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Integrity Evaluation System of CANDU Reactor Pressure Tube

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The pressure tube is a major component of the CANDU reactor, which supports nuclear fuel bundle. In order to complete the integrity evaluation of pressure tube, expert knowledge, iterative calculation procedures and a lot of input data are required. More over, results of integrity assessment may be different according to the evaluation method. For this reason, an integrity evaluation system, which provides efficient way of evaluation with the help of attached database, was developed. The present system was built on the basis of 3D FEM results, ASME Sec. XI, and Fitness For Service Guidelines for CANDU pressure tubes issued by the AECL (Atomic Energy Canada Limited). The present system also covers the delayed hydride cracking and the blister evaluation, which are the characteristics of pressure tube integrity evaluation. In order to verify the present system, several case studies have been performed and the results were compared with those from AECL. A good agreement was observed between those two results.

Key Words : Integrity Evaluation, Pressure Tube, Sharp Flaw, Blunt Notch, Blister, Delayed Hydride Cracking, Stress Intensity Factor

1. Introduction

There are four CANDU type reactors in Korea. The CANDU type reactor was first designed and constructed in Canada. Since the first commercial operation of a CANDU type reactor, 17 years have been passed and the 4th CANDU type reactor is under operation in Wolsong. As shown in Fig. 1, the CANDU reactor consists of a large tank, called calandria, containing D_2O moderator at 70℃, and is penetrated by 380 horizontal fuel channels each 6 m long. Each channel consists of a pressure tube containing fuel and coolant D_2O at a pressure of 10 MPa and at a temperature ranging from 260℃ at the inlet to 300℃ at the outlet. The surrounding pressure tubes are insulated from the cold moderator by a calandria tube. The space between the pressure tube and the calandria tube is filled with recirculating CO_2 gases, which is called Annulus Gas System (AGS). The AGS is equipped with sensitive dew-point monitors to detect the presence of moisture in the AGS and with 'beetle' sensors to detect

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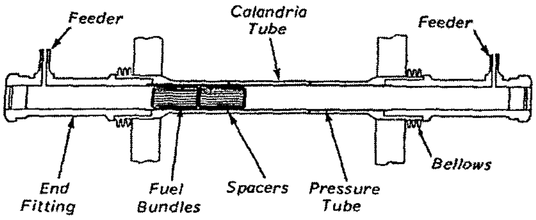


Fig. 1 CANDU Fuel channel (Moan et al., 1990)

liquid which may condense in the AGS. The pressure tubes are made from cold-worked Zr-2. 5 Nb with a wall thickness of 4.3 mm and inside diameter of 104 mm. The pressure tubes are rolled into the end fittings at each end of the fuel channel. The residual stress produced by the rolled joint fabrication process is still considered as a potential cause of developing delayed hydride cracking (DHC), even though it has been remarkably reduced by using a zero clearance rolled joint (Moan et al., 1990). .

The residual stresses lead to DHC by combining with hydrides that have been already formed. Actually, 17 pressure tubes of the Pickering unit 3 were replaced in 1974 because of this problem (Perryman, 1977). After that, a series of similar accidents happened at Pickering unit 4 (Ross and Dunn, 1976) in 1975, at Bruce unit 2 (Jackman, 1982) in 1982, at Pickering unit 2 (Field and Cheadle, 1984) in 1984, and at Pickering unit 3 in 1985. Also, during the periodic inspections in Wolsong, several flaws have been detected which exceeded the maximum allowable size, and flawed pressure tubes were replaced as a result. Therefore, significant efforts have been made to improve the pressure tube integrity through design, material and fabrication upgrades during last decades. In particular, it is necessary to establish the integrity evaluation system to avoid a pressure tube rupture accident which is important for the safety.

While the ASME Sec. XI (ASME, 1995) provides the general integrity evaluation procedures for the flawed structures, the effects of hydrogen inclusion and irradiation embrittlement of pressure tube material were not included. The AECL in Canada and the COG (CANDU Owner's Group) studied on this subject and published guidelines for the integrity evaluation of CANDU pressure tubes in 1991 and 1996 (Hopkins et al., 1998). However, these evaluation procedures require not only iterative calculations but also the expert knowledge on the fracture mechanics. Moreover the results of integrity assessment may be different according to the evaluation method. Therefore, an integrity evaluation system for the pressure tubes (PTIES) which provides an efficient way of the evaluation with the help of attached databases was developed. The present system consists of various evaluation modules such as crack growth both by fatigue and DHC, unstable fracture estimation, plastic collapse estimation, LBB (Leak-Before-Break) analysis, blister formation evaluation and remaining life estimation.

The present system is constructed on PC environment using Visual C++ language. Several case studies have been performed and the results were compared with those from AECL to examine accuracy and efficiency of the present system.

2. Integrity Evaluation

The evaluation procedures are different depending on the flaw shape, which can be classified as sharp flaw, blunt notch and blister. Evaluation for the sharp flaw is based on fracture mechanics analysis. The crack growth both by DHC and fatigue load, unstable fracture, plastic collapse, LBB and life estimation are required for the integrity assessment. Evaluation for the blunt notch is based on the solid mechanics. The crack and DHC initiation, plastic collapse, LBB analysis, and life estimation are required. For example, blunt notch is assessed (Hopkins et al., 1998) as being acceptable if:

(1) It can be demonstrated that fatigue crack initiation will not occur.

(2) It can be demonstrated that DHC initiation will not occur.

(3) The safety margin against plastic collapse is greater than or equal to 3.0 for Service Level A & B conditions, and 1.5 for Service Level C & D conditions.

Evaluation for the blister is based on hydrogen content analysis through time ; estimation of the blister formation time, growth of the blister, and the time elapsed to critical blister depth. While the Fitness For Service Guidelines (FFSG) in AECL describe about DHC and blister analysis, which are the characteristics of pressure tube analysis, the ASME Sec. XI describe the general evaluation procedures. The details of the integrity evaluation part can be found elsewhere (Kwak et al., 2000). The various parameters required for the integrity evaluation will be described below.

2.1 Crack initiation and crack growth

Fatigue loads are applied to the pressure tube by transients. The crack initiation life for a notch can be determined using stress-life diagram and Miner's rule (Miner, 1945) for a given material. The fatigue crack growth rate da/dN is characterized in terms of the range of the applied stress intensity factor ΔK. This characterization is of the form (ASME, 1995):

$$\frac{da}{dN}=C_1(\Delta K)^{n1} \qquad (1)$$

where: a is crack growth in mm

N is the number of each transient cycles expected during the evaluation period

C_1 is the scaling constant, i.e. 3.438×10^{-10} m/cycle

n_1 is the slope of the log (da/dN) versus log (ΔK) relation, i.e. 3.439

ΔK is the range of the stress intensity factor in MPa$\sqrt{m}$.

While the fatigue crack growth which is considered as a principal cracking mechanism for PWR reactors in an order of 10^{-8} m/cycle, the crack growth by DHC is an order of 10^{-4} m/cycle. Thus the contribution of DHC to crack growth is much more dominant, so that DHC is taken into account for integrity evaluation of pressure tubes.

The operating experience (Park et al., 2002) showed that 8% of the inspected tubes was affected by flaws greater than code allowable and about 60% was damaged by debris and 33% was in contact with calandria tube. It means that the pressure tube is exposed to various degradation mechanisms that are likely to develop cracks. As shown in the inspection data, the major cause to produce flaws is debris defects that are similar to notch in shape. Once such a sharp notch is made, the stress concentrates at the tip. The hydride formation and its associated crack is much more susceptible to high stress location. When a hydrogen concentration is higher than terminal solid solubility (TSS), and a stress intensity factor is above a threshold value K_{IH} as given by Eq. (2), hydrides precipitate and crack grows by DHC (Moan et al., 1990).

$$K_{IH}\geq\begin{cases}4.5\ \mathrm{MPa}\sqrt{m} & (\textit{radial direction})\\ 15\ \mathrm{MPa}\sqrt{m} & (\textit{axial direction})\end{cases} \qquad (2)$$

The DHC velocity was independent of the stress intensity factor once the threshold was exceeded. Since the velocity is a function of temperature, the cumulative crack growth was determined by numerically integrating the velocity over the cooldown cycle. Axial crack velocity is used to estimate flaw growth along the tube length. From Eq. (3), the DHC growth can be integrated numerically by sectioning the cooldown transient curve.

$$\Delta a=\left(\sum_{j=1} DHCV\times\Delta t_j\right)\times N \qquad (3)$$

where $DHCV$ is the DHC velocity in m/s, Δa is the crack extension in m, Δt_j is time period for each transient loading condition in seconds and N is number of cooldown cycles expected during the evaluation period.

2.2 Unstable fracture and plastic collapse

To prevent the unstable fracture, the stress intensity factor does not exceed the fracture toughness. Various methods such as ASME Sec. XI (ASME, 1995), Raju-Newman (Newman and Raju, 1981), Handbook data (Zahoor, 1989) and finite element analysis can be applied for the determination of stress intensity factor. The fracture toughness of irradiated pressure tube material can be expressed (Kwak et al., 2000).

$$K_{IC}=26.3+0.022T[\mathrm{MPa}\sqrt{m}] \qquad (4)$$

where K_{IC} is in MPa$\sqrt{m}$ and T is the temperature in degrees C. This relation is based on lower bound K_{IC} values measured from Zr-2.5 Nb pressure tubes removed from reactors. The K_{IC} values correspond to axial crack growth in the radial-axial plane, but they can be applied to radial crack growth in the radial-axial plane. The K_{IC} values from which Eq. (4) was derived correspond to a temperature range of 20 to 300℃, a neutron fluence of 0.18×10^{25} to 9.8×10^{25} n/m^2, and a maximum equivalent hydrogen concentration of 35 ppm.

The following provides procedures for calculating the applied loads and the allowable loads to ensure that failure by plastic collapse will not occur. To prevent the plastic collapse, the hoop stress (or axial stress) does not exceed the required plastic collapse stress for axial (or circumferential) flaw (Kiefner et al., 1973).

2.3 Leak-Before-Break

In a deterministic LBB analysis, lower-bound values of critical crack length (CCL) are compared with values of crack length, based on upper-bound values of DHCV (Moan et al., 1990). Also, the LBB analysis integrates the AGS response to leakage from an assumed through-wall DHC crack with the change in crack velocity and CCL as the reactor goes from full power to a cold depressurized condition. The time to identify leaking tube and shutdown should be greater than the time that the growing crack become unstable during the shutdown/cooldown to the cold depressurized state in order to satisfy LBB requirement (Moan et al., 1990; Park et al., 1996; Walker, 1990). For this analysis we integrate the leakage detecting system response, crack growth velocity by DHC, CCL, crack length at penetration and leak rate and calculated time to crack reaches CCL.

2.4 Blister formation and growth

Movement of garter springs from design location can induce the contact between pressure tube and calandria tube. Blister can be formed at the contact region of the two tubes by temperature gradient and hydrogen. For the evaluation of pressure tubes in contact with their calandria tubes, analytical procedures and acceptance criteria have been developed to ensure that critical hydride blister will not be present in the pressure tubes during the evaluation period (Canadian Standards Association, 1994). A critical hydride blister is defined as the lower bound blister size that could crack under Level A or Level B service loadings, and would provide an initiation site for DHC. During operation time, the concentration of hydrogen has been checked to see whether it exceeds the solubility of pressure tube to prevent the tube failure. When the concentration of hydrogen exceeds the blister formation threshold (BFT), blister formation is expected. And the growth of blister can be determined by hydrogen concentration, temperature gradient and transient data. When a blister is found at the pressure tube, which has no previous inspection data, hydrogen concentration and contact period is assumed. The exact analysis for the blister is difficult consequently. When there has no initial blister depth, the present system calculate initial blister depth by the simulation with the assumption that the contact between the two tubes was happened from the reactor starting, and use 95% upper bound hydrogen increase rate. The integrity evaluation system developed will be supported various options to solve these problems.

3. Outline of the Pressure Tube Integrity Evaluation System

The biggest advantage of the present integrity evaluation system is a very simple operation to analyze complex phenomena such as sharp crack, blunt notch and blisters. A structure and main screen of analyses using the present system are shown in Figs. 2 and 3. The present system named PTIES consists of four main parts; data input part, database/database management part, calculation part and results output part. The PTIES can support various integrity assessment procedure mentioned at the previous section. The details of the theory part can be found elsewhere (Canadian Standards Association, 1994). For it was developed for the MS-Windows operating system, it also support windows GUI such as toolbar, menu, help system, graphic output, file input/output and database compatible with other

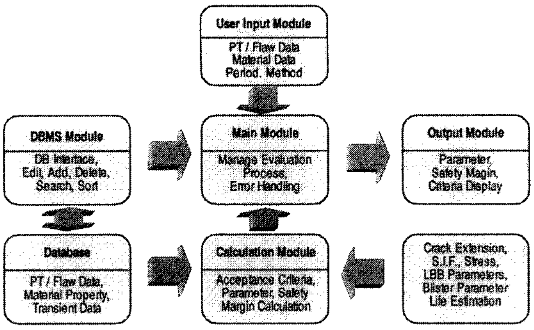


Fig. 2 Structure of the present system

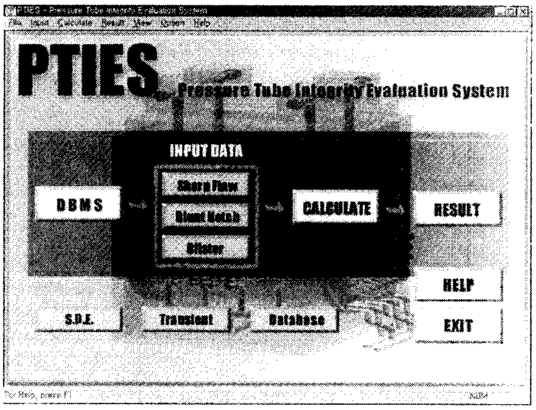


Fig. 3 Main screen of the present system

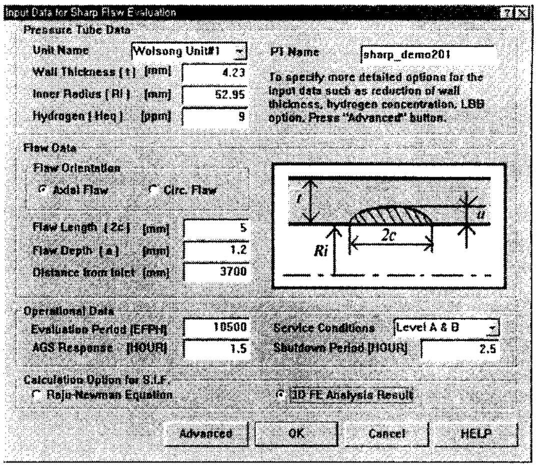
commercial database product.

3.1 Data input part

For the pressure tube integrity assessment, various kinds of data are required, such as pressure tube dimensions, flaw dimensions, material properties, transient data and so on. And required data are different according to flaw type. In order to reduce the error during the input process, the automatic data validation check routine which accepts only reasonable data was included in this module. The database can also be used for the data input process for the efficiency of assessment. Figures 4 to 6 shows the input screen for sharp flaw, blunt notch and blister evaluation respectively.

3.2 Database/Database management part

In order to manage the input data efficiently, a database and database management module were developed. The developed database provides fre-



Pressure Tube Data

Unit Name: Wolsong Unit#1
PT Name: sharp_demo201
Wall Thickness (t) [mm]: 4.23
Inner Radius (Ri) [mm]: 52.95
Hydrogen (Heq) [ppm]: 9

To specify more detailed options for the input data such as reduction of wall thickness, hydrogen concentration, LBB option, Press "Advanced" button.

Flaw Data

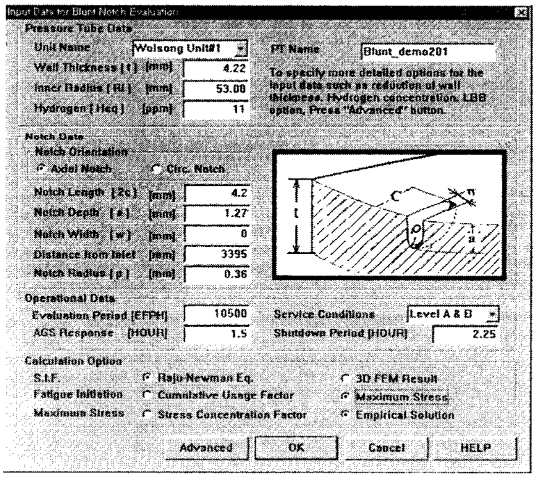
Flaw Orientation: ● Axial Flaw ○ Circ. Flaw
Flaw Length (2c) [mm]: 5
Flaw Depth (a) [mm]: 1.2
Distance from Inlet [mm]: 3700

Operational Data

Evaluation Period [EFPH]: 10500
AGS Response [HOUR]: 1.5
Service Conditions: Level A & B
Shutdown Period [HOUR]: 2.5

Calculation Option for S.I.F.: ○ Raju-Newman Equation ● 3D FE Analysis Result

Fig. 4 Input screen of sharp flaw evaluation



Pressure Tube Data

Unit Name: Wolsong Unit#1
PT Name: Blunt_demo201
Wall Thickness (t) [mm]: 4.22
Inner Radius (Ri) [mm]: 53.08
Hydrogen (Heq) [ppm]: 11

To specify more detailed options for the input data such as reduction of wall thickness, Hydrogen concentration, LBB option, Press "Advanced" button.

Notch Data

Notch Orientation: ● Axial Notch ○ Circ. Notch
Notch Length (2c) [mm]: 4.2
Notch Depth (a) [mm]: 1.27
Notch Width (w) [mm]: 0
Distance from Inlet [mm]: 3395
Notch Radius (ρ) [mm]: 0.36

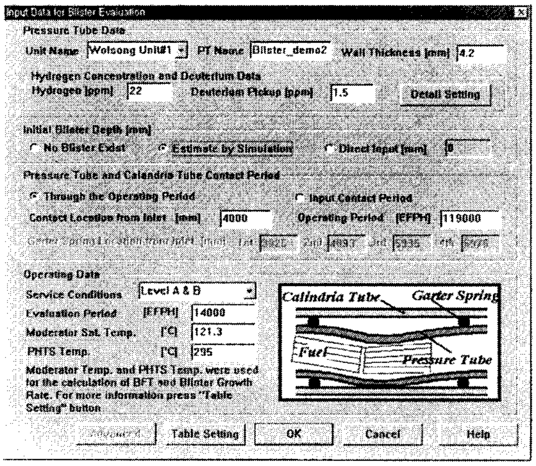
Operational Data

Evaluation Period [EFPH]: 10500
AGS Response [HOUR]: 1.5
Service Conditions: Level A & B
Shutdown Period [HOUR]: 2.25

Calculation Option

S.I.F.: ● Raju-Newman Eq. ○ 3D FEM Result
Fatigue Initiation: ○ Cumulative Usage Factor ● Maximum Stress
Maximum Stress: ○ Stress Concentration Factor ● Empirical Solution

Fig. 5 Input screen of blunt notch evaluation



Pressure Tube Data

Unit Name: Wolsong Unit#1
PT Name: Blister_demo2
Wall Thickness [mm]: 4.2

Hydrogen Concentration and Deuterium Data

Hydrogen [ppm]: 22
Deuterium Pickup [ppm]: 1.5

Initial Blister Depth [mm]: ○ No Blister Exist ● Estimate by Simulation ○ Direct Input [mm] 0

Pressure Tube and Calandria Tube Contact Period: ● Through the Operating Period ○ Input Contact Period
Contact Location from Inlet [mm]: 4000
Operating Period [EFPH]: 119000
Garter Spring Location from Inlet [mm] 1st [illegible] 2nd 4897 3rd 5935 4th [illegible]

Operating Data

Service Conditions: Level A & B
Evaluation Period [EFPH]: 14000
Moderator Sat. Temp. [°C]: 121.3
PHTS Temp. [°C]: 295

Moderator Temp. and PHTS Temp. were used for the calculation of BFT and Blister Growth Rate. For more information press "Table Setting" button

Fig. 6 Input screen of blister evaluation quently required data, such as ISI data for specific power plant, pressure tube dimensions, flaw dimensions, material properties, transient data, sequence of cooling data and finite element analysis data. Also, a file maintenance program can manipulate the contents of data files. Followings are the details of ISI data and also included in the developed database module ;

(1) Manufacturing and installation data : measured data at installation or replacement such as installations date, ingot number, tensile test data, hardness data, dimensions at installation, and hydrogen concentration at installation.

(2) CIGAR inspection data : CIGAR (Channel Inspection and Gauging Apparatus for Reactors) is an specialized inspection tool for pressure tube, and give information such as pressure tube dimensions, flaw dimensions, type and location, garter spring locations, and sagging along pressure tube length.

(3) Elongation data : elongation due to the irradiation and creep are periodically measured and give information such as elongation of each side, and status of each end.

(4) Scrape sampling data : Hydrogen concentration and deuterium increase is the most important factor for DHC and blister evaluation, for the integrity scrape sampling are carried out periodically and give information about deuterium increase rate as a function of location and operation time.

(5) Garter spring location data : The locations of garter spring are measured periodically as movement of garter springs is the cause of blister. When the locations of garter spring are large enough, repositioning work are required.

The database management module provides functions for data insertion, deletion, sorting and searching, and is compatible with other commercial database programs. Figures 7 to 9 show the screens of database management on pressure tubes.

The stress intensity factor K data included in the developed database were prepared by performing K calculation with three-dimensional finite element models for various surface cracks. A total of 40 analyses were performed by varying the crack depth to crack length ratio from 0.2 to 1.0, and the crack depth to crack wall thickness ratio from 0.2 to 0.8. The loading condition was set to 10.4 MPa of internal pressure considering normal operating condition. Material properties were adopted from a CANDU type nuclear power plant constructed in Korea. Figure 10 shows a typical finite element mesh of a quarter portion

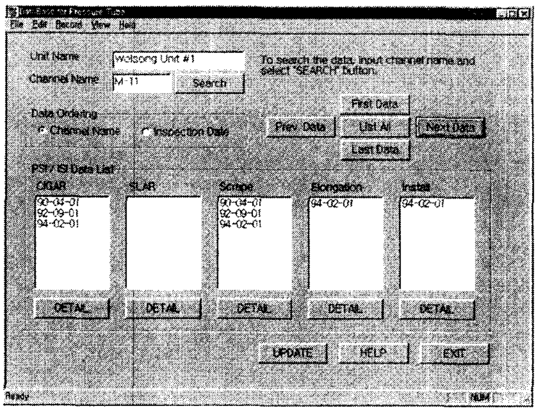

Unit Name: Wolsong Unit #1
Channel Name: M-11
To search the data, input channel name and select "SEARCH" button.
Data Ordering: ● Channel Name ○ Inspection Date
PSI/ISI Data List
CIGAR: 90-04-01, 92-09-01, 94-02-01
SLAR:
Scrape: 90-04-01, 92-09-01, 94-02-01
Elongation: 94-02-01
Install: 94-02-01

Fig. 7 Database management screen

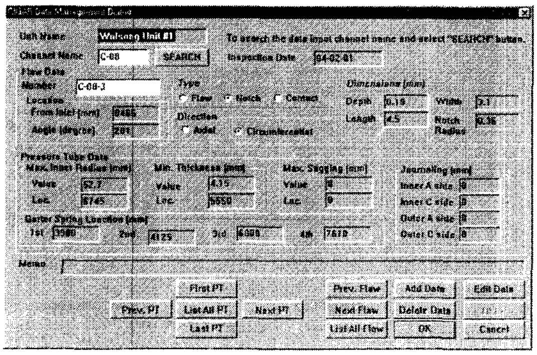
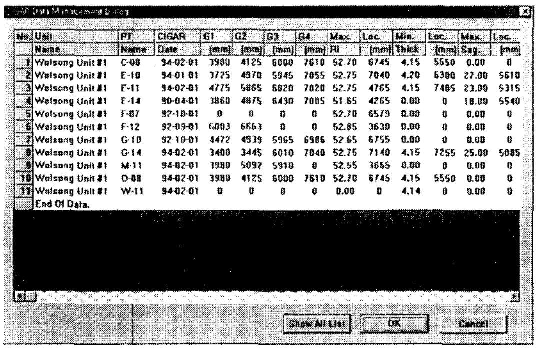

Unit Name: Wolsong Unit #1
To search the data input channel name and select "SEARCH" button.
Channel Name: C-08
Inspection Date: 94-02-01
Flaw Data
Number: C-08-3
Location
From Inlet [mm]: 8465
Angle [degree]: 201
Type: ○ Flaw ● Notch ○ Contact
Direction: ○ Axial ● Circumferential
Dimensions [mm]
Depth: 0.19
Width: 3.1
Length: 4.5
Notch Radius: 0.16
Pressure Tube Data
Max. Inner Radius [mm]: Value 52.7, Loc. 6745
Min. Thickness [mm]: Value 4.15, Loc. 5550
Max. Sagging [mm]: Value 0, Loc. 0
Journaling [mm]: Inner A side 0, Inner C side 0, Outer A side 0, Outer C side 0
Garter Spring Location [mm]: 1st 3980, 2nd 4125, 3rd 6000, 4th 7610
Memo:

Fig. 8 Data insertion screen



No.	Unit Name	PT Name	CIGAR Date	G1 [mm]	G2 [mm]	G3 [mm]	G4 [mm]	Max. RI	Loc. [mm]	Min. Thick	Loc. [mm]	Max. Sag.	Loc. [mm]
1	Wolsong Unit #1	C-08	94-02-01	3980	4125	6000	7610	52.70	6745	4.15	5550	0.00	0
2	Wolsong Unit #1	E-10	94-01-01	3725	4970	5945	7055	52.75	7040	4.20	6300	27.00	5610
3	Wolsong Unit #1	E-11	94-02-01	4775	5865	6820	7020	52.75	4765	4.15	7485	23.00	5315
4	Wolsong Unit #1	E-14	90-04-01	3860	4875	6430	7085	51.65	4265	0.00	0	18.00	5540
5	Wolsong Unit #1	F-07	92-10-01	0	0	0	0	52.70	6579	0.00	0	0.00	0
6	Wolsong Unit #1	F-12	92-09-01	6003	6663	0	0	52.85	3630	0.00	0	0.00	0
7	Wolsong Unit #1	G-10	92-10-01	4472	4939	5965	6986	52.65	6755	0.00	0	0.00	0
8	Wolsong Unit #1	G-14	94-02-01	3400	3445	6010	7040	52.75	7140	4.15	7255	25.00	5085
9	Wolsong Unit #1	M-11	94-02-01	1980	5092	5910	0	52.55	3665	0.00	0	0.00	0
10	Wolsong Unit #1	O-08	94-02-01	3980	4125	6000	7610	52.70	6745	4.15	5550	0.00	0
11	Wolsong Unit #1	W-11	94-02-01	0	0	0	0	0.00	0	4.14	0	0.00	0
	End Of Data.												

Fig. 9 Data listing screen

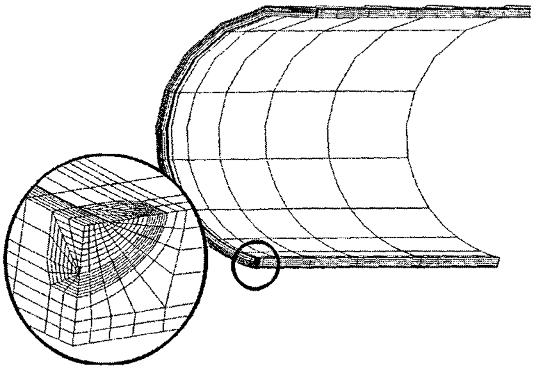


Fig. 10 Model for the finite element analysis

of a tube with a semi-elliptical crack. The finite element mesh consists of 20 node iso-parametric quadratic brick elements. One of the commercial finite element codes, ABAQUS (Hibbitt et al., 1999) was used for the analysis. Raju-Newman equation and ASME Sec. XI method has some limitations comparing with the finite element analysis (Kwak et al., 2000). The transient data which are used for crack extension analysis were prepared by considering the test loading conditions as specified in the design documents. Therefore, plant specific crack extension analysis is available from the present system. Since the transient database is also included in the database, it is possible to add or change transient data considering practical operating condition.

3.3 Calculation part

Various evaluation parameters are calculated, using user input data, database, and reference table from the design document. User can set the calculation option such as radius and thickness change rate, hydrogen concentration increase rate, and evaluation criteria. In many cases initial blister depth cannot be determined, the present system can determine initial blister depth by simulation, using operating period and hydrogen concentration change. In addition to above input data, transient data are not frequently changed but important factors for the integrity evaluation. These data can also be set in the present system.

For the sharp flaw evaluation, the determination of minimum evaluation flaw size, stress intensity factor calculation as the increases of crack size, fracture toughness calculation, fatigue crack extension calculation, DHC extension calculation, plastic collapse stress, terminal solid solubility calculation, LBB analysis and remaining life estimation. For the blunt notch evaluation, the determination of minimum evaluation flaw size, fatigue crack initiation, DHC initiation, terminal solid solubility calculation, plastic collapse analy-

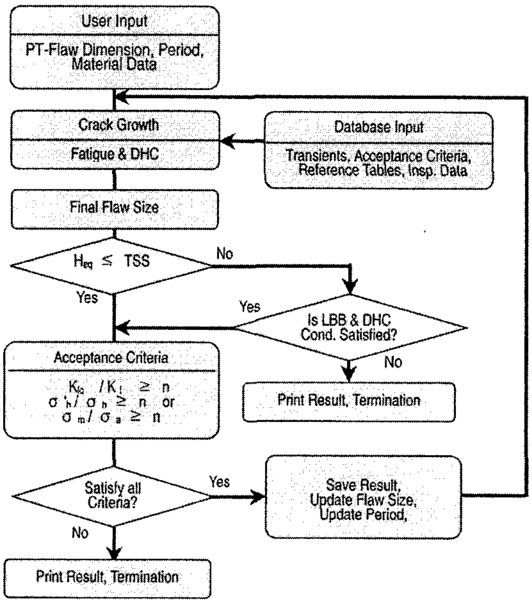


Fig. 11 Flow chart for sharp flaw evaluation

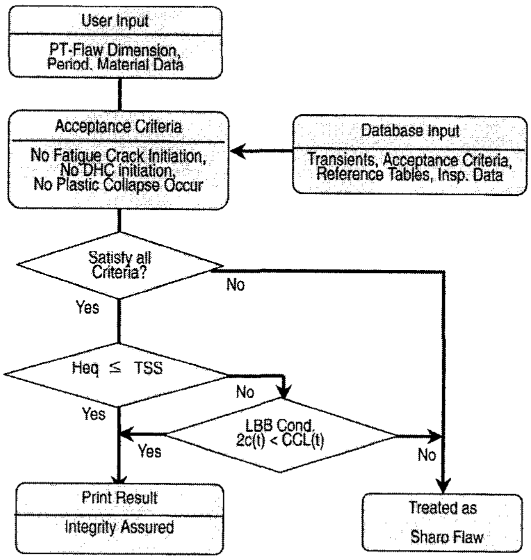


Fig. 12 Flow chart for blunt notch evaluation

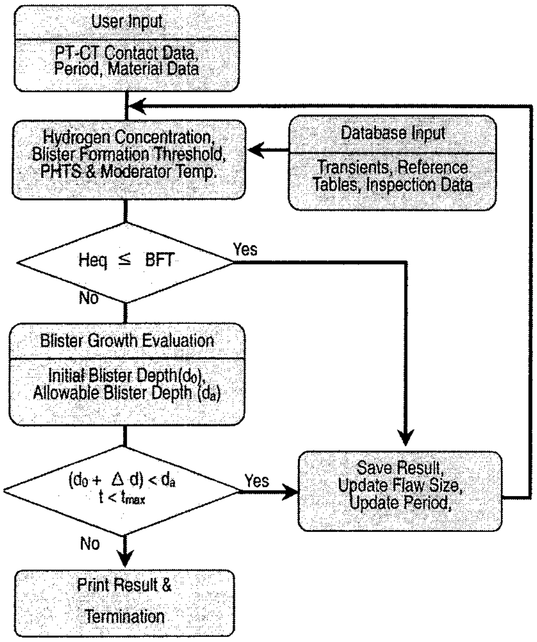


Fig. 13 Flow chart for blister evaluation

sis, and LBB analysis are provided. For the blister evaluation, formation of blister, growth of blister, remaining life and integrity results are provided. Figure 11 to 13 show the flow chart for integrity evaluation procedure used for the evaluation system.

3.4 Output part

This part provides the resulting output for the entire analysis. The structure of output was developed so that a user can easily determine the integrity, which is based on the standard failure criteria. The output part provides integrity determination, remaining life of analyzed pressure tube, and resulting parameters such as stress intensity factors, fracture toughness, plastic collapse stress, the applied stress, crack extension, hydrogen concentration, terminal solubility and so on. Several user-friendly tools were added for graphic display, table display, summary report and so on. For the LBB analysis, critical crack length, penetrated crack length, the velocity of crack extension by DHC, and time for the flaw to reach the critical crack length are also provided. Figure 14 to 16 show the result display screens of the present system.

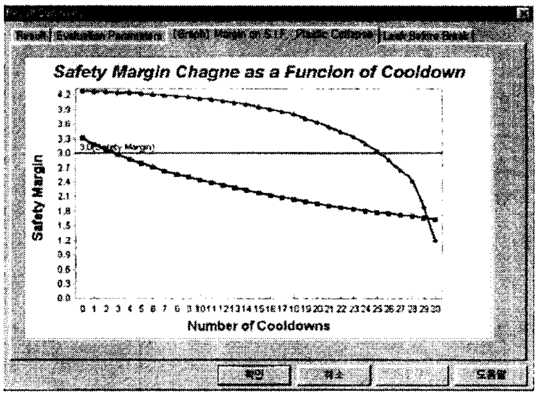
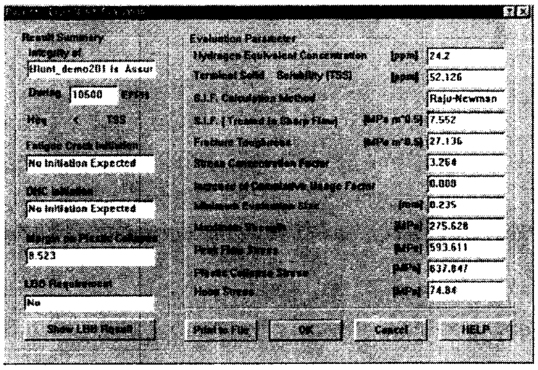


Fig. 14 Result output screen of sharp flaw evaluation



Result Summary

Integrity of
Blunt_demo201 is Assur

During 10500 EFPH

Heq < TSS

Fatigue Crack Initiation
No Initiation Expected

DHC Initiation
No Initiation Expected

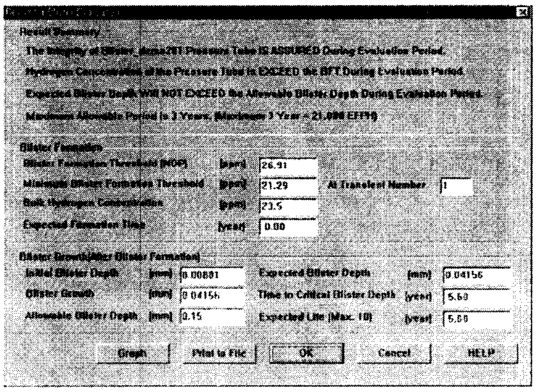
Margin on Plastic Collapse
8.523

LBB Requirement
No

Evaluation Parameter

Hydrogen Equivalent Concentration	[ppm]	24.2
Terminal Solid Solubility (TSS)	[ppm]	52.126
S.I.F. Calculation Method		Raju-Newman
S.I.F. (Treated as Sharp Flaw)	[MPa m^0.5]	7.552
Fracture Toughness	[MPa m^0.5]	27.136
Stress Concentration Factor		3.264
Increase of Cumulative Usage Factor		0.000
Minimum Evaluation Size	[mm]	0.235
Maximum Strength	[MPa]	275.628
Peak Flaw Stress	[MPa]	593.611
Plastic Collapse Stress	[MPa]	637.847
Hoop Stress	[MPa]	74.84

Fig. 15 Result output screen of blunt notch evaluation



Result Summary

The Integrity of Blister_demo201 Pressure Tube IS ASSURED During Evaluation Period.
Hydrogen Concentration of the Pressure Tube is EXCEED the BFT During Evaluation Period.
Expected Blister Depth Will NOT EXCEED the Allowable Blister Depth During Evaluation Period.
Maximum Allowable Period is 3 Years. (Maximum 1 Year = 21,000 EFPH)

Blister Formation

Blister Formation Threshold (BFT)	[ppm]	26.91		
Minimum Blister Formation Threshold	[ppm]	21.29	At Transient Number	1
Bulk Hydrogen Concentration	[ppm]	23.5		
Expected Formation Time	[year]	0.00		

Blister Growth(After Blister Formation)

Initial Blister Depth	[mm]	0.00801	Expected Blister Depth	[mm]	0.04156
Blister Growth	[mm]	0.04156	Time to Critical Blister Depth	[year]	5.60
Allowable Blister Depth	[mm]	0.15	Expected Life (Max. 10)	[year]	5.60

Fig. 16 Result output screen of blister evaluation

4. Examples and Discussion

In order to verify the present system, three case studies were performed on a sharp flaw embedded in the axial direction, a blunt notch in the axial

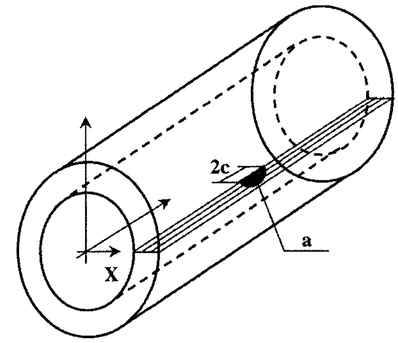


Fig. 17 Geometry for axial sharp flaw

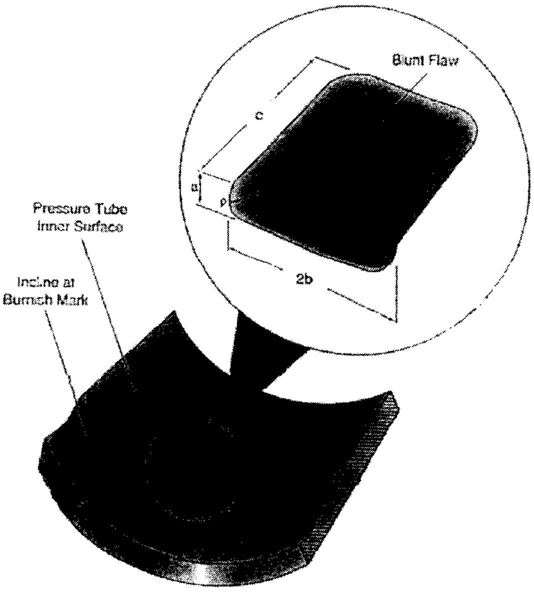


Fig. 18 Geometry for blunt notch

direction and a blister. Schematic diagram are shown in Figs. 17 and 18. The input data required for evaluation were adopted from the test report (Newman, 1992; Scarth, 1990; Shin, 1994; AECL, 1992) prepared by Ontario Hydro. The analysis results and input data are summarized in Table 1 to 3, and showed a good agreement with the results reported in the reference.

4.1 Sharp flaw evaluation

The axial component of the sharp flaw has a length and a depth given by the profile of the actual flaw in the radial-axial plane. The flaws were sized by CIGAR and were reported as being indications on the inside surface of the pressure tube. Table 1 provides the input data such as flaw dimensions from CIGAR. The initial hydrogen concentrations were based on the values taken from off-cut analysis. For the assessment, the margin on safety for an axial flaw including predicted flaw growth due to DHC associated with cooldown cycle was evaluated. The results of the assessment for Service Levels A and B loading conditions are summarized in Table 2 with AECL results. Evaluation parameters, presented in the Table 2, vary as the crack size increase and listed values are determined for initial crack size. It can be seen from the table that the present results agree well with AECL results. It shows that margin against unstable fracture is the dominant factor for the integrity evaluation. In design documents, maximum 250 cooldowns are expected during 30 years but only 3 cooldowns are allowed during evaluation period.

Table 1 Summary of input data for sharp flaw and blunt notch

	Sharp flaw	Blunt notch
Operation conditions	Level A & B	Level A & B
Evaluation Period [EFPH]	10,500	10,500
Wall thickness [mm]	4.23	4.22
Inner radius [mm]	52.95	53.08
Flaw /Notch depth [mm]	1.20	1.27
Flaw/Notch length [mm]	5.00	4.30
Notch radius [mm]	N.A.	0.36
Location of contact [mm]	3,700	3,395
Initial hydrogen [ppm]	9.00	11.00
Deuterium increase [ppm]	11.30	26.40

Table 2 Comparison of evaluation parameter for sharp flaw

	AECL	Evaluation System
Crack Extension per cooldown [mm]	0.085	0.083
Margin on S.I.F.	3.16	3.20
Margin on Stress	4.43	4.38
Number of allowable cooldonw	3	3
Continued operation ?	No	No

Table 3 Comparison of evaluation parameter for blunt notch

	AECL	Evaluation System
DHC initiation	No	No
Fatigue crack initiation	No	No
Margin on stress	4.16	4.22
Continued operation ?	Yes	Yes

4.2 Blunt notch evaluation

For a flaw to be characterized as blunt notch, the geometry such as length, depth, width and root radius must be known so that a stress analysis to determine the peak value of the notch tip stress concentration can be performed.

The blunt notch dimensions used during the analysis are shown in Table 1. Service Levels A and B loading conditions are considered. The evaluation of the blunt notch addressed fatigue and DHC. When integrity of blunt notch is not assured, remaining life can be determined by assuming blunt notch as a sharp flaw. The blunt notch has been evaluated for an additional operating period of 10,500 EFPH. Comparison for evaluation parameter from AECL and the present system are listed in the Table 3. It can be seen from the table that the present results agree well with AECL results. Based on the assessment completed it has been concluded that the pressure tube is acceptable for return to service for an additional operating period of 10,500 EFPH.

4.3 Blister evaluation

Evaluation is carried out for Service Levels A and B transients. In service inspection, carried on pressure tube is sampling test, there has no initial blister depth and contact period, which is essential for the integrity assessment. In the analysis contact period between the tubes is assumed from the start of reactor operation, and initial blister depth is determined from simulation using initial hydrogen, deuterium increase rate, contact period, and blister growth rate. Input data and results are listed in the following.

-Location of contact : 5,000 mm
-Initial hydrogen : 9.00 ppm
-Deuterium increase : 22.00 ppm
-Operating period : 112,000 EFPH
-Evaluation period : 14,000 EFPH
-PHTS temperature : 293℃
-Moderator saturation temperature : 121.3℃

Integrity is assured during the evaluation period and details of output results are listed in the following. For the blister evaluation no comparable data is open to the public, comparison is not listed.

-Hydrogen at the end of evaluation period : 23.5 ppm
-Blister formation threshold for normal operation condition : 26.58 ppm
-Minimum blister formation threshold for Level A & B condition : 21.3 ppm
-Expected blister formation time : 15.2 years
-Calculated initial blister depth : 0.01 mm
-Blister growth at the end of evaluation period : 0.07 mm
-Allowable blister : 0.1 mm
-Time to critical blister depth : 2.9 years

Based on the above assessment, it has been concluded that the pressure tube is maintained the integrity until next inspection period. However, more accurate evaluation requires actual transient history because integrity of blister is very sensitive to the transient data.

5. Conclusion

An integrity evaluation system of CANDU reactor pressure tube was developed in the present study. It provides efficient and accurate integrity evaluations for pressure tubes with the aid of attached databases in various methods. Here interactive operations to be done by a user can be performed in a few minutes even for complicated problems. Three case studies were successfully performed and showed a good agreement with other results. The 3D finite analyses were performed for more exact analysis and verification, and the results were included in the present system. From the various analysis of each flaw type, margin on unstable fracture is the most critical factor for sharp flaw, and DHC initiation for blunt notch, respectively.

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