CREPT PRESSURE TUBE MODEL FOR HEAT TRANSPORT SYSTEM AGING ANALYSIS

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ABSTRACT

As part of an overall program to quantitatively examine the integrated effects of Heat Transport System (HTS) aging, Bruce Power and Ontario Power Generation (OPG) have collaborated on the development of a crept pressure tube model. This paper presents the model for the prototype station; Bruce B. Available pressure tube inspection data for Bruce B has been used to develop the model. Ten potential forms of correlations were examined. Multiple linear regression on the inspection data was used to determine the coefficients for the correlations. The recommended model is capable of predicting the current and future axial profile of crept pressure tubes.

1.0 INTRODUCTION

In safety analysis, the variation of pressure tube diametral creep along its axial length affects parameters such as the flow area, hydraulic diameter, view factors for radiation calculations, loss factor, two-phase pressure drop multiplier, onset of subcooled boiling and the value of Critical Heat Flux (CHF) and sheath to coolant heat transfer coefficient (in particular under post-dryout conditions). These variations affect the channel thermal hydraulic conditions, the Heat Transport System (HTS) operating conditions, and thus trip set-points and the system response during accidents. A realistic representation of the geometry of the pressure tube along its axial length that reflects physical plant conditions has been developed to model the effects of this HTS aging mechanism on safety analysis.

A best-fit model, based on plant data, has been developed and the systematic and random errors of the correlations are treated as uncertainties. Inspection data used is discussed in Section 2, methodology and assumptions are presented in Section 3, results are discussed in Section 4 and conclusions and recommendations are presented in Sections 5 and 6, respectively.

2.0 INSPECTION DATA

Gauging data from inspections carried out at Bruce B using the Channel Inspection and Gauging Apparatus for Reactors (CIGAR) has been obtained for the development of pressure tube creep model. The data includes measurements of pressure tube diameter along the length of the inspected channels. The locations of fuel bundles were established by utilizing the diametral creep data because of the lower neutron flux at the locations of the end plates of fuel bundles. Pressure tube diametral creep is expected to be minimal at the end plates locations compared with the heated portions of a fuel channel. This expectation was corroborated by the axial profiles of the pressure tube diameter. Therefore, by inspecting the plots for each channel, the locations of fuel bundles were identified in the data supplied for each channel.

The inspection data cover the following range of conditions:

Fluence:	0.53×10^{25} to 1.543×10^{26} n/m^2
Neutron Flux:	0.1246×10^{17} to 3.711×10^{17} n/(m^2 .s)
Time:	101530 to 118665 EFPH
Channel Average Fluence:	4.936×10^{25} to 1.121×10^{26} n/m^2
Channel Average Neutron Flux:	1.161×10^{17} to 2.708×10^{17} n/(m^2 .s)
Coolant Temperature:	253.0 to 303.15°C.
Pressure Tube Diameter:	103.86 to 106.04 mm

It is observed that the pressure tube diametral creep profiles have maximum values located at the downstream end of flow direction (outlet end of the fuel channel). The measured pressure tube diameters are shown as functions of local fluence (normalized by 10^{25}) and time-average local flux (normalized by 10^{17}) in Figures 1 and 2, respectively. It is evident that the data exhibit almost linear dependence of the pressure tube diameter on fluence or flux. However, the data scattering suggest that other secondary parameters may affect the pressure tube creep. The same trend is observed for maximum mean diameter of the pressure tube.

3.0 ASSUMPTIONS AND METHODOLOGY

3.1 Assumptions

- The proposed models are based on the mean values of pressure tube diameter at various locations along its axial direction. The original gauging data included maximum, mean and minimum internal diameter measurements along the length of the pressure tube. The mean internal diameter is the average of all measurements around the circumference of the PT at a specific axial location.
- The initial diameter of the pressure tube is assumed to be constant along its axial direction. Its value is 103.79 mm.
- The model is to be a best-fit model providing systematic and random errors to be treated as uncertainties.

3.2 Methodology

The local pressure tube diameter depends greatly on two variables, namely time, t (in EFPH) and time-averaged neutron flux, ϕ at the location, or alternatively, it depends on the fluence, ψ at the location in the pressure tube (PT). Other factors such as coolant temperature and pressure are considered secondary. The methodology development considered the impact of temperature as it varies along the length of the channel. The effect of the pressure variation along the length of the channel is expected to be smaller than the effect of the temperature. Therefore, the development of the correlation did not consider the pressure as a parameter. For each measurement at a specific axial location, the local fluence is determined by interpolating the mid-bundle fluence values provided in the fluence maps. The local flux is then determined by dividing the local fluence values by the corresponding time. Then:

$$\phi = \psi / (3600\ t) \tag{a}$$

The channel average flux ϕ_{avg} and fluence ψ_{avg} are given by:

$$\phi_{avg} = (1/2\ \phi_1 + 1/2\ \phi_{13} + \sum_{i=2}^{12} \phi_i) / 12 \tag{b}$$

$$\psi_{avg} = (1/2\ \psi_1 + 1/2\ \psi_{13} + \sum_{i=2}^{12} \psi_i) / 12 \tag{c}$$

where ϕ_i and ψ_i are the flux and fluence of ith bundle, respectively.

However, the noticeable scattering of the data (Figures 1 and 2) could be attributed to the variation within acceptable and specified metallurgical properties and operating conditions for each channel, and therefore, each channel undergoes a different rate of diametral expansion.

For safety analysis purposes, the local pressure tube diameter model will be based on one of the candidate forms given below. The first five forms are functions of neutron flux and the time variable is treated as a separate parameter, whereas the other five forms are functions of fluence. The effects of secondary parameters such as channel average flux or channel average fluence as well as lifetime average temperature, T (^{o}C), are also considered. The effect of channel average flux is considered in functions 2 and 4, whereas the effect of channel average fluence is considered in functions 7 and 9. The effect of lifetime average temperature is considered in functions 3, 4, 5, 8, 9 and 10. For equations (5) and (10), it is assumed that the coolant temperature T has an insignificant effect on the pressure tube creep as long as it is smaller than a certain reference temperature T_0. These forms of correlations will be examined and evaluated to establish the best fit to the inspection data.

The following correlations are mainly functions of flux and time:

$$D = [A_1 + A_2 (\phi / 10^{17}) + A_3\ (t / 10^5)]\ D_0 + D_0 \tag{1}$$

$$D = [A_1 + A_2 (\phi / 10^{17}) + A_3\ (t / 10^5) + A_4 (\phi_{avg} / 10^{17})]\ D_0 + D_0 \tag{2}$$

$$D = [A_1 + A_2 (\phi / 10^{17}) + A_3\ (t / 10^5) + A_5 (T / 10^2)]\ D_0 + D_0 \tag{3}$$

$$D = [A_1 + A_2 (\phi / 10^{17}) + A_3\ (t / 10^5) + A_4 (\phi_{avg} / 10^{17}) + A_5 (T / 10^2)]\ D_0 + D_0 \tag{4}$$

For $T > T_0$

$$D = [A_1 + A_2 (\phi / 10^{17}) + A_3\ (t / 10^5) + A_5 (\{T - T_0\} / 10^2)]\ D_0 + D_0$$

For $T \leq T_0$

$$D = [A_1 + A_2 (\phi / 10^{17}) + A_3\ (t / 10^5)]\ D_0 + D_0 \tag{5}$$

The following correlations are mainly functions of fluence:

$$D = [A_1 + A_2 (\psi / 10^{25})] D_0 + D_0 \tag{6}$$

$$D = [A_1 + A_2 (\psi / 10^{25}) + A_3 (\psi_{avg} / 10^{25})] D_0 + D_0 \tag{7}$$

$$D = [A_1 + A_2 (\psi / 10^{25}) + A_4 (T / 10^2)] D_0 + D_0 \tag{8}$$

$$D = [A_1 + A_2 (\psi / 10^{25}) + A_3 (\psi_{avg} / 10^{25}) + A_4 (T / 10^2)] D_0 + D_0 \tag{9}$$

For $T > T_0$

$$D = [A_1 + A_2 (\psi / 10^{25}) + A_4 (\{T - T_0\}/ 10^2)] D_0 + D_0$$

For $T \leq T_0$

$$D = [A_1 + A_2 (\psi / 10^{25})] D_0 + D_0 \tag{10}$$

where D is the mean diameter of crept pressure tube, and D_0 is the initial diameter of pressure tube. The coefficeints A_1, A_2, A_3, A_4, A_5, and T_0 are determined from fitting the data.

The proposed models for safety analysis make use of the experience acquired in fuel channel integrity analysis where it is possible. Hence these proposed models to be used for safety analysis are consistent with those used to correlate the maximum pressure tube diameter for fuel channel integrity assessment purposes. Equation (1) is the form of the equation recommended for Pickering B pressure tubes whereas the form of equation (6) has been recommended for Bruce B pressure tubes.

The developed model(s) can be used to predict the current and future axial profile of crept pressure tubes provided the time (EFPH) and neutron flux profiles (or alternatively fluence profiles) are available. Also, the diametral strain S can be calculated and it is given by:

$$S = (D - D_0) / D_0 \tag{d}$$

The developed models were checked against station inspection data to evaluate systematic and random errors. The error is given by:

$$\varepsilon = D_{measured} - D_{predicted} \tag{e}$$

The systematic and random errors are given by:

$$\varepsilon_{avg} = [\Sigma (\varepsilon_i)]/n \tag{f}$$

$$\varepsilon_{rms} = \{[\Sigma (\varepsilon_i)^2]/(n-m)\}^{1/2} \tag{g}$$

where n is the number of data points and m is the number of the coefficients in the selected correlation.

4 RESULTS AND DISCUSSIONS

The coefficients in the forms, 1 to 10, were obtained by correlating a total of 513 data points. The associated errors such as systematic, random and maximum positive and negative errors were calculated for each correlation and are listed in Table 1 (for forms 1 - 5) and Table 2 (for forms 6 - 10). The systematic error is very small for all correlations. Close examination of Tables 1 and 2 reveals that including channel average flux or channel average fluence, as a variable parameter, has an insignificant effect on the accuracy of these correlations. However, including lifetime average coolant temperature, as a variable parameter, improves the accuracy of the correlations and reduces the random error significantly. This is also confirmed by the comparisons between the predicted and measured axial profiles of the pressure tube diameters as illustrated in Figure 3 (for correlations 1 to 5) and in Figure 4 (for correlations 6 to 10).

Since the channel average flux has an insignificant effect on the pressure tube creep, the predicted profiles using correlations 2 and 4 are close to those predicted by correlations 1 and 3, respectively, as shown in Figure 3. Also, since the channel average fluence has an insignificant effect on the pressure tube creep, the predicted profiles by correlations 7 and 9 are close to those predicted by correlations 6 and 8, respectively, as shown in Figure 4. However, introducing lifetime average coolant temperature in correlations 3, 4, 8 and 9 improves the accuracy of the predicted profiles. Moreover, introducing the parameter T_0 in correlations 5 and 10 improves the accuracy of the predicted profiles, in particular for the upstream portion of the channels, as illustrated in Figures 3 and 4, respectively. Consequently, it can be concluded that correlations 5 and 10 are superior to correlations 1 to 4 and 6 to 9, respectively. Comparisons between the predicted and measured pressure tube diameters are illustrated in Figures 5 and 6 for correlations 5 and 10, respectively.

The random error of each of the two correlations (5 and 10) is 0.17 mm whereas the maximum positive error (under-prediction) is 0.41 and 0.39 mm, for correlations 5 and 10, respectively and the maximum negative error (over-prediction) is 0.43 and 0.49 mm, for correlations 5 and 10, respectively. The profiles of lifetime average coolant temperature and channel time-average flux (consequently channel-average flux) are not expected to vary with time significantly based on observations to date. Then, the rate of diameter and strain change with time are represented by:

For correlations 1 to 5:

$$dD/dt = (A_3 / 10^5)\, D_0 \qquad [\text{mm/EFPH}] \qquad (h)$$

$$dS/dt = (A_3 / 10^5) \qquad [\text{(mm/mm)/EFPH}] \qquad (i)$$

For correlations 6 to 10:

$$dD/dt = 3600\, (A_2\, \phi / 10^{25} + A_3\, \phi_{avg} / 10^{25})\, D_0 \qquad [\text{mm/EFPH}] \qquad (j)$$

$$dS/dt = 3600\,(A_2\,\phi / 10^{25} + A_3\,\phi_{avg} / 10^{25}) \qquad [(mm/mm)/EFPH] \qquad (k)$$

It should be noted that the coefficient A_3 is zero for correlations 6, 8 and 10. Under these assumptions, the rates of diameter and strain change with respect to time are constant along the channel and do not differ from one channel to another if correlation 1, 2, 3, 4 or 5 is used. For correlations 6 to 10, these rates are functions of the flux along the channel and do differ from one channel to another.

As expected, the diameter and diametral strain increase when time increases. Using correlation 5 yields the same profile scaled by the time. Correlation 10 yields a more peaky profile at high flux locations (in the middle of the channel) than at low flux locations (at the channel ends). Consequently, correlation 10 is more conservative than correlation 5 in predicting the future axial profile of diameter and strain for a crept pressure tube, in particular for a high-power channel and high flux regions in the channel. As an example, the values predicted for the maximum diameter and corresponding diametral strain of channel P10 at 220,000 EFPH are 106.9 and 3.04%, respectively, using correlation 5 and 107.5 and 3.57%, respectively, using correlation 10.

Based on the preceding discussions, correlation 10 is recommended to predict the axial profile of the diameter for crept pressure tubes in safety analysis for the following reasons:

- Correlation 10 has the correct asymptotic behaviour at time zero. The value of the coefficient, A_1 is small which means that the deviation in the assumed initial diameter is small and within the value of the tolerance allowed.
- The correlation has the more appropriate form than the other correlations since the rates of diameter change and consequently diametral strain change with respect to time are functions of the flux along the channel and they differ from one channel to another, as expected.
- The accuracy of correlation 10, with respect to associated errors, is superior to the other correlations.
- Correlation 10 is more conservative (gives larger values of predicted pressure tube diameters and diametral strains) than correlation 5 in predicting the future axial profile of diameter and strain for a crept pressure tube, in particular for a high-power channel and high flux regions in the channel.

Correlation 10 is also used to predict the maximum mean diameter. Comparisons between the predicted and measured pressure tube diameters are illustrated in Figure 7. The systematic error is about 0.04 mm (under-prediction), whereas the random error is about 0.17 mm. The maximum positive error (under-prediction) is 0.32 mm, whereas the maximum negative error (over-prediction) is 0.27 mm.

The error between the predicted and measured diameters as a function of various parameters such as measured diameter, fluence, flux, time and coolant temperature is illustrated in Figures 8 to 12. In general, there is no noticeable abnormality in the variation of the error. However, the error as a function of axial distance shows a pattern in the error distribution. For example, the correlation over-predicts the diameter at the location of the down-stream bundle and under-predicts (in most cases) the diameter at the location of the up-stream bundle. This pattern may be attributed to the uncaptured dependency of the axial position on the metallurgical properties of the pressure tube combined with the effect of the coolant pressure.

To examine the error normality, the frequency distribution of the error are constructed by dividing the overall range of the error (from -1 to +1 mm) into a number of classes and counting the number of observations that fall into each of these classes. Histogram profile for the error using an equal class interval of 0.04 mm is shown in Figure 13 for correlation 10. This indicates that the error distribution is close to the normal distribution and about 95% of all data are observed to fall between $\pm 2\ \varepsilon_{rms}$. Just as a frequency distribution can be represented graphically by a histogram, a cumulative frequency distribution can be represented graphically by an ogive as illustrated in Figure 14. From the cumulative frequency distribution, it can be estimated that about 95% of the number of observations have errors less than 0.267 mm.

The predictions of pressure tube diameter and diametral strain as functions of fluence and lifetime average coolant temperature using correlation 10 are illustrated graphically in Figures 15 and 16, respectively. Also, correlation 10 is used to predict the pressure tube diameter and corresponding diametral strain at various times (100,000 to 220,000 EFPH) for all the inspected channels. In these predictions, the lifetime average coolant temperature and channel time-average flux (at the time of inspection) are used. As a sample of calculations, the predicted pressure tube diameter profiles and the corresponding strain profiles for various times from 100,000 to 220,000 EFPH are shown, for channel P10, in Figures 17 and 18 using correlation 10. The diametral strain is based on the initial diameter of 103.79 mm.

5 CONCLUSIONS

As part of an overall program to quantitatively examine the integrated effects of HTS aging, Bruce Power and Ontario Power Generation (OPG) have collaborated on the development of a crept pressure tube model. This paper presents the model for the prototype station, Bruce B. Available pressure tube inspection data for Bruce B is utilized to develop a model to be used in predicting the axial profile of the diameter of crept pressure tubes.

Ten forms of correlations are examined. The first five correlations are functions of time-average neutron flux and the time variable is treated as a separate parameter, whereas the other five forms are functions of fluence. Including channel-average flux or channel-average fluence, as a variable parameter, has an insignificant effect on the accuracy of these correlations. However, including lifetime average coolant temperature, as a variable parameter, improves the accuracy of the correlations and reduces the random error significantly.

The developed models are capable of predicting the current and future axial profile of crept pressure tubes provided the time (EFPH) and neutron flux profiles (or alternatively fluence profiles) are available. It is concluded that correlation 10 has the correct asymptotic behaviour and is superior to other correlations. The random error of the correlation is 0.17 mm whereas the maximum positive error (under-prediction) is 0.39 mm and the maximum negative error (over-prediction) is 0.49 mm. It is estimated that about 95% of the number of observations have errors less than 0.267 mm. The correlation under-predicts the data of the maximum mean diameter by

0.04 (systematic error) and 0.17 mm (random error). The magnitude of the observed under-prediction does not impact the safety analysis in any significant manner.

For the 37 inspected channels, the maximum pressure tube diameter is about 107.50 mm and the corresponding diametral strain is about 3.6% at 220,000 EFPH. These values are based on the profiles of lifetime average coolant temperature and channel time-average flux at the time of inspection and the diametral strain is based on the initial diameter of 103.79 mm. The values of diametral strains increase as the value of the initial diameter decreases.

6 RECOMMENDATIONS

- It is recommended to explore utilization of all available data for 37-element fuel channels to develop the pressure tube creep model.
- It is recommended to introduce the coolant pressure as a variable in the developed correlations if further refinement is required.
- It is also recommended to use correlation 10 to predict the maximum diameter for pressure tube structural integrity. A correction of 0.267 mm and 0.26% should be added to the best estimate values predicted by correlation 10 for maximum diameter and corresponding diametral strain, respectively. These values may be used to ensure that the correlation gives an upper bound prediction for 95% of the inspected data assuming that the error associated with the correlation will not increase with time.
- The reported values of the diametral strain are based on the initial diameter of 103.79 mm. It is recommended that these values be updated accordingly if it is decided that a different initial diameter should be used.
- The developed methodology in this report can be used in predicting the pressure tube thickness using the available inspection data.

ACKNOWLEDGMENTS

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TABLE1: PRESSURE TUBE DIAMETER CORRELATIONS (BASED ON TIME AVERAGE NEUTRON FLUX)

Correlation	1	2	3	4	5
Errors (based on all data)					
Systematic Error (mm)	0.74509×10^{-4}	-0.16002×10^{-4}	0.17594×10^{-4}	0.97859×10^{-5}	0.28941×10^{-4}
Random Error (mm)	0.27319	0.27192	0.18548	0.18160	0.17187
Maximum Positive Error (mm)	0.72684	0.70867	0.48118	0.42696	0.40537
Maximum Negative Error (mm)	-0.59413	-0.59922	-0.43010	-0.48031	-0.43462

TABLE2: PRESSURE TUBE DIAMETER CORRELATIONS (BASED ON FLUENCE)

Correlation	6	7	8	9	10
Errors (based on all data)					
Systematic Error (mm)	-0.18120×10^{-3}	0.76115×10^{-4}	-0.32272×10^{-5}	0.27915×10^{-4}	-0.22903×10^{-5}
Random Error (mm)	0.27256	0.27177	0.18408	0.18117	0.17153
Maximum Positive Error (mm)	0.71739	0.70766	0.50536	0.44615	0.39447
Maximum Negative Error (mm)	-0.58651	-0.60081	-0.46986	-0.51231	-0.48572

FIGURE 1 : MEASURED PRESSURE TUBE DIAMETER AS FUNCTION OF FLUENCE

BRUCE B

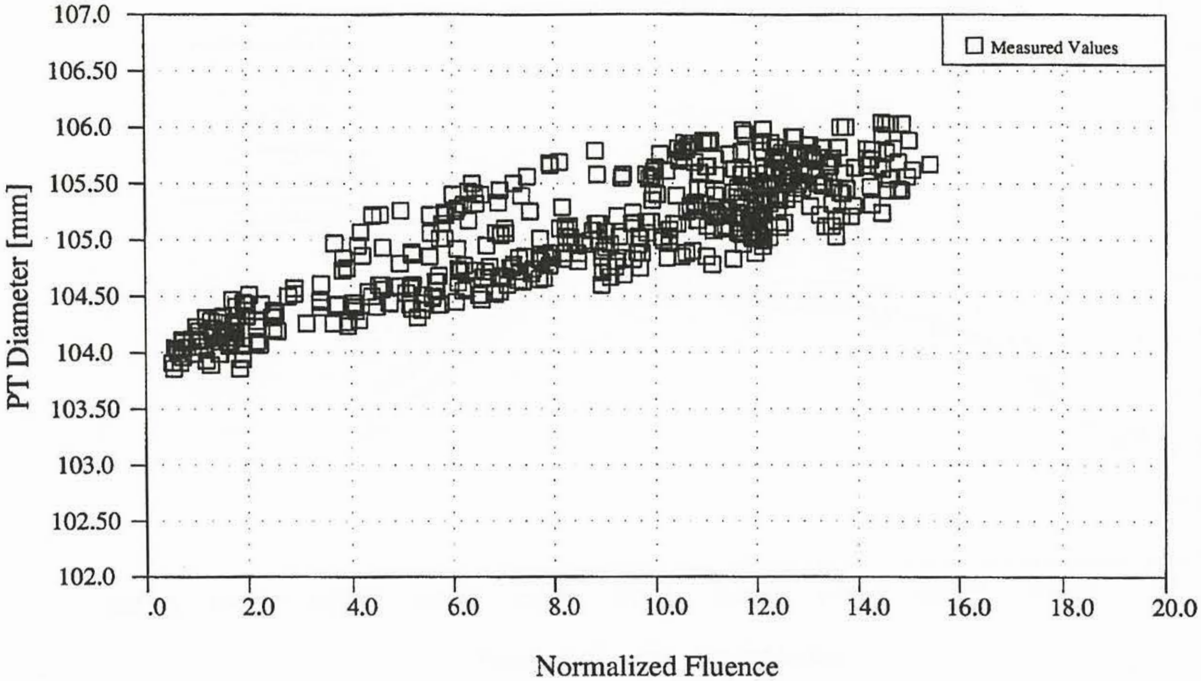

FIGURE 2 : MEASURED PRESSURE TUBE DIAMETER AS FUNCTION OF FLUX

BRUCE B

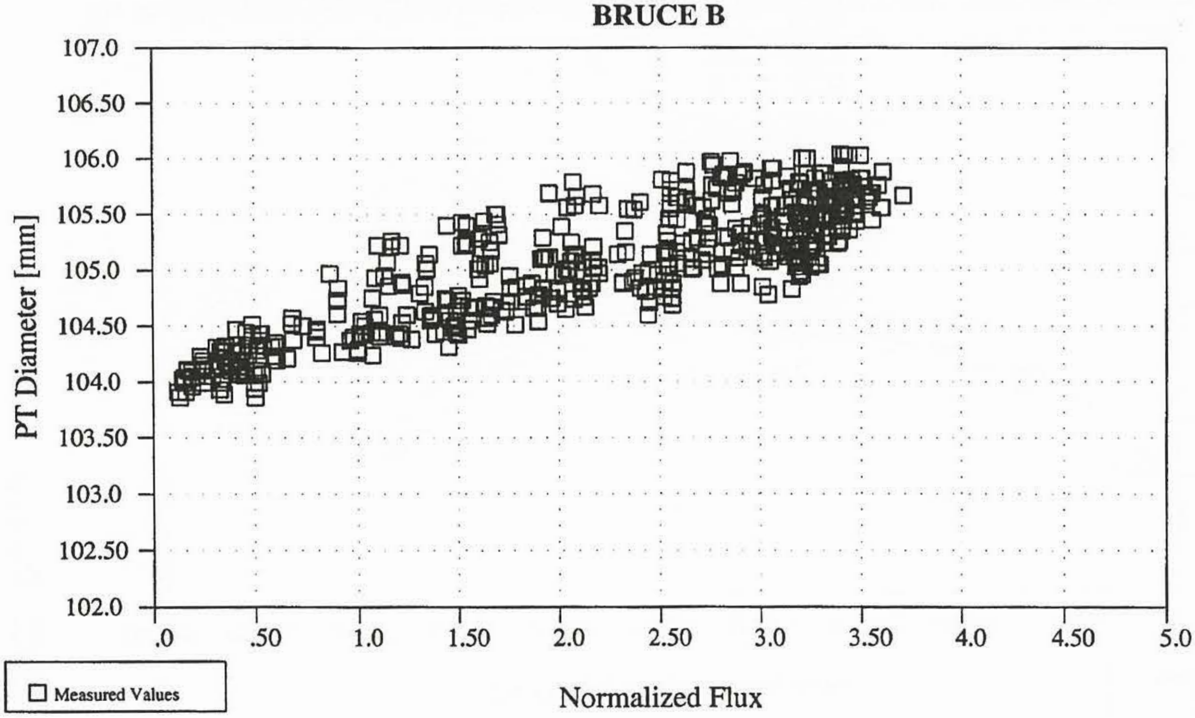

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FIGURE 3 : COMPARSION BETWEEN PREDICTED AND MEASURED PRESSURE TUBE DIAMETER PROFILES BRUCE B (CHANNEL G08 AT 105395 EFPH) USING VARIOUS CORRELATIONS (1 to 5)

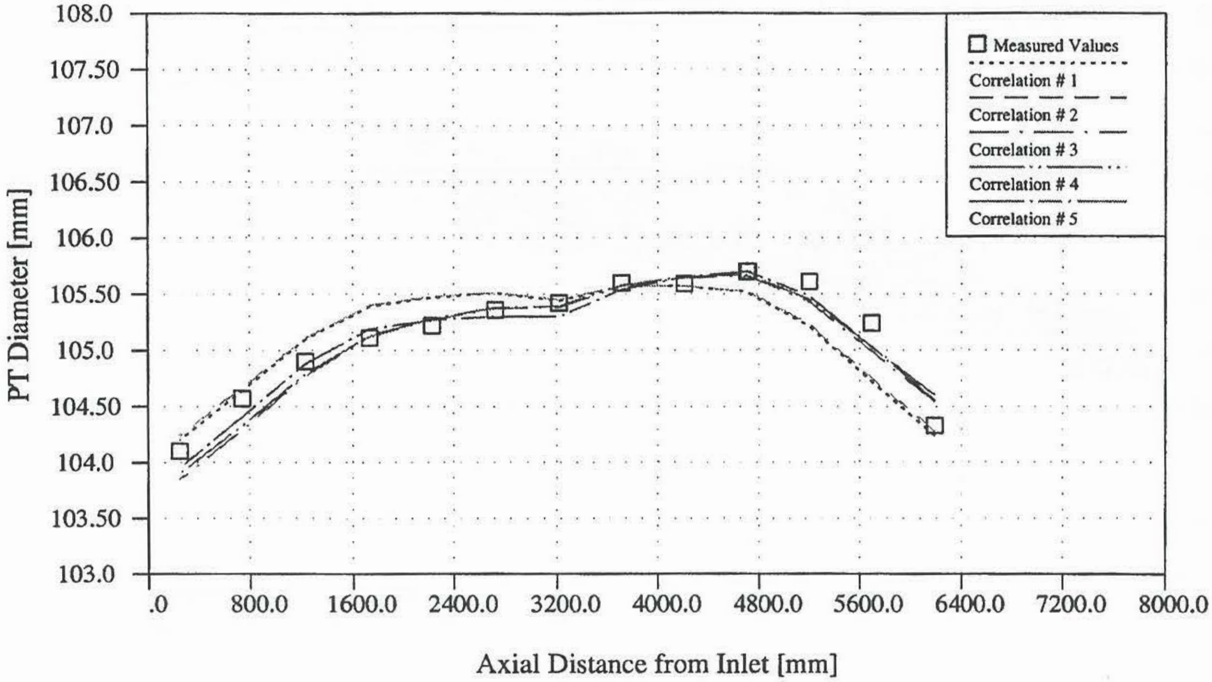

FIGURE 4 : COMPARSION BETWEEN PREDICTED AND MEASURED PRESSURE TUBE DIAMETER PROFILES BRUCE B (CHANNEL G08 AT 105395 EFPH) USING VARIOUS CORRELATIONS (6 to 10)

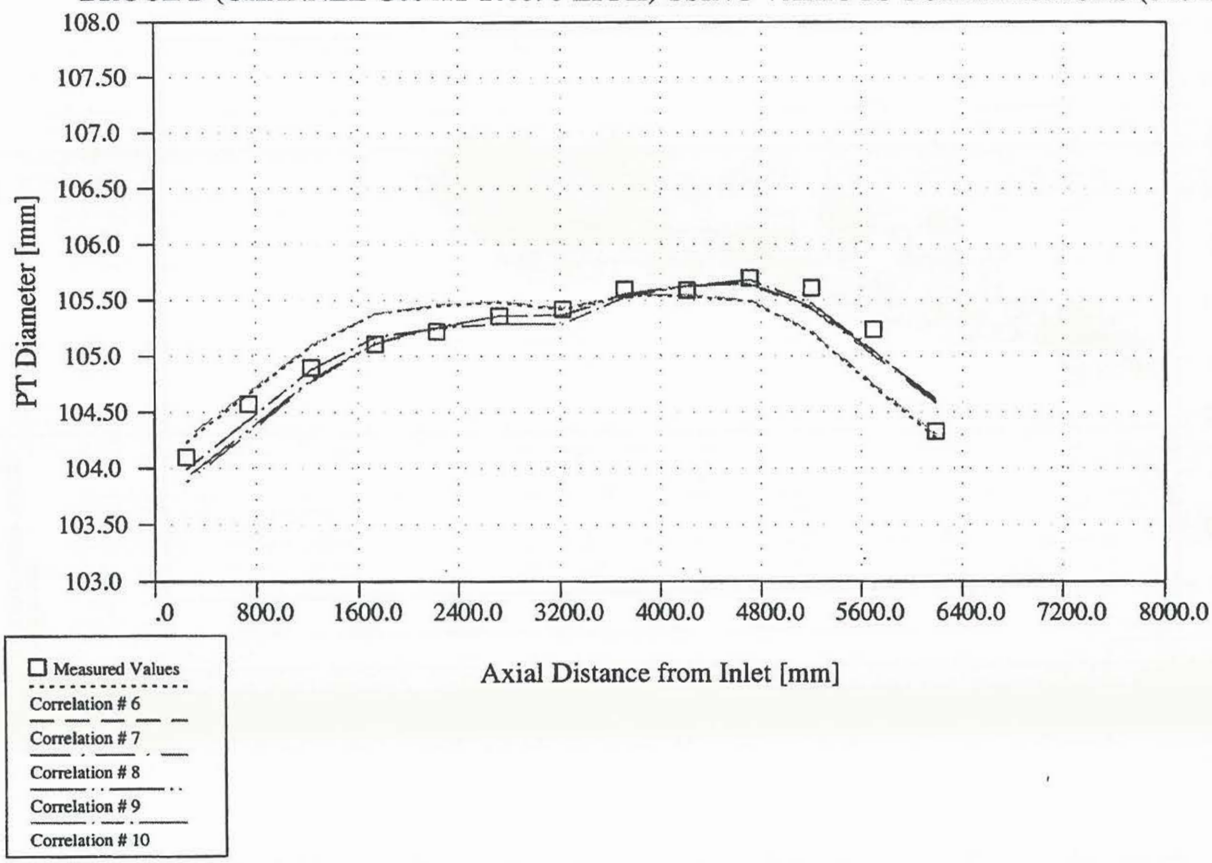

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FIGURE 5 : COMPARSION BETWEEN MEASURED AND PREDICTED PRESSURE TUBE DIAMETERS BRUCE B, USING CORRELATION # 5

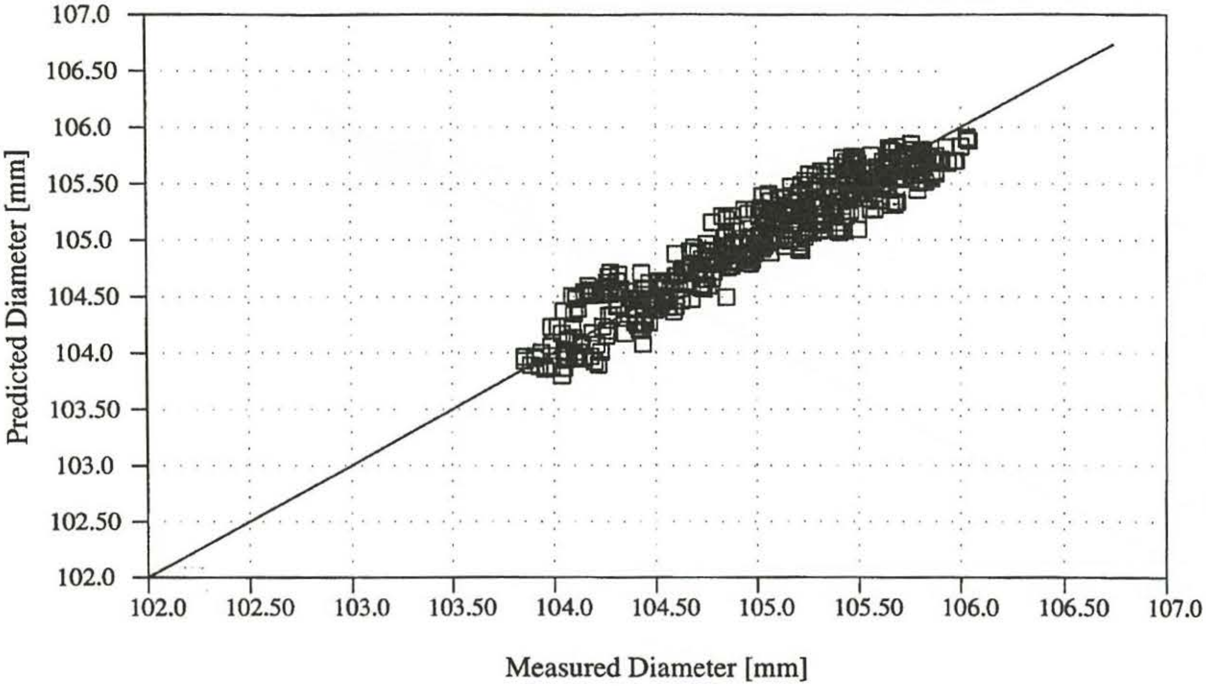

FIGURE 6 : COMPARSION BETWEEN MEASURED AND PREDICTED PRESSURE TUBE DIAMETERS BRUCE B, USING CORRELATION # 10

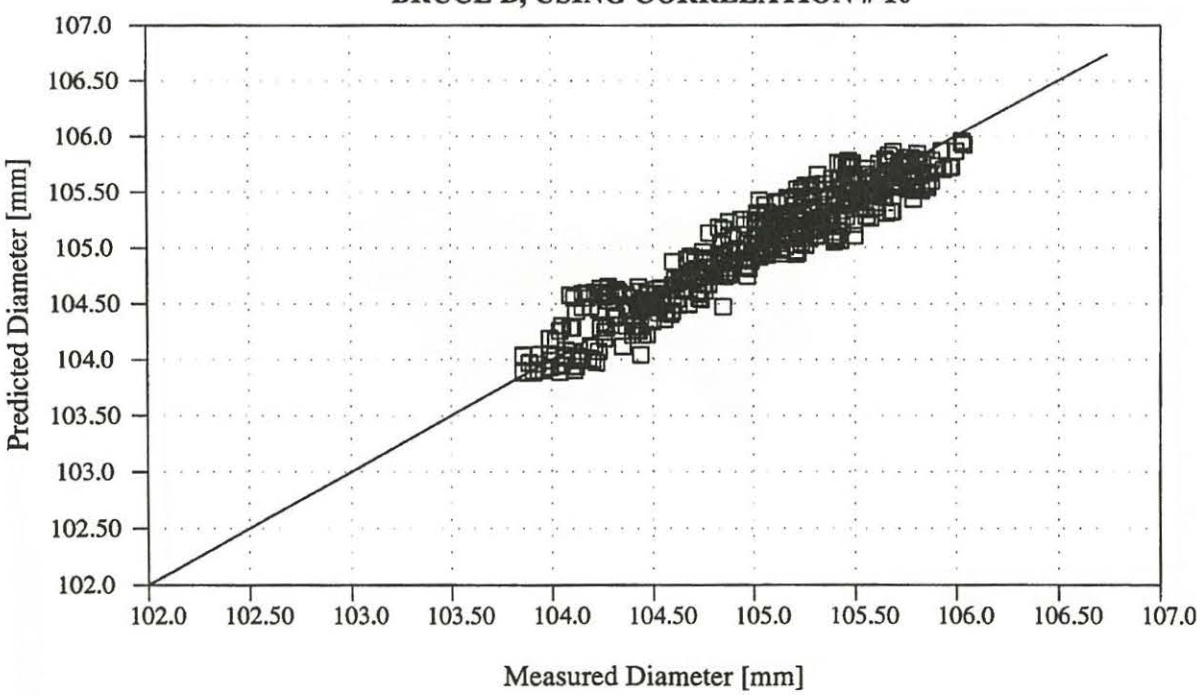

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FIGURE 7 : COMPARSION BETWEEN MEASURED AND PREDICTED MAXIMUM PRESSURE TUBE DIAMETERS BRUCE B, USING CORRELATION # 10

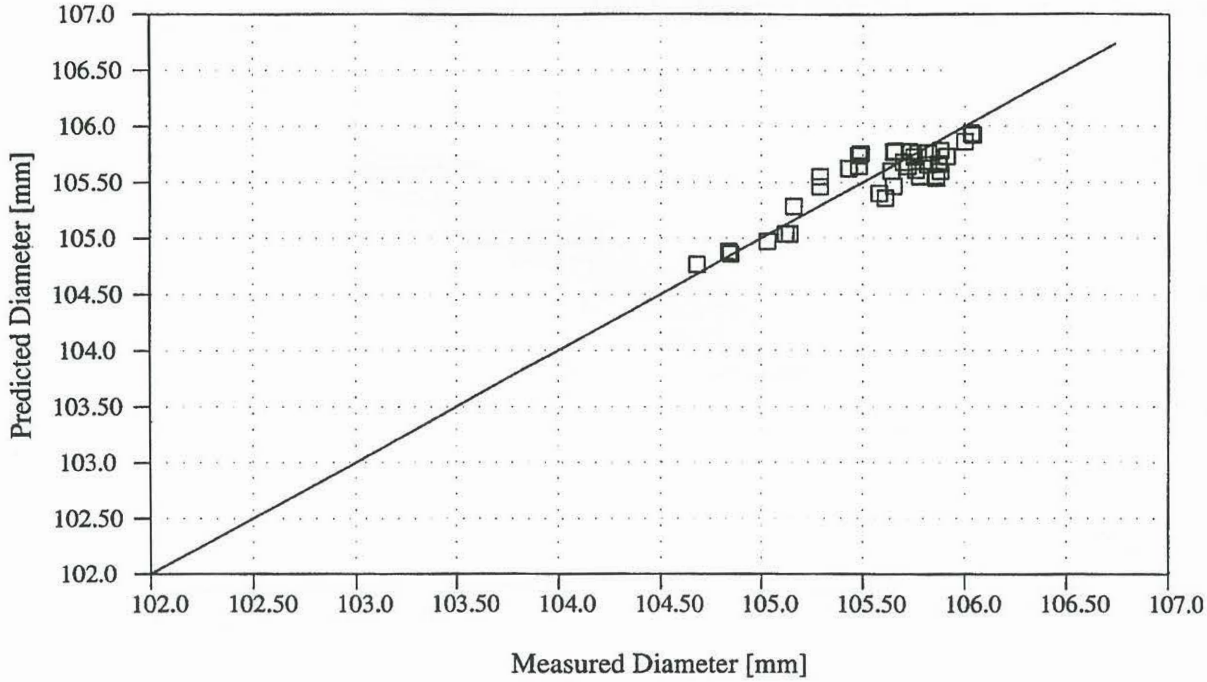

FIGURE 8 : ERROR IN PREDICTED PRESSURE TUBE DIAMETER AS FUNCTION OF MEASURED DIAMETER BRUCE B, USING CORRELATION # 10

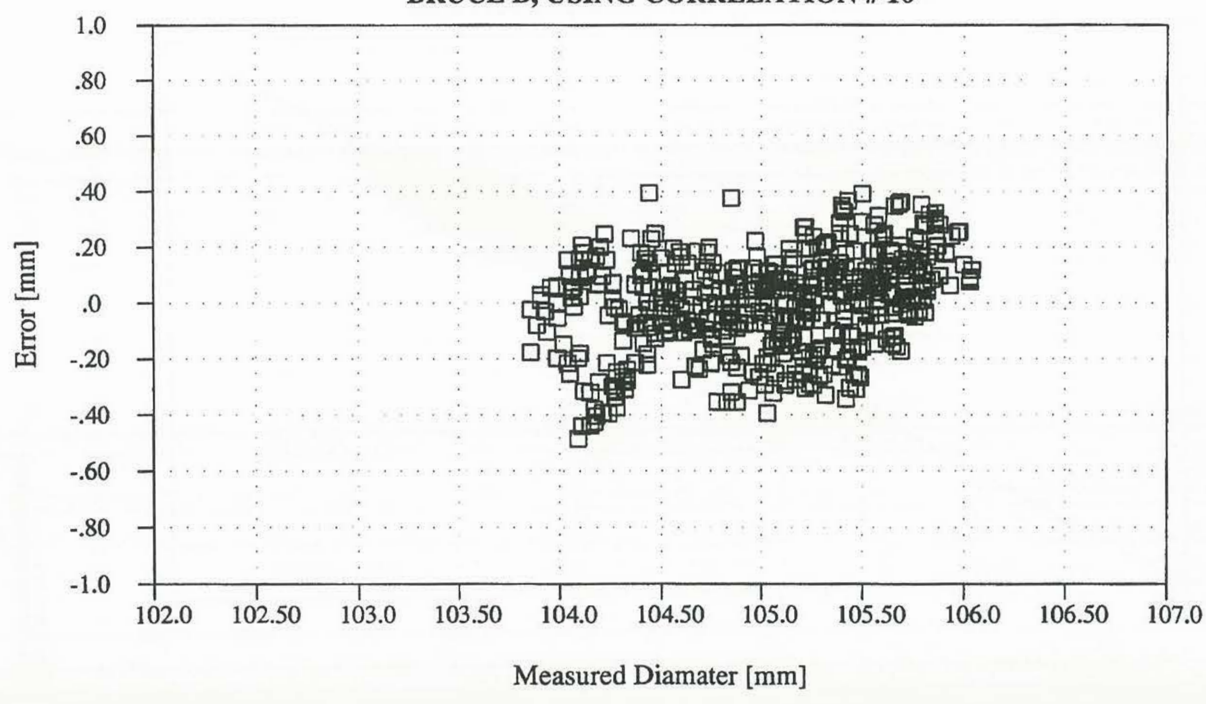

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FIGURE 9 : ERROR IN PRESSURE TUBE DIAMETER AS FUNCTION OF FLUENCE BRUCE B, USING CORRELATION # 10

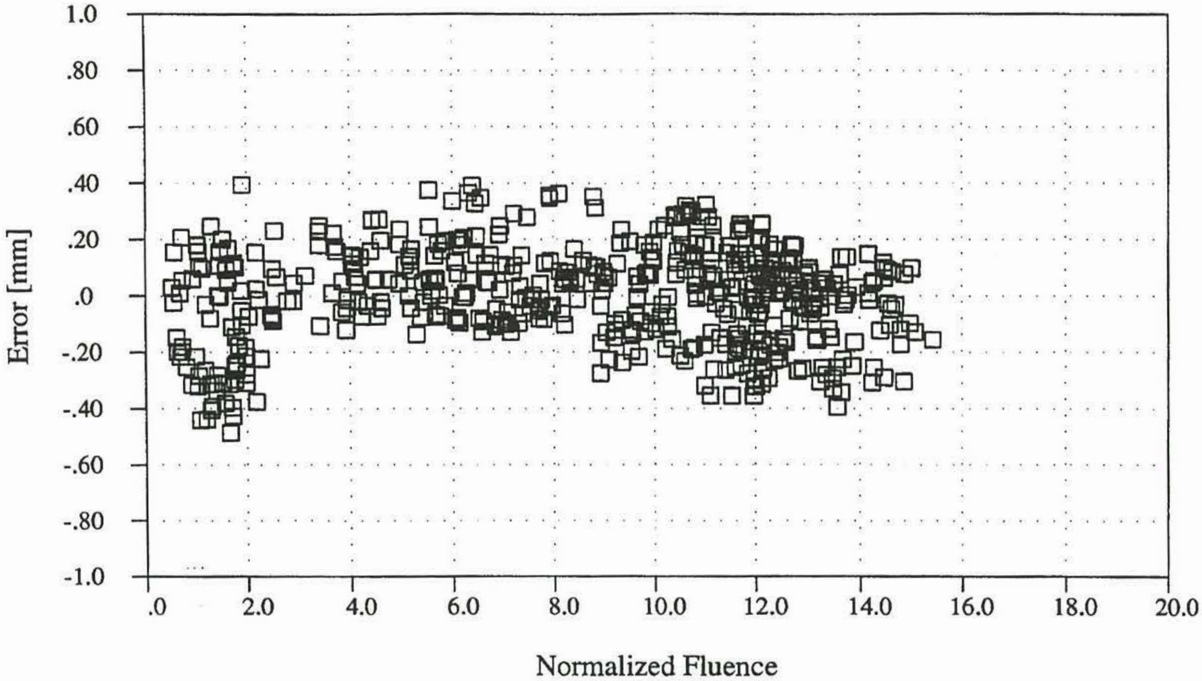

FIGURE 10 : ERROR IN PRESSURE TUBE DIAMETER AS FUNCTION OF FLUX BRUCE B, USING CORRELATION # 10

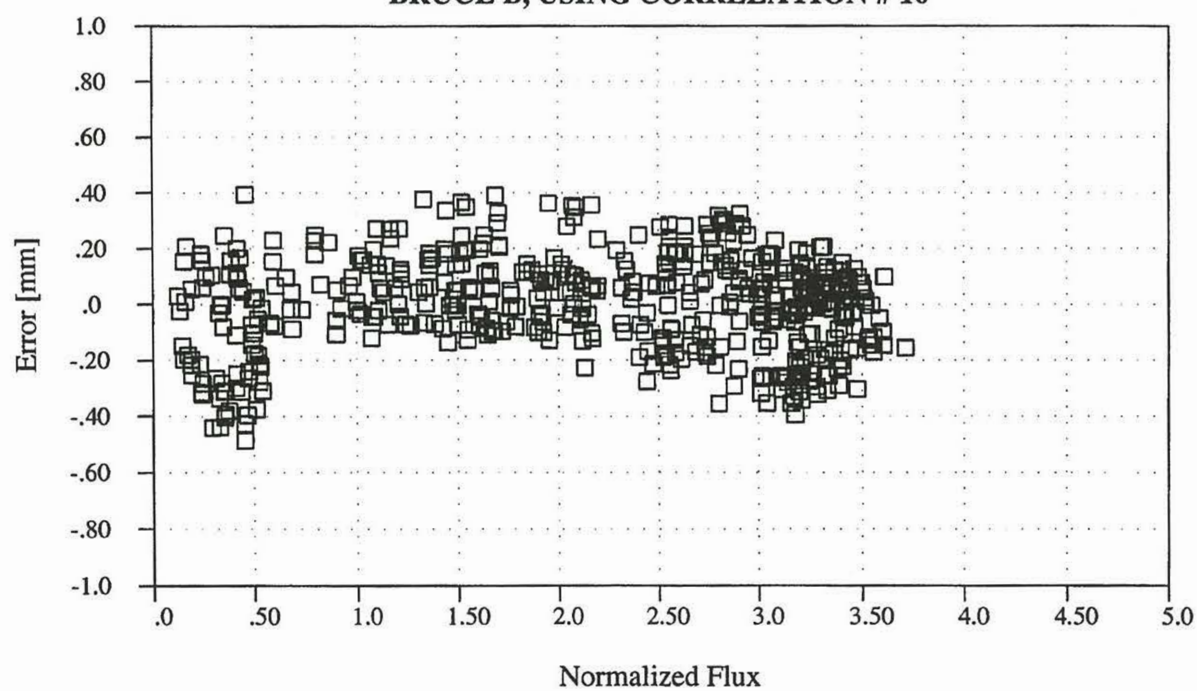

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FIGURE 11 : ERROR IN PRESSURE TUBE DIAMETER AS FUNCTION OF TIME
BRUCE B, USING CORRELATION # 10

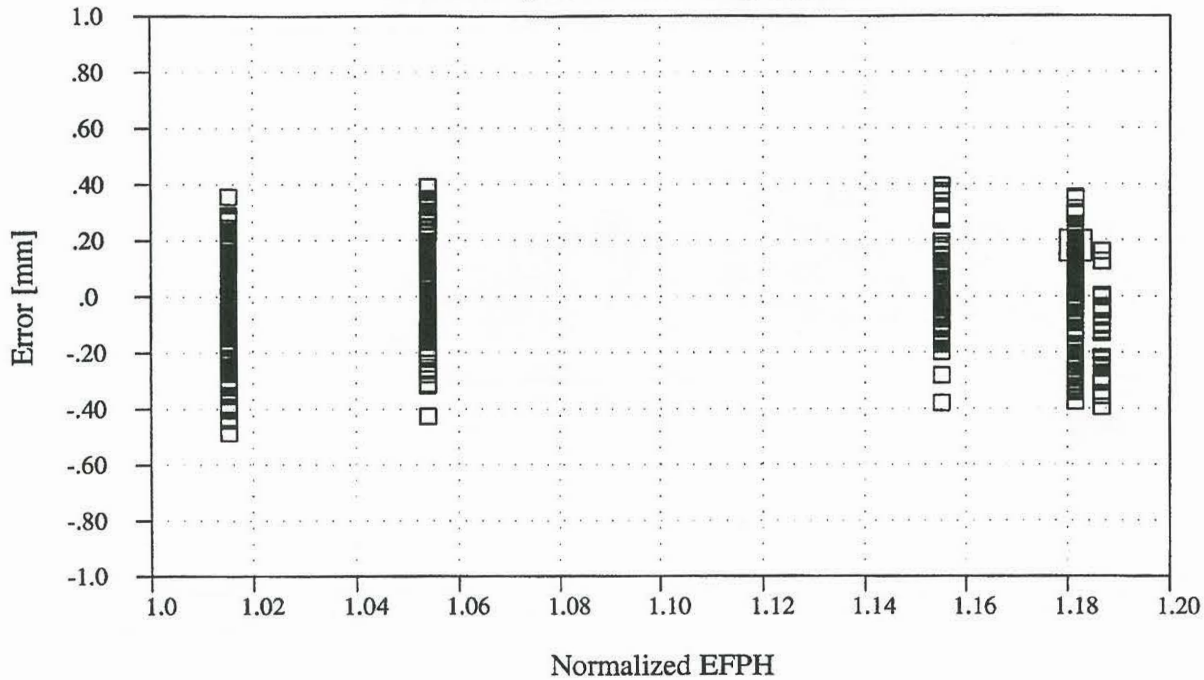

FIGURE 12 : ERROR IN PRESSURE TUBE DIAMETER AS FUNCTION OF TEMPERATRURE
BRUCE B, USING CORRELATION # 10

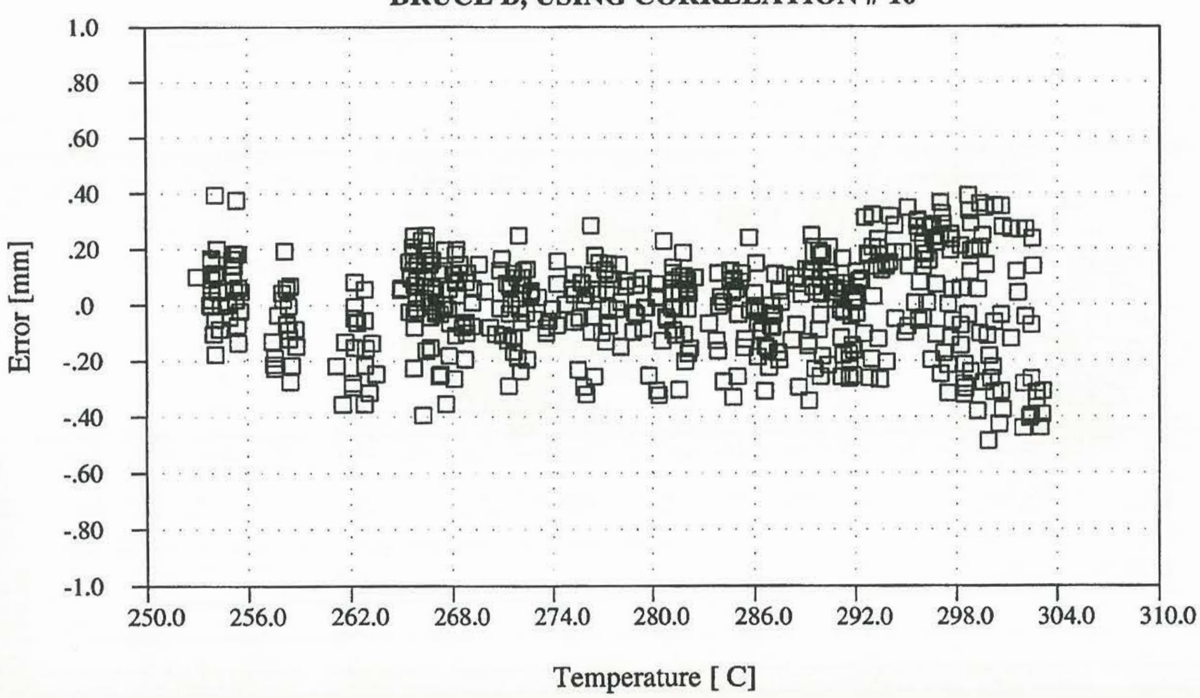

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FIGURE 13 : HISTOGRAM OF ERROR BETWEEN PREDICTED AND MEASURED DIAMETERS BRUCE B, USING CORRELATION # 10

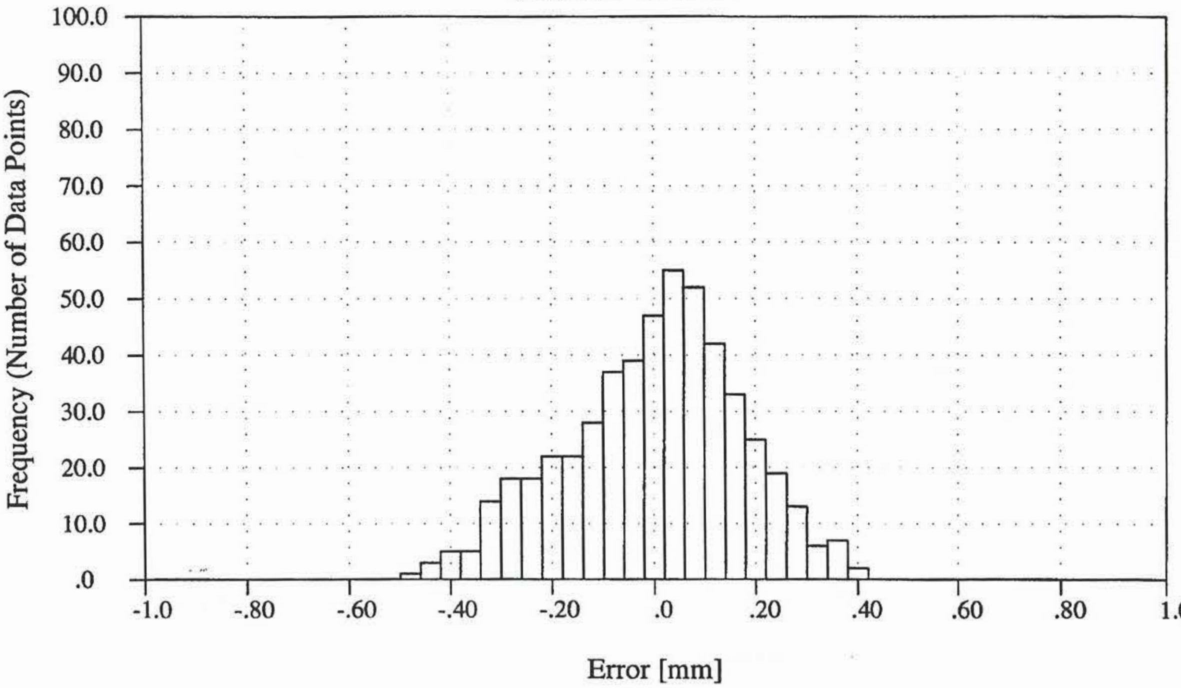

FIGURE 14 : OGIVE FOR THE CUMULATIVE FREQUENCY OF ERROR BRUCE B, USING CORRELATION # 10

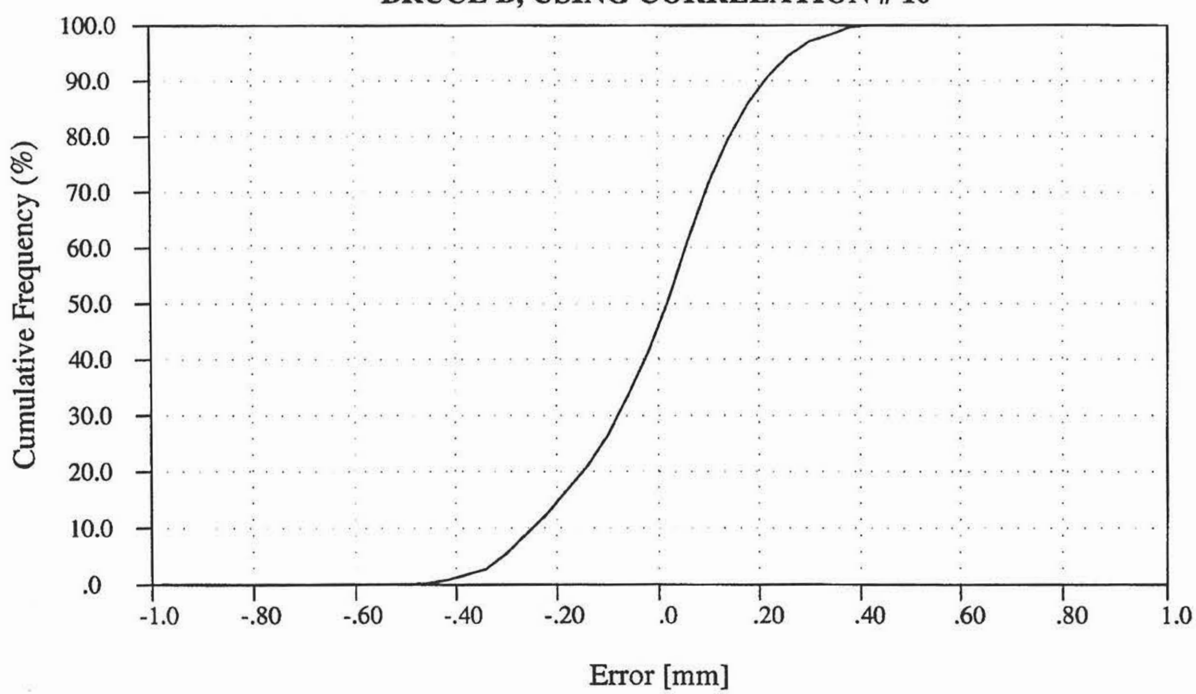

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FIGURE 15 : PRESSURE TUBE DIAMETER AS FUNCTION OF FLUENCE AND TEMPERATURE BRUCE B, PREDICTED USING CORRELATION # 10

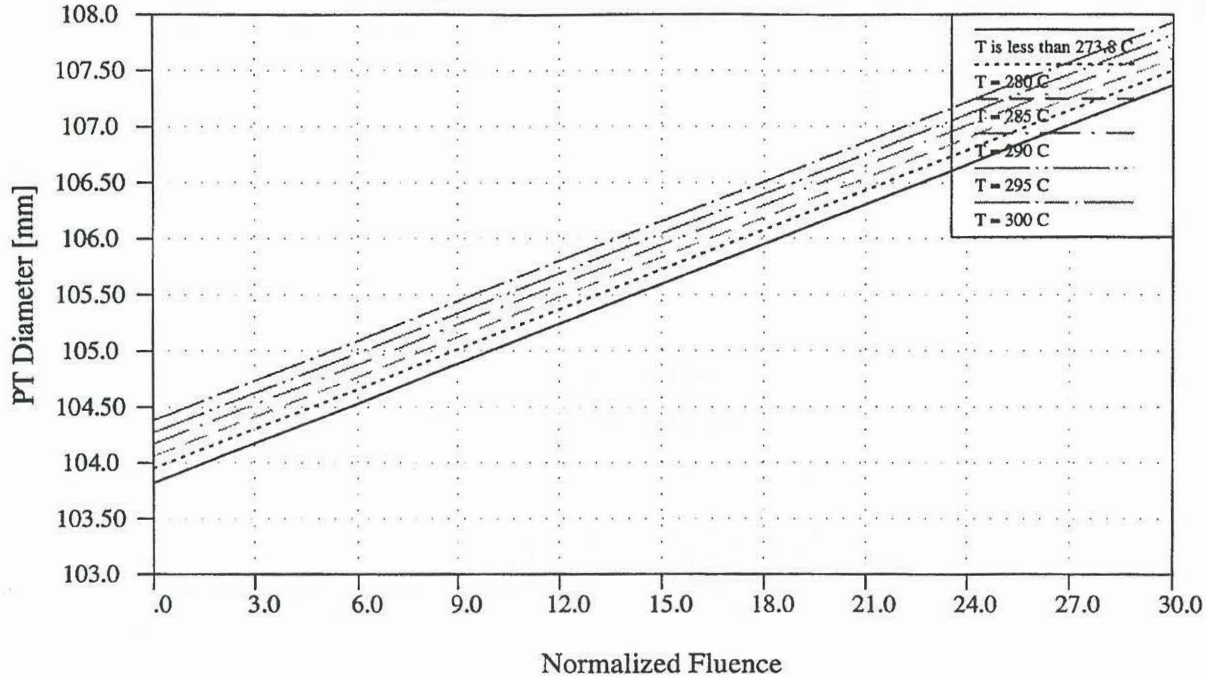

FIGURE 16 : PRESSURE TUBE DIAMETRAL STRAIN AS FUNCTION OF FLUENCE AND TEMPERATURE BRUCE B, PREDICTED USING CORRELATION # 10 (D0 = 103.79 mm)

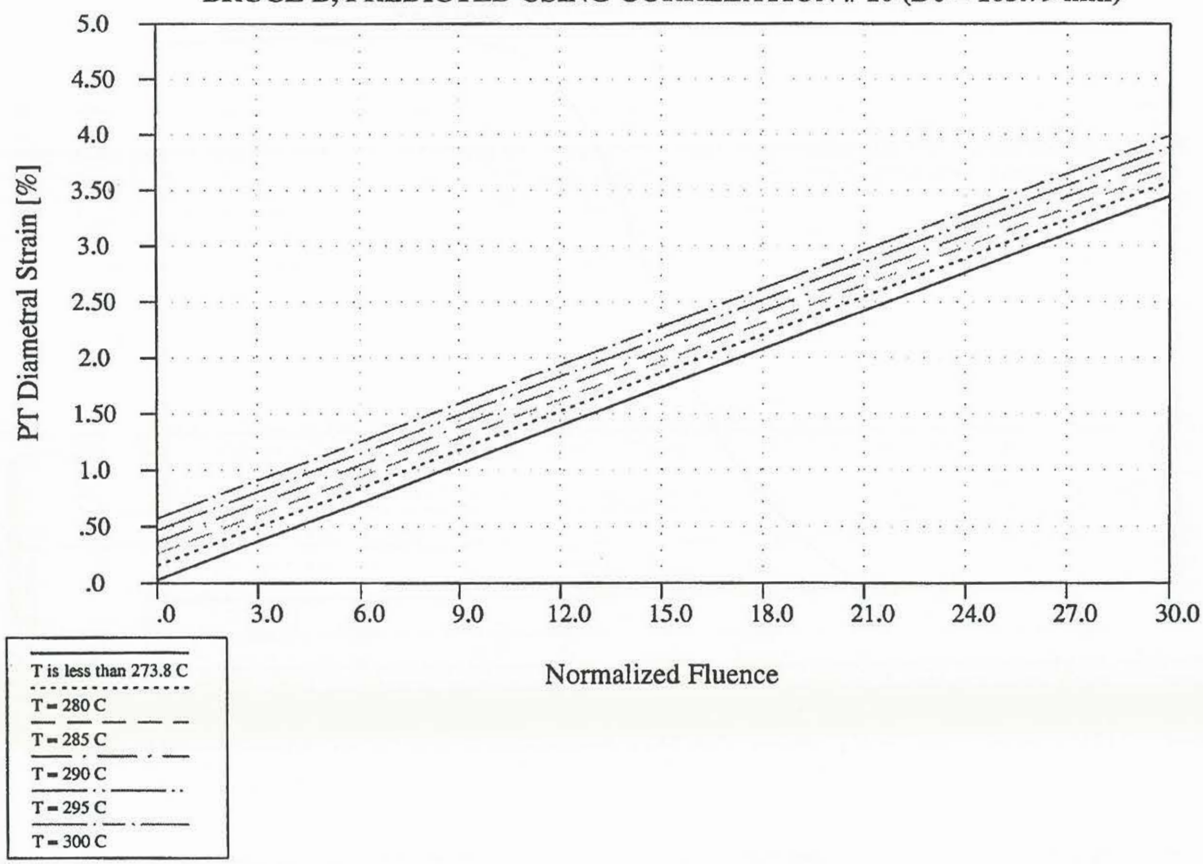

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FIGURE 17 : PREDICTED PRESSURE TUBE DIAMETER PROFILES AS FUNCTION OF TIME BRUCE B (CHANNEL P10) USING CORRELATION # 10

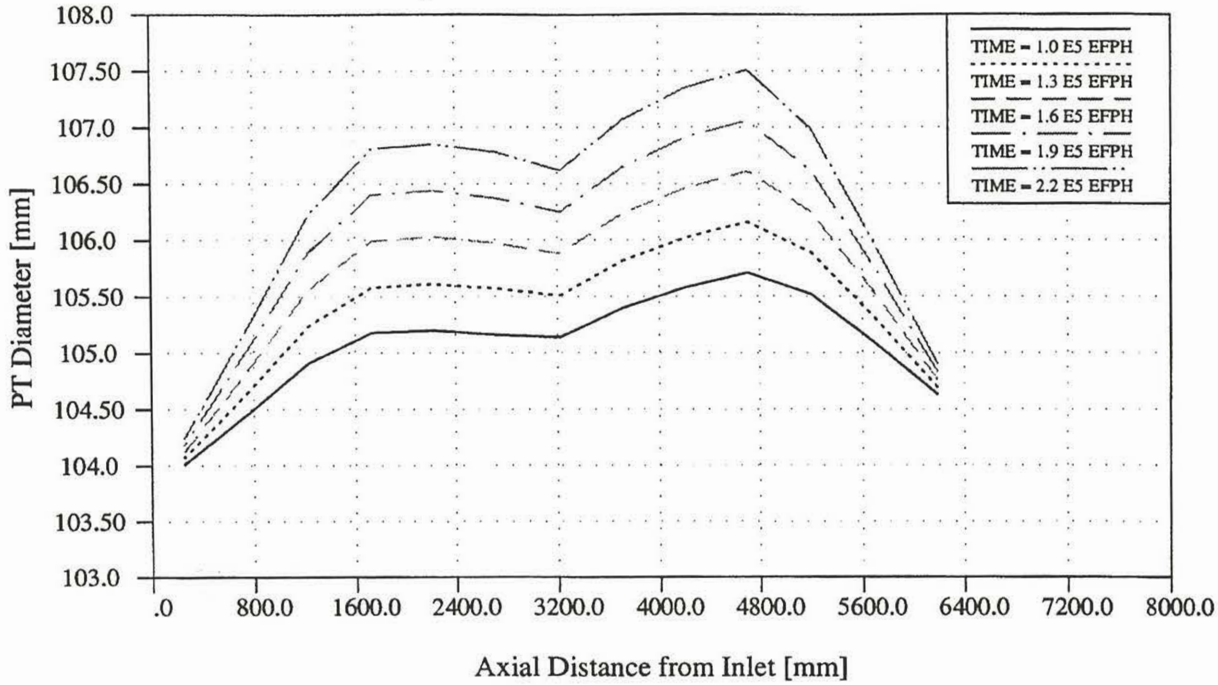
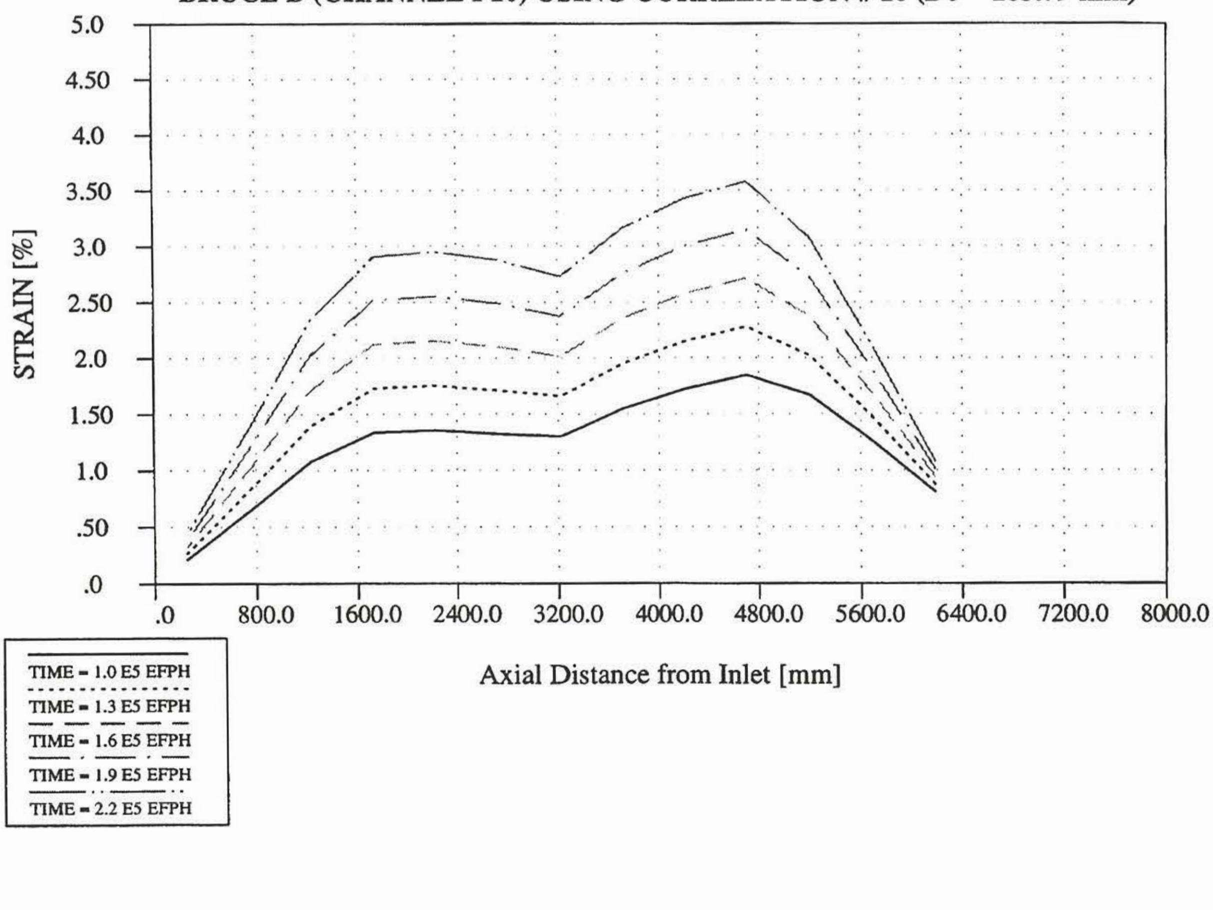


FIGURE 18 : PREDICTED PRESSURE TUBE DIAMETRAL STRAIN PROFILES AS FUNCTION OF TIME BRUCE B (CHANNEL P10) USING CORRELATION # 10 (D0 = 103.79 mm)



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