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CCP Evaluation for CANDU Pressure Tubes under Maximum Allowable Creep

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1. Introduction

CANDU (CANadian Deuterium Uranium) reactors account for a significant portion of the global nuclear power generation capacity, owing to their unique pressure tube design, which offers distinct advantages in terms of fuel utilization and online refueling capabilities [1,2]. However, the pressure tube design also introduces unique challenges, particularly with respect to maintaining long-term structural integrity under prolonged exposure to high temperature, high pressure, and intense neutron irradiation [3].

Among various degradation mechanisms affecting pressure tubes, diametral creep deformation stands out as one of the most critical phenomena that directly impacts reactor safety and performance throughout the plant's operational lifetime. Creep in pressure tubes occurs due to the combined effects of thermal stress, mechanical loading, and irradiation-induced micro-structural changes in the Zircaloy material. This phenomenon manifests as gradual dimensional changes in the pressure tube geometry, including diameter expansion, length elongation and sagging, which can significantly alter the thermalhydraulic characteristics within the fuel channels.

The Critical Channel Power (CCP), which represents the maximum allowable power or heat flux that can be sustained in a fuel channel while maintaining adequate thermal margins, is particularly sensitive to these geometric changes.

The objective of this study is to quantify the effect of maximum allowable diametral creep on CCP using the NUCIRC (NUclear heat transport CIRcuit thermo hydraulics analysis Code), to specifically investigate the sole effect of maximum pressure tube creep on CCP [4,5]. In this paper, all other potential aging factors, such as fuel element elongation or pressure tube sag, are excluded to isolate the impact of creep.

2. Methodology and Assessments

This paper depicts evaluation methodologies and results for CCP values of generic CANDU reactors under maximum allowable creep condition using NUCIRC version 2.3.5 (NUCIRC 2.3.5) [4,5]. NUCIRC 2.3.5 is one of the code versions that include the range of pressure tube diametral creep up to 6.8%. Key assumptions and modeling are stated, followed by the results and trend analysis.

2.1 Key modeling assumptions

In the present study, maximum allowable creep is defined as the design limit diametral creep established by the effective range of Critical Heat Flux (CHF) correlation for modified 37-fuel elements (37M). For the generic CANDU, this limit could be set at 6.8% strain, representing the threshold beyond which continued operation may compromise the thermal-hydraulic safety margins of the pressure tube. Thus, conditions and correlations for Onset of Significant Void (OSV) and Two-Phase Frictional Multiplier (TPFM) were applied according to 37M correlation framework in NUCIRC.

In addition, all other aging degradation mechanisms (fuel sheath defect, feeder resistance, steam generator fouling, and etc.) were excluded.

2.2 Modeling

The evaluation was conducted using NUCIRC 2.3.5, which allows modeling of pressure tube diametral creep up to its design limit of 6.8%. In this investigation, NUCIRC and NUPREP, the input pre-processor, are employed for establishing model and calculating thermalhydraulic conditions and CCP. NUCIRC and NUPREP 2.3.5 can designate and apply the CHF, OSV, TPFM correlation and correction factors within the maximum allowable creep.

Figure 1 and 2 present the calculated creep distribution profiles for 37M fuel channels in the generic CANDU under maximum allowable creep conditions. The red mark in Figure 1 indicates the threshold of 6.8%, corresponding to the maximum allowable creep condition.

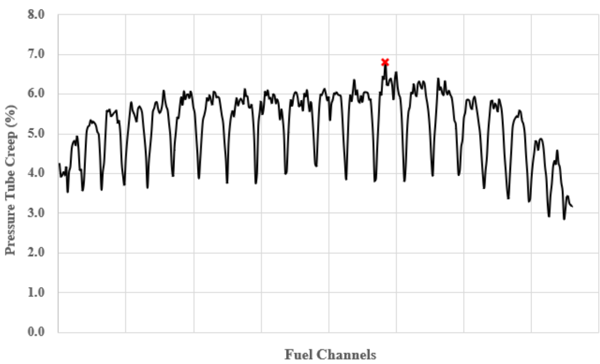

Fig. 1. Distribution of diametral creep in fuel channels under maximum allowable creep condition.

Figure 2 shows the axial creep profile along the length from the inlet under the same condition.

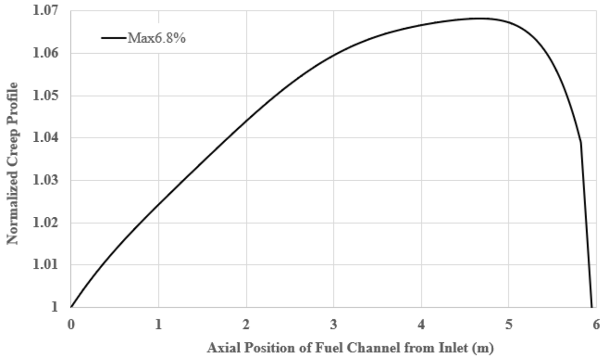

Fig. 2. Axial creep profile of maximum creep channel.

2.3 Results

The CCP modeling results of NUCIRC 2.3.5, obtained by applying the conditions of Figure 1 and 2 as well as the corresponding creep profile, are shown in Figure 3 and 4. Figure 3 illustrates the estimated CCP values map for all 37M fuel channels of the generic CANDU under normal neutron flux shape case. A comparative representation of the distribution for each fuel channel under several different neutron flux shape cases (Cases A, B and C) is presented in Figure 4.

The results indicate that CCP trends to be higher in the central fuel channels and lower in the peripheral channels, demonstrating a distribution pattern independent of the creep profile shown in Figure 1.

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22
A									4484	4859	4836	4788	4816	4470								
B						4474	4842	5787	6090	5987	6256	6207	5981	6008	5779	4817	4429					
C					4779	5253	5946	6603	6876	7236	7250	7282	7234	6914	6578	5983	5241	4783				
D				4757	5583	6138	6798	7564	7904	8043	7955	7998	8070	7939	7637	6823	6170	5606	4746			
E			5002	5495	6469	7159	7748	8134	8479	8492	8574	8627	8533	8513	8212	7770	7139	6495	5511	4985		
F			5583	6435	7225	7618	8178	8559	8390	8548	8370	8430	8569	8433	8589	8241	7636	7190	6401	5623		
G		5205	6106	6946	7544	8039	8245	8494	8556	8507	8475	8487	8587	8569	8556	8239	8072	7551	6958	6172	5207	
H		5775	6722	7581	7825	8100	8288	8632	8534	8503	8417	8450	8516	8603	8664	8357	8116	7888	7622	6725	5795	
J	4676	5924	7077	7868	8301	8405	8621	8749	8688	8664	8434	8469	8735	8688	8799	8637	8441	8325	7896	7068	5833	4650
K	4857	6033	7258	8054	8578	8501	8615	8772	8646	8612	8416	8506	8634	8716	8831	8695	8532	8646	8111	7303	6112	4870
L	5169	6504	7487	8402	8912	8681	8774	8903	8715	8579	8269	8283	8658	8745	8972	8808	8750	8985	8465	7527	6484	5101
M	5126	6437	7439	8322	8804	8805	8704	8883	8968	8594	8393	8492	8655	9058	8944	8825	8879	8895	8381	7541	6496	5131
N	5153	6335	7303	8108	8821	8574	8666	8854	8738	8554	8357	8385	8681	8804	8951	8760	8691	8882	8246	7368	6325	5146
O	4921	6036	6991	7808	8305	8350	8467	8652	8607	8565	8128	8271	8622	8772	8752	8575	8434	8415	7866	7040	6101	4939
P		5910	6967	7502	8141	8232	8535	8592	8741	8534	8390	8427	8631	8779	8698	8559	8356	8176	7619	7026	5852	
Q		5096	6039	6995	7512	7925	8188	8624	8617	8697	8375	8523	8753	8734	8704	8350	8103	7711	7043	6074	5084	
R			5643	6419	7213	7628	8083	8431	8520	8386	8395	8457	8496	8574	8560	8132	7770	7223	6467	5661		
S			4734	5809	6458	6962	7515	8035	8348	8756	8494	8609	8834	8469	8086	7611	6980	6445	5844	4773		
T				4972	5592	6299	6812	7404	7814	7867	7866	7881	7994	7860	7539	6869	6350	5582	5045			
U					4664	5224	6047	6921	6942	7318	7198	7247	7324	7013	6939	6077	5214	4733				
V						4413	5024	5607	5802	5968	5952	5905	5994	5835	5736	4979	4450					
W									4853	4948	5058	5157	4965	4880								

Fig. 3. CCP map under maximum allowable creep condition.

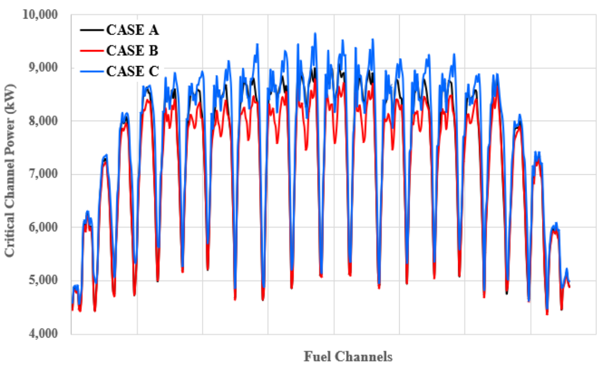

Fig. 4. CCP distributions at various neutron flux shapes under maximum allowable creep condition

3. Conclusions

This work tries to provide a clear, quantitative evaluation of the impact of maximum pressure tube creep on CCP in CANDU reactors using NUCIRC. The results confirm that the general trend of CCP is not significantly affected by only the maximum allowable creep. It is therefore recommended that additional analyses be undertaken on CCP-associated parameters or other relevant factors, including Critical Power Ratio (CPR), to ensure safety margin assessments.

The present work, in conjunction with a series of related studies, is expected to provide a fundamental safety margin assessment to support continued operation of CANDU reactors with or without refurbishment and replacement of pressure tubes.

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