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ANALYSIS OF PRESSURE TUBE MEASURED DATA FOR CANDU REACTORS

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ABSTRACT –Given that pressure tube deformation can affect the operational margin and the lifetime of a reactor, it should be measured periodically. In this study, measured data pertaining pressure tube diameterswere analyzed in an effort to understand the deformation behavior. An evaluation methodology pertaining to the maximum diametral expansion and axial elongation of pressure tubes was established based on the results of a data analysis. From the evaluation results, it was found that the diametral expansion values of most pressure tubes were within the limits established for diameters in a critical heat flux experimental data base. Axial elongation values for most pressure tubes were found to be within the limits in the data base. However, when using a conservative methodology, which considers the increase in the elongation rate as a function of the operation time, some pressure tubes may exceed these limits at the end of the reactor lifetime.

Introduction

The pressure tubes of the CANDU reactor are designed with a long cylindrical shape with a diameter of approximately 10 cm and a length of about 6 m. Zirconium-2.5%niobium alloys are used as the pressure tube material consideringthe neutron economy, a lower creep rate in the reactor environment, superior corrosion resistance, and more favorable hydrogen pick-up characteristics [1-2]. Pressure tubes constitute the primary pressure boundary within the core of CANDU reactors and determine the operational and safety margin when operating the CANDU. Cold- worked Zr-2.5%Nb pressure tubes are deformed in the radial (diameter creep) and axial (elongation) directions and also subjected to sagging and wall thinning due to the severe operational environments, which is characterized by high temperatures and pressures as well as neutron irradiation when the reactor is operating. Diametral expansion results in a reduction of fuel cooling due to the increased bypass flow; this increases the possibility of fuel dry-out and thus limits the operating power of the reactor. Axial elongation may also interfere with the fuel handling machine and feeder pipe and can therefore, influence the continued operation of a currently operating reactor. Therefore, a proper understanding of the deformation phenomena and an evaluation methodology for deformation predictions are necessary. The power plant measures the dimensions of the pressure tubes in operation periodically and examines their integrity.

In this study, an evaluation methodology for maximum diametral expansion and axial elongation of pressure tubes was established based on measured data from the CANDU 6 nuclear power plant. In the evaluation results, it was found that the diametral expansion values of most pressure tubes were within the limitsestablished forthe diameters of these tubes in the critical heat flux experimental data base. Axial elongation values of most pressure tubes were found to be within the limits in the data base. However,when using a conservative methodology, which considers increase in theelongation rate as a function of the operation time, some pressure tubes may exceed the limits at the end of the reactor lifetime.

1. Measured Data of the Pressure Tube Diameter

Pressure tubesare investigaed periodically for certain selected fuel channels in the CANDU power plant.Because some of the pressure tubes are measured more thanthree times, the deformation trends of the pressure tube diameters could be analyzed. Figure 1 shows an example of the change in the pressure tube diameter according to the operation time.The left side of the figure shows the inlet of a fuel channel and the right side is the outlet to release the coolant. It is well known that the diametral creep of a pressure tube depends on the neutron flux and temperature, and this figure depicts this relationship. Because the coolant temperature increases from the inlet to the outlet parts and the neutron flux is high in the middle region of the pressure tube, as shown in Figure 2, the maximum diametraldeformation occurs at the outlet region, especially at bundles 9 and 10,due to the combined effect of the temperature and the neutron flux. Bundles 5 and 8 show irregular deformation in the middle of the bundle owing to the typical depressioncaused by the adjuster effect.

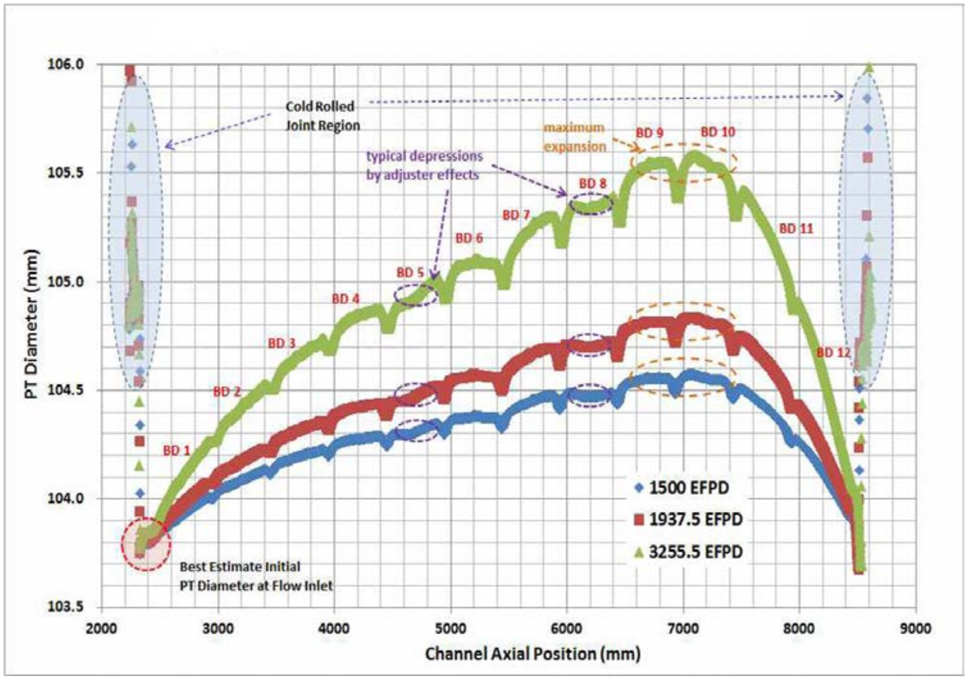

Figure 1Example of a measured diameter for a CANDU 6 pressure tube

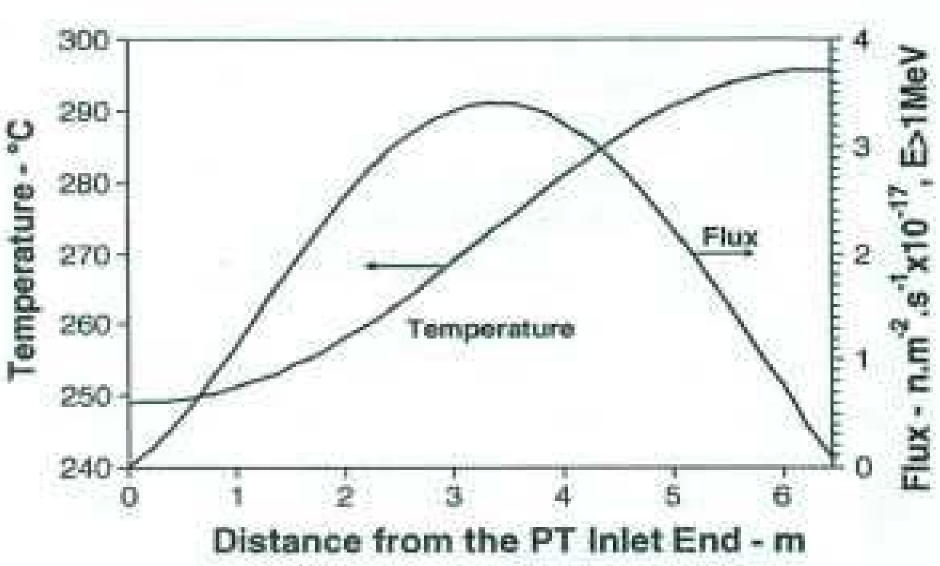

Figure 2Distributions of thetemperature and neutron flux

Figure 3 shows the diameter deformation of each bundle according to the effective full power day for the same pressure tube shown in Figure 1. As shown in the figure, the pressure tube diameter deforms linearly with the operating time.

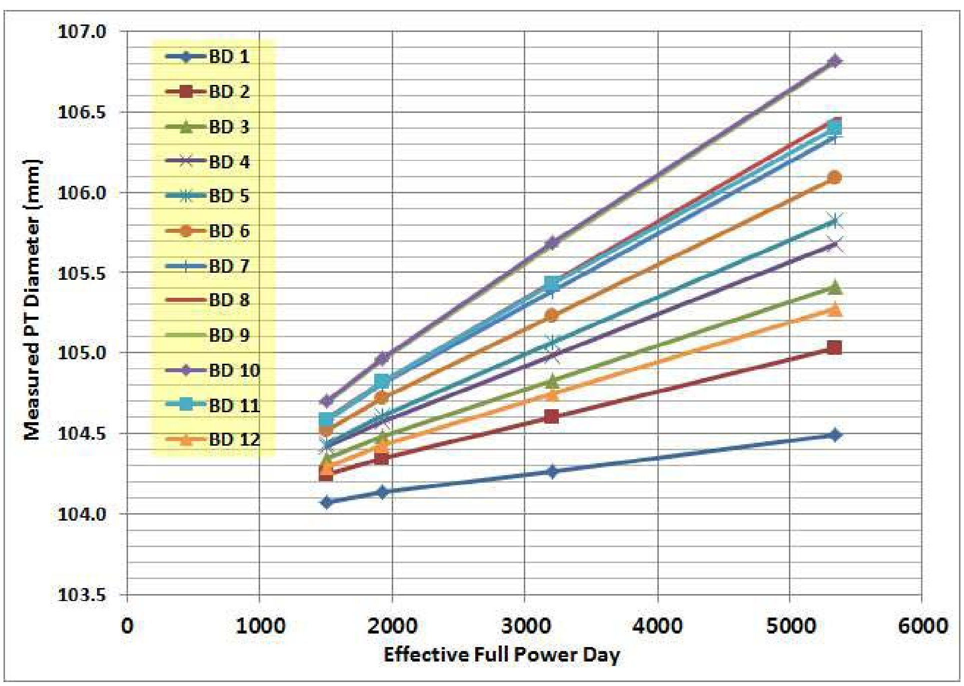

Figure 3 Bundle-wise diameter deformation

2. Methodology for Axial Elongation Estimation

As shown in Figure 1, both ends of the pressure tube are fixed with a cold rolled joint, but the end boundary conditions are different at both ends. One end region is a fixed end, which prevents axial elongation at that end, whereas the other end region is a free end such that axial elongation occurs at that end. Figure 4 shows the fixed end of the pressure tube at the inlet region. Regardless of the operation time, the end positions of the pressure tube are nearly identical, indicating that no axial displacement occurs at the fixed end. However, at the outlet region, the end positions of the pressure tube have shifted to the right according to the effective full-power day, as shown in Figure 5, indicating that the pressure tube is elongated in the axial direction with the operation time and that the axial elongation rate can be evaluated if the displacements and times are known.
When axial elongation occurs beyond the design limit, it may interfere with the fuel handling machine and feeder pipe and may result in a serious issue during continuous operation. Figure 5 indicates that the total axial elongation is 23.8 mm during the 1755.5 EFPDs between 1500 EFPD and 3255.5 EFPD. The total axial elongation includes 4.4 mm of axial elongation during the first 437.5 EFPDs and 19.4 mm more during the ensuing 1318 EFPDs. The axial elongation rate (mm/EFPD) could be extrapolated at the different EFPDs based on these measured data until the end of the design lifetime of 8750 EFPD, as shown in Table 1. This result shows that the axial elongation rate increases with the operation time, and the conservative axial elongation can be evaluated at any operation time using the results shown in Table 1. Table 2 summarizes the estimation results for the axial elongation up to 8750 EFPD, the end of the lifetime. The total axial elongation is estimated to be 171 mm, which is beyond the design limit for axial elongation. Although this evaluation was carried out under a conservative assumption, it remains necessary to monitor the axial elongation during the operation of a power plant.

Table 1 Predictions of the axial elongation rate

EFPD	Axial Elongation Rate (mm/EFPD)
0	0
1500	0.00851
1937.5	0.01006
3255.5	0.01472
4000	0.01736
5000	0.02090
6000	0.02444
7000	0.02798
8750	0.03418

Table 2 Evaluation of axial elongation

EFPD	Applied Elongation Rate (mm/EFPD)	Axial Elongation (mm)	Remark
0 ~ 1500	0.00851 (elongation rate at 1500 EFPD)	12.8	
1500 ~ 1937.5	-	4.4	Measurement

1937.5 ~ 3255.5	-	19.4	Measurement
3255.5 ~ 8750	0.02445 (average elongation rate at 3255.5 EFPD and 8750 EFPD)	134.4	
Total Axial Elongation		**171.0**	**Beyond design limit**

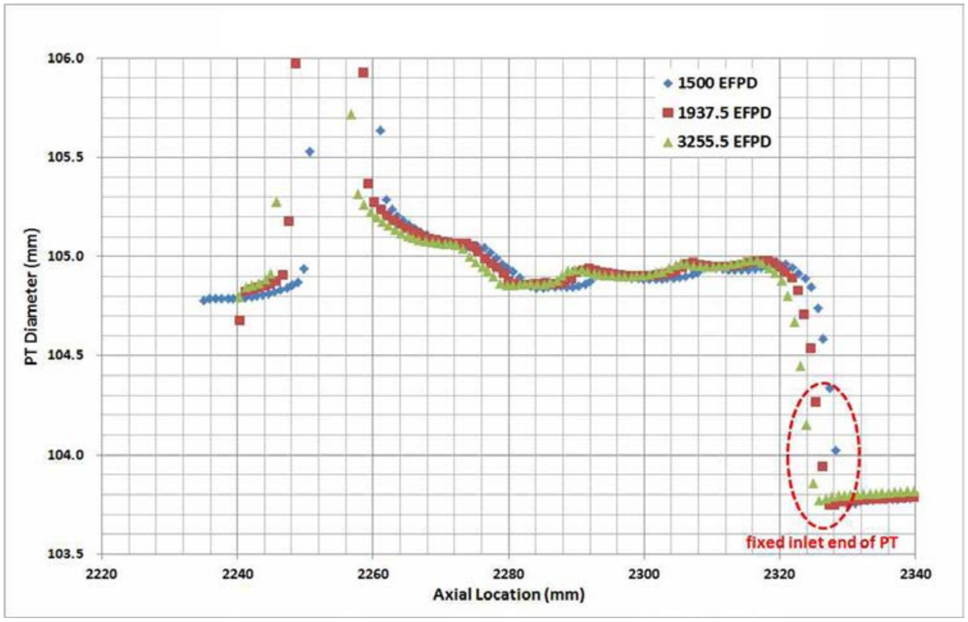

Figure 4 Fixed end of the pressure tube at the Inlet Region

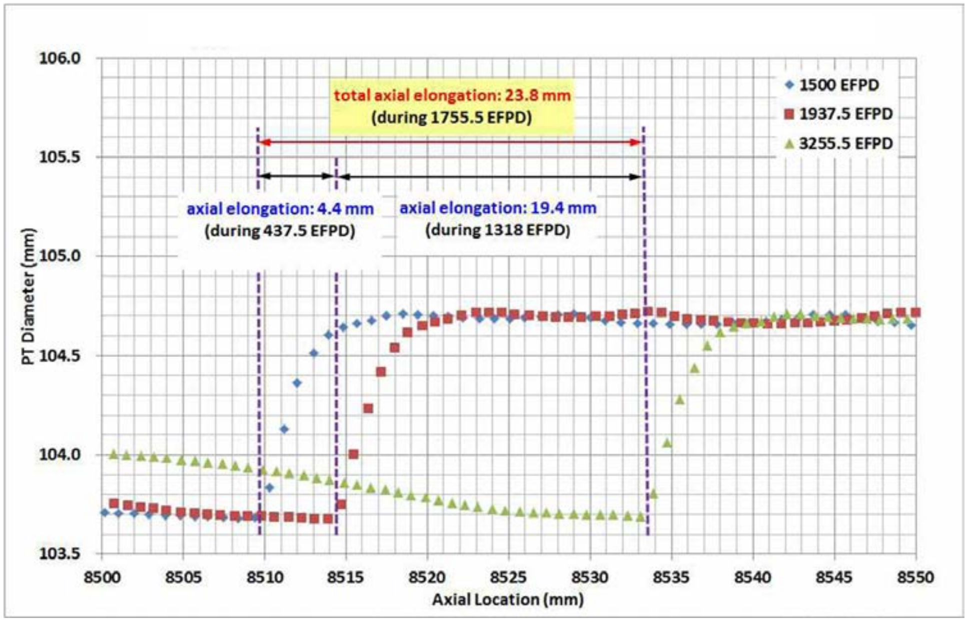

Figure 5 Free end of thepressure tube at the outlet region

3. Methodology for Maximum Diameter Estimation

As shown in Figure 6, the maximum diametral creep deformation occurs at bundle 10, and the measured maximum diameters are 104.58, 104.83 and 105.58 mm at 1500, 1937.5 and 3255.5 EFPD, respectively. From these measured data and considering the initial diameter of 103.7 mm, the maximum diametral deformation and the maximum diametral %creep can be calculated as shown in Table 3 for each measurement time. A linear relationship between the measured %creep and the EFPD can be interpolated, as shown in Figure 7. From these measured data for the diametral deformation, the maximum diametral %creep can be evaluated by extrapolating the linear relationship between the %creep and EFPD, as summarized in Table 4. Figure 8 shows the extrapolated results for the maximum diametral %creep until the end of the design lifetime of 8750 EFPD. As shown by this result, the diametral %creep at the end of the design lifetime for this pressure tube is within the %creep limit of 5.3% as set in the critical heat flux experimental database.

Table 3 Maximum diametral %creep for each measured time

EFPD	Max. Diameter (mm)	Max. Deformation (mm)	Max. %creep (Deformation/initial dia) x 100
0	103.70	0.00	0.0000
1500	104.58	0.88	0.8486
1937.5	104.83	1.13	1.0897
3255.5	105.58	1.88	1.8129

Table 4 Predictions of the max. diametral %creep

EFPD	Max. %creep extrapolation
0	0
1500	0.85
1937.5	1.09
3255.5	1.81
4000	2.22
5000	2.77
6000	3.32
7000	3.87
8750	4.42

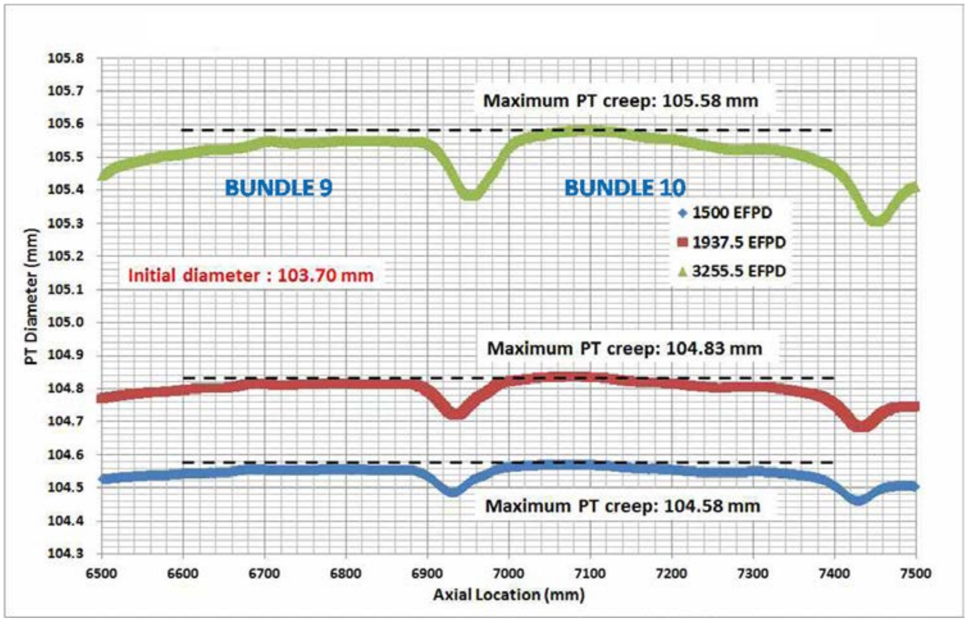

Figure 6 Maximum diametraldeformation

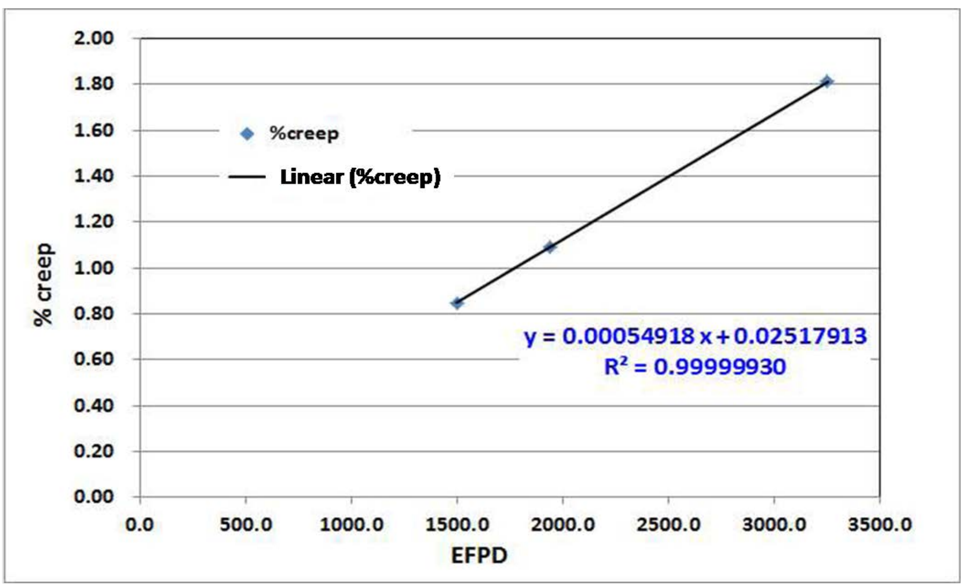

Figure 7 Linear interpolation of themaximum %creep

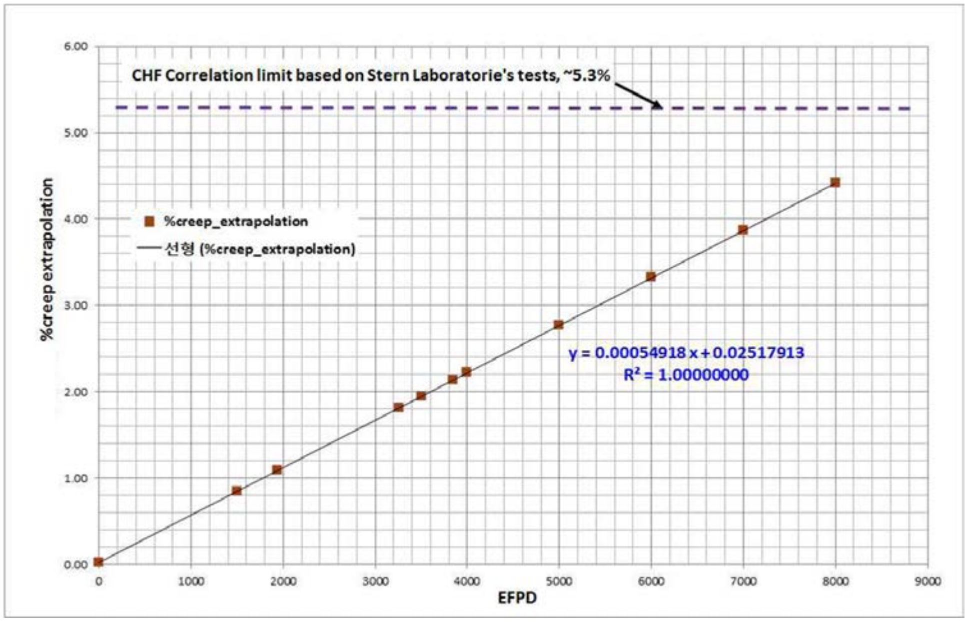

Figure 8 Extrapolation of themaximum diametral %creep

4. Conclusions

In this study, an evaluation methodology for maximum diametral expansion and axial elongation of a pressure tube was established based on measured data from the CANDU 6 nuclear power plant. In the evaluation results, it was found that the diametral expansion values of most pressure tubes were within the limits for the diameter in an experimental databasepertaining to the critical heat flux. Axial elongation of most pressure tubes was found within the limits established in the database as well. However, when using a conservative methodology which considers the increase in the elongation rate as a function of the operation time, some pressure tubes may exceed the limits at the end of the reactor lifetime.

5. References

[1] R.A. Holt, "In-Reactor Deformation of Cold-worked Zr-2.5Nb Pressure Tubes", Journal of Nuclear Materials, Vol. 372, 2008, pp 182-214.

[2] J.Y. Jung, "Database and Prediction Model for CANDU Pressure Tube Diameter", Proceedings of the 19th Pacific Basin Nuclear Conference, Vancouver, British Columbia, Canada, 2014 August 24-28.

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