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The Effect of Pressure Tube Creep Rates on Linear Dryout Power of CANFLEX-NU Bundle

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ABSTRACT

The freon CHF tests of CANFLEX-NU bundles in the three kinds of 0 %, 3.1 % and 5.1 % of uniform crept pressure tubes were performed at MR-3a Loop in AECL-CRL. Those CHF data were investigated with respect to the pressure tube creep rate. The LDP (Linear Dryout Power) of CANFLEX-NU bundles in the crept pressure tube was compared to that in the uncrept pressure tube.

The LDP correlations of CANFLEX-NU bundle were derived based on inlet flow conditions, and then the LDPs of the bundles in 3.1 % and 5.1 % crept pressure tubes were compared with those in uncrept pressure tube. The LDP ratio is defined by the ratio of the LDP in crept pressure tube to that in uncrept pressure tube. The LDP ratios were discussed with respect to the pressure tube creep rates, and the effect of flow conditions on LDP ratios were presented. It was found that LDP of CANFLEX-NU bundle decreases with increases of pressure tube creep rate due to the different by-pass flow area in the one side of pressure tube. And the effects of pressure tube creep rate on LDP depend on the flow conditions.

1. INTRODUCTION

CANDU reactors have a lot of pressure tubes in Calandria tube so as to carry out on-power refueling. The pressure tube is 10.3 cm diameter and its life time was designed about 30 years. During the reactor operation, it is irradiated and developed to the expansion by thermal and irradiation creep.

Nowaday, CANDU reactor has been seriously considered the reactor aging problems such as pressure tube creep and steam generator degrading because those problems make lower power operation of the reactor and so the capacity factor of reactor operation degrade. Hence, re-analyses of ROPT (Regional Overpower Protection Trip Set-point) system for several CANDU reactors aged have been performed[1,2]. In order to calculate ROP trip set-point, the effect of pressure tube creep rate or degraded steam generator on CHF or Critical Channel Power(CCP) should be known. There may be two methods to overcome the lowering power by pressure tube creep. One thing is to change the aged pressure tubes with new ones, the other thing is to change the present bundle with high performance of new fuel bundle. By the economics study in consideration of changing the aged pressure tube and usage of new developed fuel bundle, that is, CANFLEX-NU bundle, usage of CANFLEX-NU bundles is more effective and economic than the pressure tube replacement[3]. Recently, it results in the demonstration irradiation of CANFLEX-NU bundles in Point Lepreau reactor in Canada[3].

A CANFLEX (CANdu FLEXible fuelling) 43-element bundle has been developed for a CANDU-6 reactor as an alternative of 37-element fuel bundle. CANFLEX bundle has two diameter elements to reduce maximum element power rating and to enhance the Critical Heat Flux (CHF) with buttons attached on the surfaces of rods, compared to the standard 37-element bundle. Using the CANFLEX-NU bundle is very useful to overcome the aged problems of reactor because the minimum CCP enhancement is over 6 % compared to reference 37-element bundle[4].

Generally, CHF is decreasing as increasing creep rates of pressure tube. And it is very important to understand the effect of pressure tube creep rate on CHF to keep the effective reactor operation or reactor safety.

The freon CHF experiments with simulated CANFLEX-NU bundles have been performed in the three kinds of 0 %, 3.1 % and 5.1 % crept pressure tube, loaded with simulated CANFLEX-NU bundles. The axial heat flux of a simulated CANFLEX-NU bundle is uniform and the modeling fluid is freon-134a. The LDP or CHF were investigated from the CHF experimental data of CANFLEX-NU bundle according to the pressure tube creep rates to show how much CHF would be deteriorated, comparing to the case of uncrept pressure tube. And the LDP's were compared in terms of various flow conditions.

2. CHF EXPERIMENTS

The freon-134a CHF experiments for the CANFLEX-NU bundle have performed in MR-3a Test Loop at AECL(Atomic Energy Canada Limited)-CRL (Chalk-River Laboratory). The CANFLEX bundle has two sized diameters, 11.5 mm for outer 35 rods and 13.5 mm for inner 8 rods and axial two button planes which are different from 37-element bundle in order to enhance CHF. Its cross-sectional view is shown in Figure 1. The heating rods were made of Inconel-718, and have uniform axial heat flux profile in the bundle string, but non-uniform radial heat flux profile of a CANFLEX-NU bundle as shown in Figure 2.

The coolant is non-toxic freon-134a as a modeling fluid and flows upward. The bundle was eccentrically mounted by lift spring in a vertical flow tube to simulate the horizontal flow geometry of a CANDU reactor. The simulated fuel bundle has the heating rods and appendages such as fuel rods, spacers, bearing-pads, buttons and end-plates. The simulated fuel bundle was installed in the three kinds of 0 %, 3.1 % and 5.1 %, uniform crept pressure tubes.

The insides of all heating rods allowed the special thermocouples to move and rotate so as to check the inner temperatures of heating rods when CHF is occurring. During the CHF tests, the pressure drops were measured at six pressure tap locations as shown in Figure 3.

In order to evaluate the pressure tube creep effect on LDP and CHF of the CANFLEX fuel bundle, three sets of CHF experimental data were considered as followings :

- LDP Data for uncrept pressure tube with CANFLEX bundle
- LDP Data for 3.1 % crept pressure tube with CANFLEX bundle
- LDP Data for 5.1 % crept pressure tube with CANFLEX bundle

The number of data for CANFLEX-NU bundles in the 0 %, 3.1 % and 5.1 % crept pressure tubes are 82 points, 38 points and 57 points, respectively.

3. Results and Discussion

3.1 CHF of CANFLEX-NU Bundle with Uncrept and Crept Pressure Tubes

In the CHF tests, most of initial CHF were occurred at the end of fuel channel because of the uniform axial heat flux condition. But, several initial CHF data were found at the upstream of fuel channel end in the case of 5.1 % crept pressure tube. Hence, the repeat CHF runs were carried out at several times to check and confirm the CHF value and its axial location.

In CANDU fuel channel, the high crept pressure tube allows a by-pass flow on the larger flow area of one side of pressure tube due to the bundle eccentricity. The larger by-pass flow area by the bundle eccentricity makes more liquid or vapor flow, especially in the high crept pressure tube. And, it may result in highly enthalpy or flow imbalance under some flow conditions due to wider by-pass flow area. But it can be explained if CHF type and pattern of drypatches are known as subchannel-wise. In the present evaluation of the LDP, initial CHF or minimum CHF data among the repeat CHF runs only were selected.

Generally, the subchannels near the contacted area between the pressure tube and the bundle have higher enthalpy region than the other side because of narrow flow area due to the bundle eccentricity. Higher enthalpy subchannel carries more vapor due to void drift while the other region carries larger amount liquid preferably clinged to lower heated surface[5]. It makes great enthalpy imbalance among the subchannels of high crept pressure tube. Therefore, dryout of higher crept pressure tube finally occurs earlier than lower crept pressure tube.

On the meanwhile, most of CHF preferably occur on rod number 1, 2 and 20 faced to the subchannel center adjacent to unheated pressure tube as shown in Figure 3 because those regions are usually the hottest among the subchannels.

3.2 Linear Dryout Power Correlations

The LDP of CANFLEX-NU bundle in the uncrept pressure tube is used as the reference data for the comparison with the LDP for CANFLEX-NU bundle in the 3.1 % and 5.1 % crept pressure tubes. In order to compare the experimental LDPs of three kinds of crept pressure tubes, the correlations for the LDP data obtained in the crept pressure tubes should be derived because the flow conditions for each CHF test in the crept tubes could not be exactly the same as those in the uncrept tube. Hence, the LDP correlations for CANFLEX-NU bundles in the crept pressure tubes are derived using SYSTAT ver. 8.0 application program.

The LDP correlations based on inlet flow conditions are considered, and then basic formula for constant inlet condition are presented,

$$LDP = A + B \cdot \left(\Delta h_{in}\right) \tag{1}$$

where $A = a \cdot P^b \dot{m}^c, B = d \cdot P^e \dot{m}^f$, $\dot{m}$ is flow rate in kg/s instead of mass flux. And a, b, c, d, e, f are the coefficients for the best fitted equation (1) with CHF data. Δh_{in} is inlet subcooling in kJ/kg and P is pressure in MPa. Especially, some CHF tests were carried out at the low flow rate and low pressure on the purpose of the safety point view. Then mass flow less than 9 kg/s and pressure less than 1.0 MPa under freon-134a flow conditions were not considered in the present study.

The prediction error of the best-fitted equations (1) for CANFLEX-NU bundle are listed in the followings.

Table. Prediction Errors of Best Fitted Correlations of CANFLEX-NU Bundle in the Uncrept, 3.1 % Crept and 5.1 % Crept Pressure Tubes

Type of PT Coefficient	Uncrept PT	3.1 % Crept PT	5.1 % Crept PT
Avg.Error	0.000	0.000	0.000
RMS Error	0.008	0.015	0.016
No. of CHF Data Used in Eq(1)	51(82)	37(38)	49(57)

Note: () indicates the number of all CHF data
PT is pressure tube

Figure 4 shows the predicted LDP versus measured LDP for the tests in the uncrept pressure tube. The RMS error is less than 1 % and the averaged errors are amost zeros. The relative errors under the various pressure, inlet subcooling and flow rate are very small and have no bias for all flow conditions. Figure 5 and Figure 6 show the comparison of measured LDP with predicted values for the tests in the 3.1 % and 5.1 % crept pressure tube, respectively. The RMS and relative errors for tests in the 3.1 % and 5.1 % crept pressure tubes are very small and have no bias for all flow conditions similar to the uncrept pressure tube case.

3.3 LDP Ratios According to Pressure Tube Creep Rates

The effects of pressure tube creep rates on the LDP depends on flow conditions. In order to investigate the effects of pressure tube creep rates on LDP of CANFLEX-NU bundle, the LDP ratio was defined as following :

$$LDP\ \text{ratio} = \left(\frac{LDP_{\text{i\%crept}}}{LDP_{\text{0\%crept}}}\right)$$

where, $LDP_{\text{i\%crept}}$ is for tests in the 3.1 % and 5.1 % crept pressure tubes and $LDP_{\text{0\%crept}}$ is for tests in the uncrept pressure tube as a reference. To calculate the LDP ratio for each crept pressure tube, LDP correlations derived in previous section were used.

The LDP ratios for each flow conditions and each crept pressure tube were calculated and presented in Figure 7 to Figure 15. As shown in these figures, LDP's are decreasing with increasing of the creep rate of pressure tube. This trend is the same as water CHF test results[6]. And also, the LDP ratio decreases linearly with increasing of the creep rate of pressure tube. The LDP ratios of the tests in 3.1 % crept pressure tube is ranged over 75 % to 80 % compared to those in the uncrept pressure tube, while ranging over 60 % to 65 % in the case of 5.1 % crept pressure tube.

The LDP ratio for the flow rate of 12 kg/s and the inlet subcooling of 12 kJ/kg decreases as pressure increases as shown in Figure 7. The decreasing rate as increasing pressure is not significant as increasing flow rates from 12 kg/s to 18 kg/s as shown in Figure 8 to Figure 9.

On the other hand, the LDP ratios for the inlet subcooling of 12 kJ/kg and the pressure of 1.5 MPa increase as flow rate increases as shown in Figure 10. But, the increasing rate of the LDP with increasing the inlet subcooling is reduced as shown in Figure 11 and Figure 12. Especially, LDP ratio as shown in Figure 12 is not changed in the high inlet subcooling conditions even if flow rate changes from 12 kg/s to 18 kg/s. It means that flow rate does not affect on the LDP if the CHF occurs at low quality or at high inlet subcooling condition.

Generally, the higher mass flux agitates subchannel flow and enthalpy distribution in a bundle, the more inter-channel mixing occurs when CHF occurs in high quality condition. But even the high mass flux can not affect significantly the LDP ratios because total liquid amount of flow channel in low quality condition is much more than that of high quality condition.

Figure 13 shows that the LDP ratios are not much changed even though inlet subcooling increases from 12 kJ/kg to 35 kJ/kg under the flow rate of 12 kg/s. But, the LDP ratios are significantly increasing when pressure is increasing from 1.77 MPa to 2.05 MPa as shown in Figure 14 and Figure 15.

As indicated previously, the larger flow area due to the bundle eccentricity and the crept pressure tube makes more liquid or vapor flow, especially in the high crept pressure tube. It may be caused by highly enthalpy or flow imbalance under some flow conditions due to wider by-pass flow area. And also, CHF usually occurs at low quality in high inlet subcooling conditions, or CHF occurs at high quality in low inlet subcooling conditions. Therefore, in the case of low quality CHF or CHF at high inlet subcooling, the other flow conditions does not dominantly affect on the LDP ratios.

4. Conclusion

The freon CHF test data of CANFLEX-NU bundles in the three kinds of 0 %, 3.1 % and 5.1 % crept pressure tubes were investigated. The LDP values of CANFLEX-NU bundle in the 3.1 % and 5.1 % crept pressure tubes were compared to those in the uncrept pressure tube. From the present study, it concluded as followings:

- The CHF of CANFLEX-NU bundle usually occurs on the outer subchannels because of the highest heat flux on the rods of outer ring.
- The higher creep rate of pressure tube gives the lower CHF. It means that the higher creep rate of pressure tube was allowed by-pass flow on the larger flow area of one side of the pressure tube due to the bundle eccentricity.
- Three kinds of LDP correlations for the CHF tests in the 0 %, 3.1 % and 5.1 % crept pressure tubes were derived based on the constant inlet condition. The predictions of these correlations very well agree with the experimental data and have the maximum 1.6 % RMS errors. The relative errors have no bias for all flow conditions.
- The LDP ratios are decreasing linearly as increasing the creep rate of pressure tube. And, those ratios are decreasing when pressure increases. But, these effect of pressure on the LDP ratios are diminished as inlet subcooling increases. Especially, in low subcooling conditions, the effect of

mass flux on LDP ratios is dominant and the LDP ratios are increasing as mass flux increasing. But the increasing rate of the LDP ratio with mass flux increase is not significant under the high inlet subcooling conditions.

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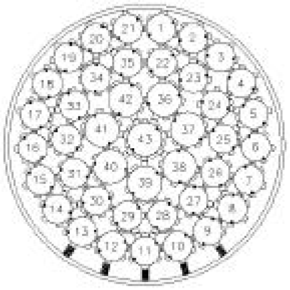

Fig. 1. Cross-Sectional View of CANFLEX Bundle

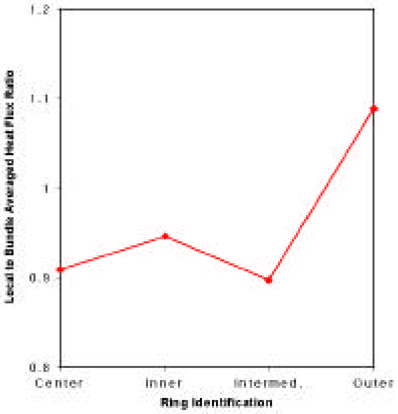

Fig. 2 Ring Heat Flux Profile of CANFLEX-NU bundle CHF Test

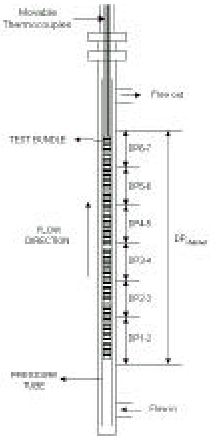

Fig. 3 Schematic Diagram for CHF Test Section

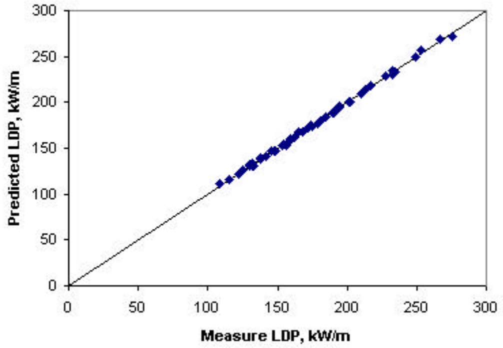

Fig. 4 Comparison of Measured and Predicted LDP of CANFLEX-NU Bundles in Uncrept Pressure Tube

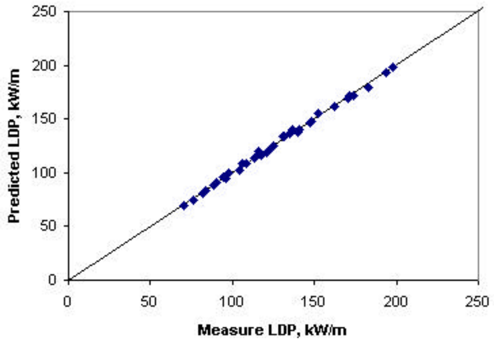

Fig. 5 Comparison of Measured and Predicted LDP of CANFLEX-NU Bundles in 3.1 % Crept Pressure Tube

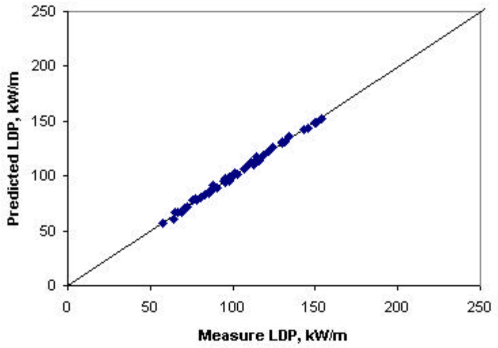

Fig. 6 Comparison of Measured and Predicted LDP of CANFLEX-NU Bundles in 5.1 % Crept Pressure Tube

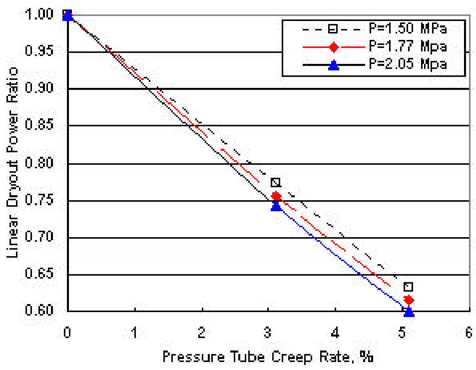

Fig. 7. LDP Ratios as a Function of Pressure Tube Creep Rate ($\dot{m}=12$ kg/s, $\Delta H=12$ kJ/kg)

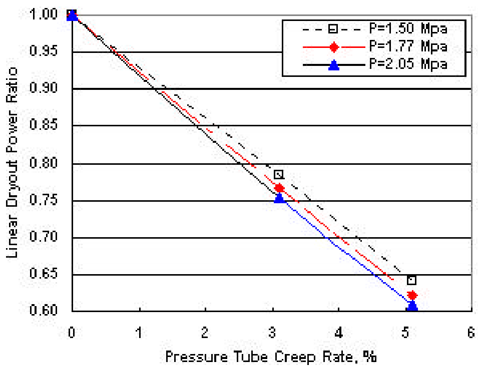

Fig. 8. LDP Ratios as a Function of Pressure Tube Creep Rate ($\dot{m}=16$ kg/s, $\Delta H=12$ kJ/kg)

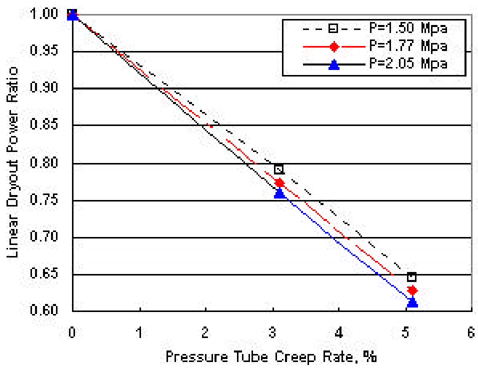

Fig. 9. LDP Ratios as a Function of Pressure Tube Creep Rate ($\dot{m}=18$ kg/s, $\Delta H=12$ kJ/kg)

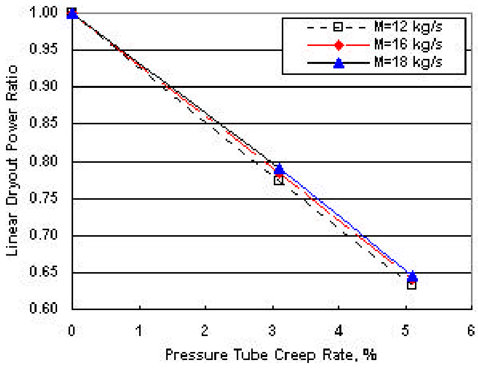

Fig. 10. LDP Ratios as a Function of Pressure Tube Creep Rate ($\Delta H=12$ kJ/kg, P=1.50 MPa)

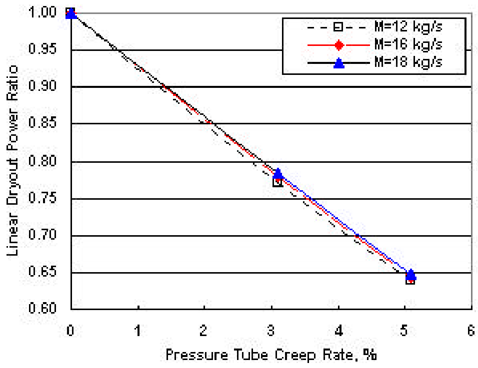

Fig. 11. LDP Ratios as a Function of Pressure Tube Creep Rate ($\Delta H=24$ kJ/kg, P=1.50 MPa)

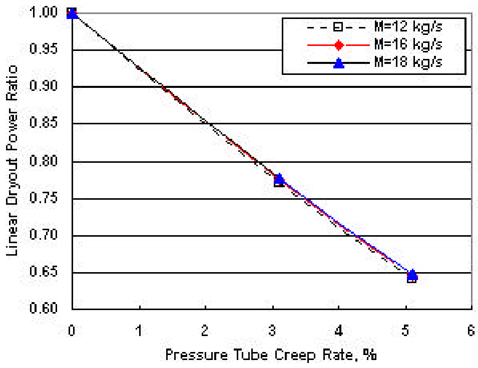

Fig. 12. LDP Ratios as a Function of Pressure Tube Creep Rate ($\Delta H=35$ kJ/kg, P=1.50 MPa)

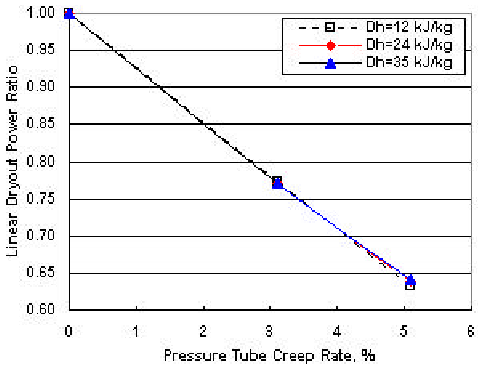

Fig. 13. LDP Ratios as a Function of Pressure Tube Creep Rate ($P=1.50$ MPa, $\dot{m}=12$ kg/s)

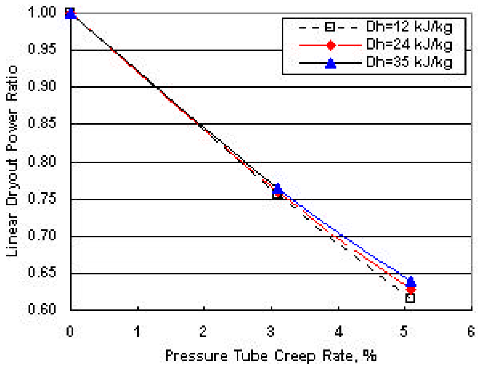

Fig. 14. LDP Ratios as a Function of Pressure Tube Creep Rate ($P=1.77$ MPa, $\dot{m}=12$ kg/s)

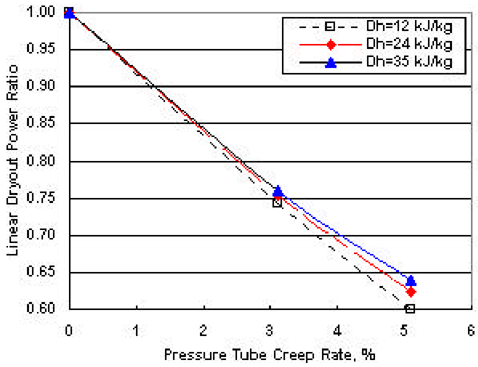

Fig. 15. LDP Ratios as a Function of Pressure Tube Creep Rate ($P=2.05$ MPa, $\dot{m}=12$ kg/s)