Transactions of the Korean Nuclear Society Virtual Spring Meeting
July 9-10, 2020

Use of 650°C Peak Cladding Temperature as a Design Goal for Design Basis Accident 1

Kyung-min Yoon [a*], Jae-il Lee [a], Do-hwan Lee [b]
[a]*KEPCO Nuclear Fuel, 242, 989 beon-gil, Daedeok-daero, Yuseong-gu, Daejeon, Korea*
[b]*Korea Hydro and Nuclear Power, 70, 1312 beon-gil, Yuseong-daero, Yuseong-gu, Daejeon, Korea*
[*]*Corresponding author: kmyoon@knfc.co.kr*

1. Introduction

Defining a state of Nuclear Power Plants (NPPs) with grouping initiating events (IEs) and setting safety goals are based on the fundamental safety philosophy of the design and operation of NPPs. Korean nuclear industry, by the efforts to export NPPs abroad, recognized the differences between US safety philosophy, which were introduced in the design and operation of domestic NPPs, and international safety philosophy (YVL, WENRA, EUR, IAEA) In this perspective, Korean nuclear industry conducted research to establish a domestic own accident categorization scheme that meets international standards for the NPPs to export. As part of results of the research, the PCT limit of 650°C is set as a design goal for Design Basis Accident group 1 (DBA 1). This paper describes the technical basis of 650°C Peak Cladding Temperature (PCT) limit and the safety analysis results applying 650°C PCT limit for APR1400.

2. Technical Basis of PCT Limit of 650°C

According to the domestic own accident categorization scheme, DBA 1 consists of IEs expected to occur 10^{-4} to 10^{-2} /RY, which is between Anticipated Operational Occurrences (AOOs), occurrence frequency of more than 10^{-2}/RY, and Design Basis Accident group 2 (DBA 2), occurrence frequency of 10^{-6} to 10^{-4}/RY. Unlike AOOs, which aims to maintain the fuel hermeticity, DBA 1 permits the Departure from Nucleate Boiling (DNB) and assumes DNB occurrence as fuel failure. However, although overheating of cladding due to DNB is occurred, the design goal is aimed to limit the cladding deformation and reduction of cladding ductility to be negligible effect on cladding integrity.

2.1 Cladding Deformation

Pressure differences across the cladding, cladding temperature and time duration are main factors to cause cladding deformation (increase in strain) during post DNB condition. As the cladding strain increases, it can lead to DNB propagation due to cladding ballooning and even cladding rupture in an extreme condition.

As fuel burnup increases, the inside gas pressure of fuel may exceed the reactor coolant system pressure. And when considering the range of possible transient system pressure among DBA 1, the external pressure difference across the fuel cladding can be conservatively assumed to be 10.34 MPa; and the circumferential stress outward the cladding is calculated as 80.67 MPa. Under the stress, when the cladding temperature is assumed to be maintained at 650°C for 5 seconds, the strain is calculated to be within 0.2% for ZIRLO cladding. When considering the conservatism on the assumptions of the pressure difference across the cladding and the time duration, the actual strain during transient at cladding temperature of 650°C would far less than 0.2%.

Fig.1 shows the calculation results of strain by cladding temperature variation from 600°C to 725°C under the same circumferential stress and time duration. The Y-axis is a normalized value to the strain of 650°C. As shown in Fig.1, the strain increase rate starts being steep when the PCT exceeds 650°C. Therefore, it can be said that if the PCT remains below 650°C during post DNB condition, the strain increase by overheating of cladding is negligible.

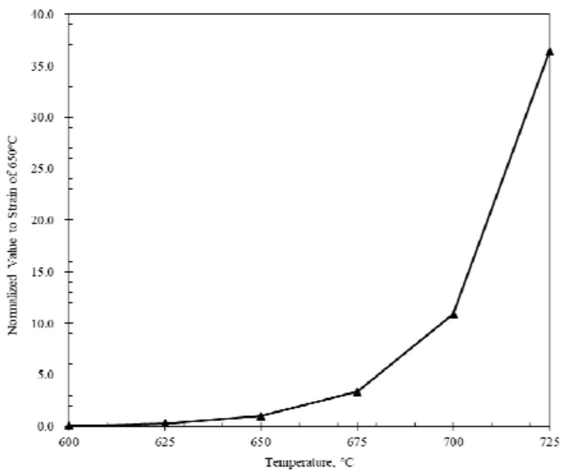

Fig. 1. Cladding strain for ZIRLO with variation of cladding temperature under constant circumferential stress outward the cladding

2.2 Reduction of Cladding Ductility

Zircaloy-water reaction at high cladding temperature results in increased ZrO_2 layer and oxygen concentration in the cladding and leads to reduction of cladding ductility: oxygen-induced cladding embrittlement. In the case of loss of coolant accident, which is included in DBA 2, the oxidation kinetics of cladding is permitted but the PCT and cladding oxidation limits are applied as an acceptance criteria for the purpose of maintaining core coolable geometry. Meanwhile, for DBA 1, 650℃ PCT limit is set to restrict the Zircaloy-water reaction so that the oxygen-induced cladding embrittlement is negligible.

In Fig.2, the parabolic rate constant for weight gain in Baker-Just model [1], which denotes the rate of the square of amount of Zircaloy reacted per unit surface, is presented as a function of cladding temperature. From Fig.2, it can be known that the reaction is insignificant under 650℃. Moreover, according to the results of experiments measuring the amount of hydrogen produced in Zircaloy-water reaction [2], the Zircaloy-water reaction is negligible during 2 hours of exposure of Zircaloy specimen at 650℃ of steam. On this basis, 650℃ PCT can be regarded as an appropriate limit to preclude the Zircaloy-water reaction during post DNB condition.

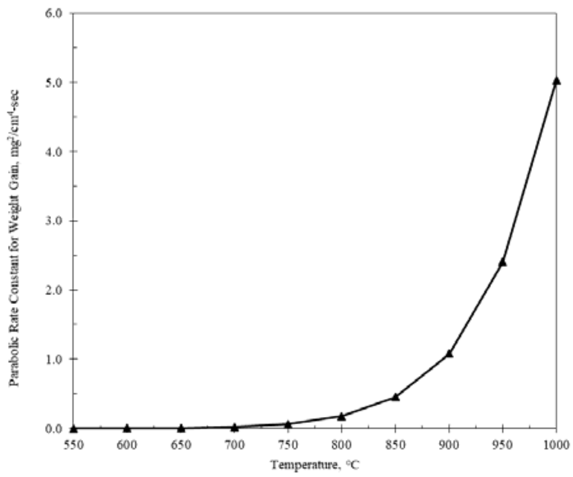

Fig.2. Parabolic rate constant for weight gain in Baker-Just model with variation of cladding temperature

3. Safety Analysis for APR1400

In order to evaluate whether the PCT limit of 650℃ is an achievable design goal or not, a safety analysis for Total Loss of Flow with Delayed scram (TLOFD) was performed for APR1400. TLOF is included in AOOs, however, since the TLOFD assumes the second reactor trip signal, TLOFD is included in DBA 1 due to its lower expected occurrence frequency than TLOF.

A detailed core model using RETRAN code [3] was used to calculate the transient parameters for DNBR calculation, and the DNBR was calculated using THALES, a sub-channel analysis code [4]. The detailed core model consists of average and hot channels and calculates fuel behavior with radially: 7 nodes per pellet, 1 node per gap, 1 node per cladding, and axially 20 nodes. PCT was calculated using the detailed core model of RETRAN, and the hot channel flow factor was assumed to adjust the minimum DNBR calculated by RETRAN to be lower than that of THALES. KCE-1 critical heat flux correlation was used and DNB occurrence was assumed to be at DNBR Specified Acceptable Fuel Design Limit (SAFDL). In addition, for an evaluation of film heat transfer coefficient on PCT, Dougall Rhosenow [5] and Groeneveld 5.7 [6] were assumed in the PCT calculation.

Fig.3 shows transient minimum DNBR calculated by THALES, and as the minimum DNBR reached below the DNBR SAFDL (1.29), the DNB fuel failure was calculated as 0.2% of total number of fuels. Fig.4 is the cladding temperature transient calculated by RETRAN at the axial node 10 at which the PCT was maximum. As seen from Fig.4, the PCT shows a quite difference results per the film boiling heat transfer coefficient, however the PCT limit for both cases were met. Fig.5 shows the radial distribution of fuel temperature at the axial node 10 with Groeneveld 5.7 film boiling heat transfer coefficient. In Fig.5, it shows that the fuel centerline temperature was decreased subsequent to reactor trip even though the cladding temperature suddenly increased due to DNB occurrence.

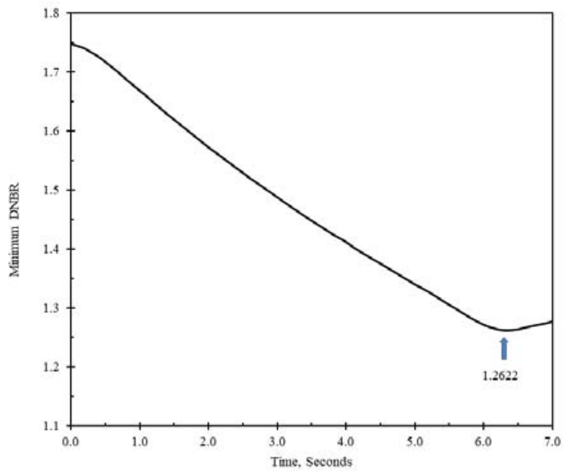

Fig.3. Minimum DNBR with time (THALES)

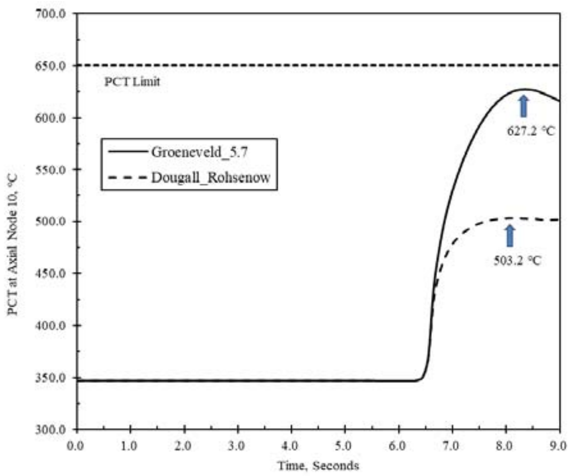

Fig.4. PCT at axial node 10 with time using different film boiling heat transfer coefficient (RETRAN)

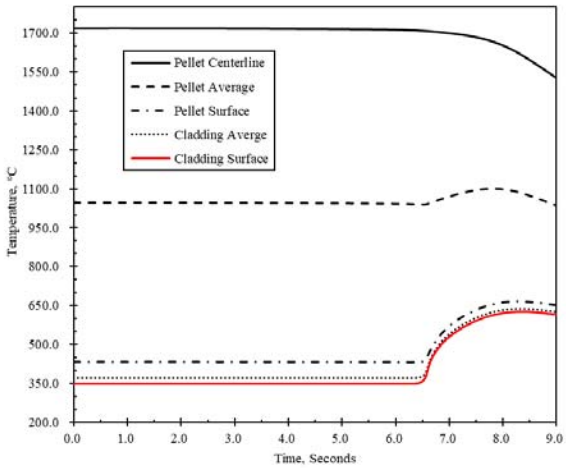

Fig.5. Radial distribution of fuel temperature at the axial node 10 with time using Groeneveld 5.7 film boiling heat transfer coefficient (RETRAN)

4. Conclusions

For DBA 1, exceeding the PCT limit of 650°C does not mean that fuel failure occurs due to cladding deformation or reduction of cladding ductility. But by showing that PCT is less than 650°C, potential concerns caused by overheating of cladding such as DNB propagation or cladding embrittlement can be avoided.

As shown from the results of safety analysis, the PCT limit was evaluated to be an achievable design goal for APR1400. On the other hand, since the PCT shows a gap depending on the film boiling heat transfer coefficient, discussions should be given for it; also, DNBR at which DNB is assumed to occur is one of the important analytical assumptions. In this context, a discussion for analytical assumptions should be given for the evaluation of PCT during post DNB transient. As the TLOFD was the only case of safety analysis in this research, further analysis is required for various accidents in DBA 1.

REFERENCES

[1] L.Baker Jr., L.C.Just, Studies of Metal-Water Reactions at High Temperatures, ANL-6548, May 1962

[2] S.Leistikow, G.Schanz, Oxidation Kinetics and Related Phenomena of Zircaloy-4 Fuel Cladding Exposed to High Temperature Steam and Hydrogen-Steam Mixtures under PWR Accident Conditions, Nuclear Engineering and Design 103, 1987

[3] EPRI NP-7450, RETRAN-3D – A Program for Transient Thermal-Hydraulic Analysis of Complex Fluid Flow Systems, Computer Code Manual, Computer Simulation & Analysis, Inc. and Electric Power Research Institute, December 1997.

[4] KNF-TR-CDT-10006/PK/A, THALES – Subchannel Analysis Code, June 2019.

[5] R.S. Dougall, W.M. Rohsenow, Film Boiling on the Inside of Vertical Tubes with Upward Flow of Fluid at Low Quantities, MIT Report Number 9079 26, Cambridge, Massachusetts, September 1963.

[6] D.C. Groeneveld, An Investigation of Heat Transfer in the Liquid Deficient Regime, AECL-3281, Revised, December 1969.