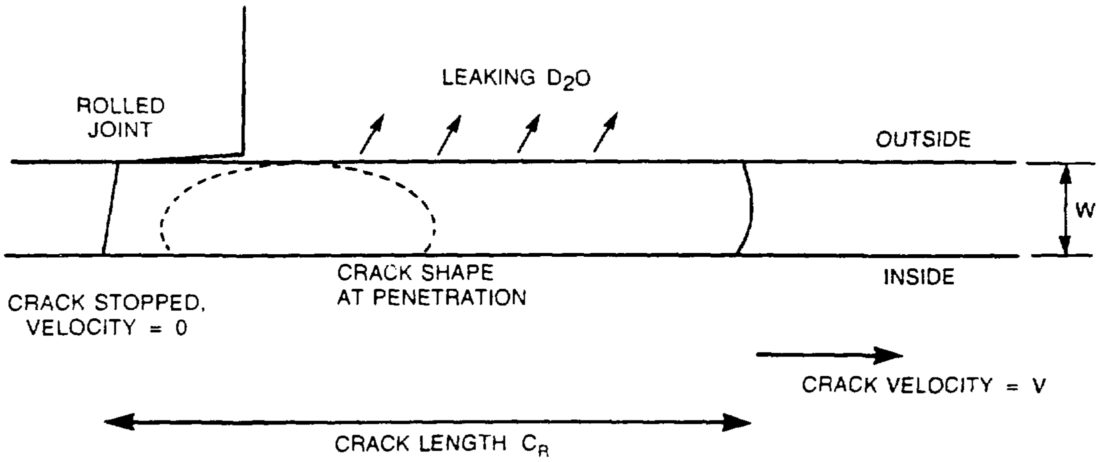


Figure 8 Detail of crack face in a pressure tube that leaked in reactor. The initiation point and the crack shape at different times can be seen. The difference in growth rates inboard and outboard is caused by the compressive residual stresses in the rolled joint. Wall thickness = 4 mm.



$$\text{TIME AVAILABLE TO TAKE ACTION} = \frac{2C - 4W - C_R}{2V}$$

Figure 9 Schematic diagram to show crack dimensions when crack growth in outboard direction is stopped by the end fitting.

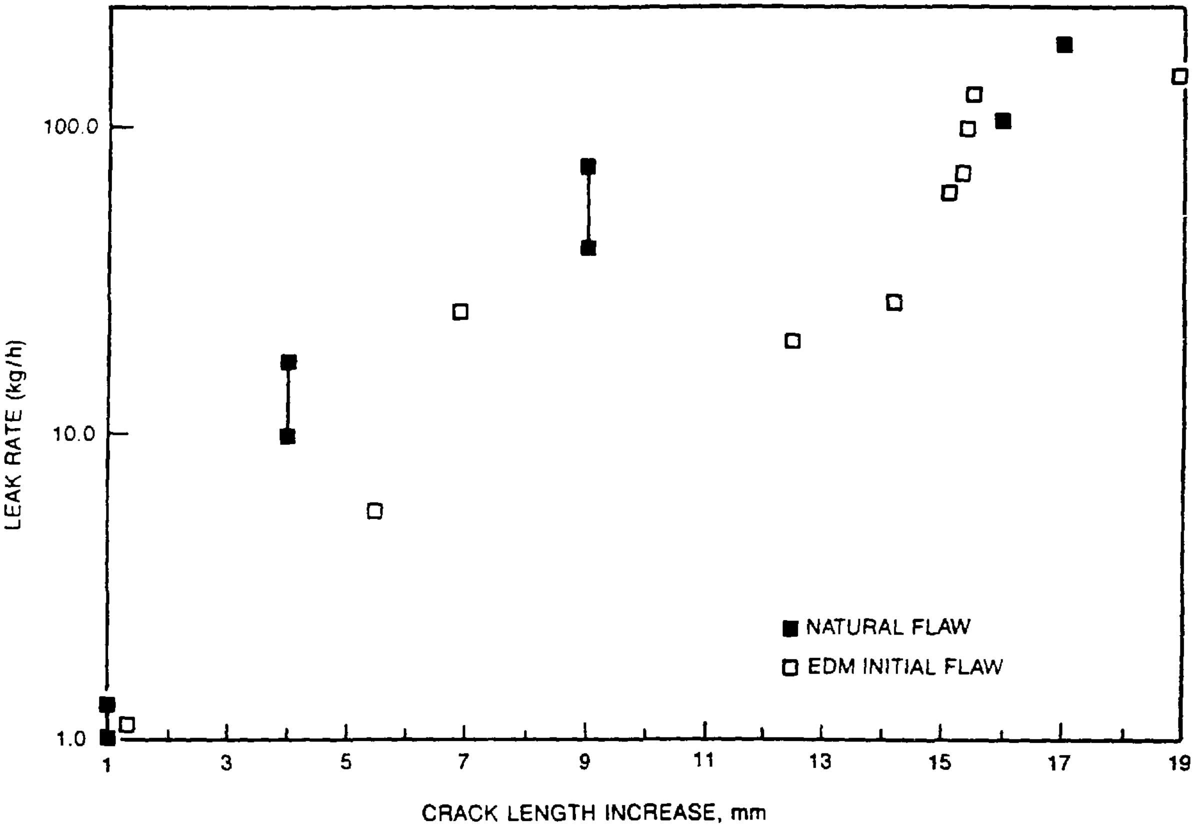


Figure 10 Graph showing the effect of crack length increase on the water leak rate measured from cracks in pressure tubes in laboratory tests after the pressure tubes were removed from reactor. Tests at 220-280°C

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