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Cooling Period Calculation of Evolutionary Power Reactor Spent Fuel for Dry Management Safety

The calculation of the evolutionary power reactor (EPR) spent fuel (SF) cooling period (CP) was performed. The CP was determined by comparing the heat load of a cask with the calculated value of EPR decay heat (DH). The EPR DH was calculated by the ORIGEN computer code based on the EPR parameters. For conservatively study, the EPR and ORIGEN parameters that lead to higher DH values were selected and safety margins were considered. The fitting tool was utilized in the calculation of CP to overcome the ORIGEN limitation. The resultant values of CP will maintain the peak cladding temperature (PCT) of SF lower than 400°C during storage, transport, and disposal. The results show that -for normal operation-the SF of EPR should stay in the pool at least 4.75 years before it is loaded to the passively cooled dry casks.

Keywords: cooling period; EPR; spent fuel; ORIGEN; peak cladding temperature; dry management

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Розрахунок періоду охолодження відпрацьованого ядерного палива еволюційного (європейського) енергетичного реактора для забезпечення безпеки в умовах подальшого сухого зберігання ВЯП

Розраховано період охолодження відпрацьованого ядерного палива (ВЯП) еволюційного (європейського) енергетичного реактора (ЕЕР). Період охолодження визначався порівнянням термічного навантаження на контейнер зберігання з обчисленим за допомогою комп'ютерного коду ORIGEN на основі параметрів ЕЕР значенням остаточного енерговиділення ЕЕР. Для консервативного аналізу обрано такі параметри ЕЕР та ORIGEN, що призводять до більш високих значень остаточного енерговиділення, а також забезпечують потрібні запаси безпеки. У розрахунку застосовано методику коригування для подолання обмеження коду ORIGEN. Отримані значення періоду охолодження забезпечать підтримку максимальної температури оболонок твелів ВЯП на рівні нижчому, ніж 400 °С, протягом зберігання, транспортування та захоронення. Результати показали, що ВЯП для нормальної експлуатації має залишатись у басейні витримки принаймні 4,75 року перед завантаженням у контейнери сухого зберігання з пасивним охолодженням.

Ключові слова: період охолодження; еволюційний (європейський) енергетичний реактор; відпрацьоване паливо; код ORIGEN; максимальна температура оболонки; сухе зберігання відпрацьованого палива.

The EPR is an evolutionary four-loop Pressurized Water Reactor design with a rated electrical power output of approximately 1600 MW. The EPR design is based on experience from operation of Light Water Reactors worldwide, primarily those incorporating the most recent technologies. EPR used M5 alloy, which is an improved alloy for cladding and structure. The use of this advanced alloy enables better behavior under irradiation regarding corrosion [1]. EPR possesses 241 combustible assemblies per core, renewed by third every 18 months, which corresponds to approximately 3400 SF assemblies to be stored at the conclusion of 60 years of operation. SF is placed in water spent fuel pool (SFP) after it is removed from the reactor to allow its DH and radioactivity to decrease. The pool CP depends mainly on the reactor, fuel types and SF management techniques. After an appropriate time, SF is placed in casks for dry storage or off-site transport. In casks, individual SF assemblies are supported by basket tubes in the cask's containment region. This region is evacuated and backfilled with helium or other non-oxidizing gas.

Dry management of SF is gaining popularity in recent years, particularly after the economic crisis, which is striking the world and the Fukushima nuclear disaster of 2011 because of its safety, security and low costs. SF dry management includes transportation, interim storage and final disposal, using dry casks like a dual-purpose cask (DPC) that is used in transport and interim storage of SF or a multipurpose cask (MPC) that is an extension of DPC toward the final disposal. A dry cask is cooled by natural convection. The dry management has many advantages such as:

- Casks are not vulnerable to loss of coolant where cooling is completely passive;
- The cost of dry cask SF storage is lower — only about \$100:200/kg of uranium (0.025—0.05 cents per kWh of electricity produced) — versus more than \$1000/kg for reprocessing [2];
- The potential consequences of an accident or terrorist attack on a dry cask are lower than that for SFP;
- Dry storage facilities can solve the problem of delays in the introduction of permanent disposal and/or reprocessing facilities.

This paper focuses on the determination of SF CP for dry transport, storage and disposal by the calculation of DH using the ORIGEN code [3]. ORIGEN is a versatile point-depletion and radioactive-decay computer code for use in simulating nuclear fuel cycles and calculating the buildup, decay, and processing of radioactive materials. The total number of power irradiation, flux irradiation and decay commands in the ORIGEN input file must be less or equal to 150. Although the last updating of ORIGEN was in 2002, it is still used as a standalone code [4, 5, 6] or in combination with other codes [7]. ORIGEN is still used especially in safety analysis because it is more conservative than some other codes, such as ORIGEN-ARP [8].

Proposed Calculation Method

Fig. 1 shows the CP calculation procedure for EPR SF using the ORIGEN code. The gray blocks denote the given data. In the following analysis, the ORIGEN input file is prepared according to the EPR parameters. The CP and DH were selected from the ORIGEN output file. As shown in Fig. 1, the CP is used in the 1st branch to calculate the minimum CP for the safety of SF dry management, while in the 2nd branch the EPR DH is used to calculate the predicted PCT that is associated with the calculated CP. CP and PCT are dependent on the used cask system heat load; the heat load is the maximum heat power withstood by the cask without SF failure.

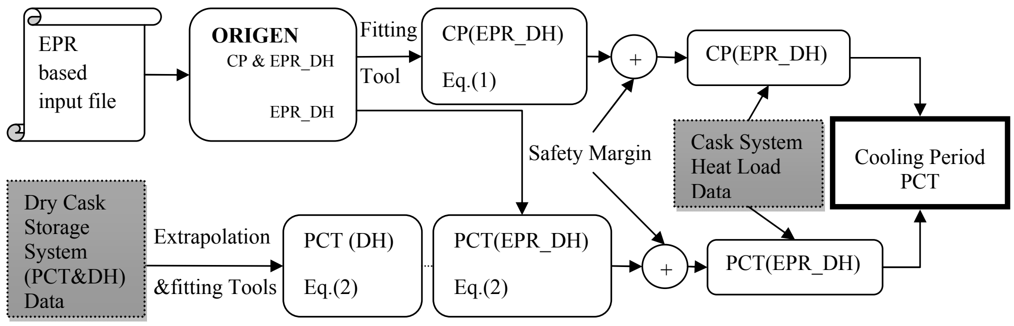


Fig. 1. CP and Associated PCT Calculation Procedure

In this paper, the curve fitting tool was used in finding the CP as a function of EPR DH to overcome the ORIGEN limitation, Eq. (1). Also, it is used in the PCT calculation from EPR DH, Eq. (2). The extrapolation tool was used to increase the DH range. For conservatively study, the EPR parameters that maximize the resultant DH were selected and safety margins were added to the CP and PCT values.

Simulation of EPR Burnup

This section is divided into three subsections. The 1st one will show the preparation of ORIGEN input file according to the EPR parameters. The simulation will be performed in three cases to determine the EPR and ORIGEN parameters that lead to higher DH values; 1) for 100 and 136.98 days irradiation time step; 2) for 3 and 5 irradiation cycles; 3) for 16, 100 and 150 days refueling outage times. The 2nd subsection will process CP of EPR to find the CP as a function of EPR DH. Finally, the equation that relates PCT and EPR DH will be in the 3rd subsection.

ORIGEN input based EPR parameters. EPR has been designed to operate more cost-effectively, compared to reactors of similar design and technology, and to use fuel as efficiently as possible, where high discharge burnup (BU) fuel reduces the volume of waste per kWh of electricity produced. EPR plant availability is about 94 % where the standard refueling outage of less than 16 days is possible and the rate of forced outage is 5 days/year. The core lifetime can be from 12 to 24 months, depending on the required energy. Core operation for 18 months between refueling will typically accumulate between 18 and 22 Giga Watt Day/Metric Ton Uranium (GWD/MTU) per cycle. At the end of the fuel cycle, approximately one third of the fuel assemblies is replaced by fresh fuel assemblies and the discharged assemblies are placed in the SFP to cool and decay for a period of approximately 10 years or less [9] before being moved to an interim storage facility. The uranium mass per assembly is 536.0 Kg [1] and masses of other assembly components are taken from reference [10].

Assuming the uniform power distribution around the core, the study uses ORIGEN with the extended BU reactor model libraries. The EPR "nearest" reactor model in ORIGEN libraries is selected [5] for 2 reasons; first, the EPR model is not available in ORIGEN libraries; second, this study is limited to show the DH trend in the time range from 0.5 to 110 years after discharge from EPR, which is relevant to transport and interim storage and/or disposal. The 17Ч17 assembly model without any burnable poison rods is used. The DH is calculated when the refueling times were 16 (to minimize the decay of inventory and maximize the plant availability), 100 and 150 days. Also, to satisfy the best operational strategy (in the sense of economics) for a typical power reactor, the fuel is simulated for 5 cycles with 12 months cycle length.

CP calculation. The ORIGEN output file gives the DH power with the decay time. The decay time is from fuel discharge to about 110 years. The decay time includes the CP where the SF should be cooled by water as in SFP or passively cooled as in dry management. The minimum CP for dry management can be calculated using the curve fitting tool, where the tool is used to find a relation between CP in years and EPR DH in W/assembly.

PCT calculation. The PCT of SF is calculated to make sure that the calculated CP will not cause the PCT to exceed 400 °C during the dry management.

The fuel cladding temperature depends on: 1) the DH, which is judged from the SF source term and CP; 2) the dry cask storage system (DCSS) heat transport characteristics, which differ for transport, interim and final storage of SF. To illustrate the thermal analysis described in this paper, we make the assumption that the DCSS is under thermal equilibrium and constant ambient temperature; so for the given SF CP, the PCT decreases in direct proportion to the DH power [11]. The thermal analysis of the DCSS for a 17Ч17 assembly geometry and 60 GWD/MTU burned fuel (such as the EPR SF) was performed by EPRI [11]. This data can be used for predicting the PCT of a helium filled cask. The DH range was from 2290 to 600 W/assembly. The DH range is extended by using linear extrapolation. Then the resulting data is fitted to find an equation that relates the PCT in °C and DH in W/assembly.

Results and Discussions

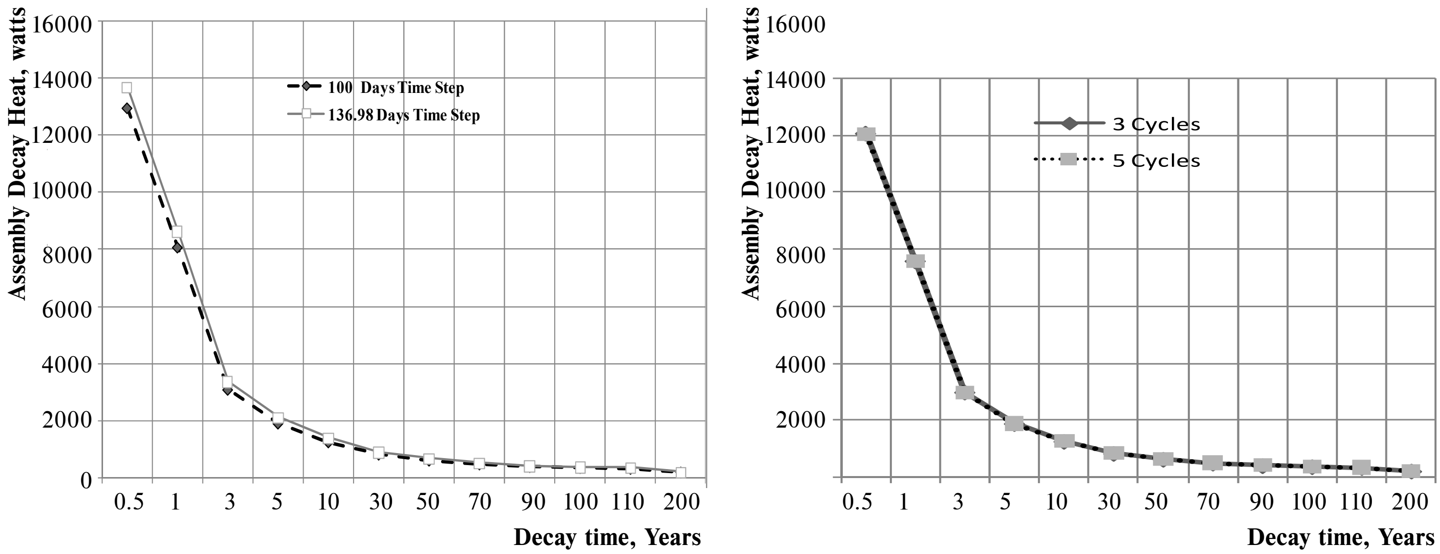
Results

• *DH versus Time*

Fig. 2, *a* shows the change of DH with time for 100 days and 136.98 days time step, the time begins after fuel discharge. It shows the dependence of DH on the time step of irradiated fuel. When the time step is more than 100 days, the relative errors in the ORIGEN output are from 5.4 % to about 11.79 %.

Fig. 2, *b* shows the DH for 2 power schemes, one for 3 cycles and the other for 5 cycles. As shown, the EPR gives the same results when the fuel is simulated with 3 cycles and the cycle length is 20 months, which is one of the EPR advantages.

The values of the DH depend on the refueling outage time. As shown in Table 1, the DH is inversely proportional to the outage time in the time range from 0.5 to about 43 years.



a *b*

Fig. 2. DH as a function of time for EPR SF:
a — DH for 100 and 136.98 days time step; *b* — DH for 3 and 5 irradiation cycles

Table 1. Comparison of DH vs. Refueling Outage Time

Refueling outage time, Days	16	100	150
Years since discharge	**Decay Heat, W/Assembly**		
0.5	1.308E+04	1.278E+04	1.264E+04
1.0	8.142E+03	7.919E+03	7.811E+03
3.0	3.106E+03	3.043E+03	3.011E+03
5.0	1.911E+03	1.890E+03	1.879E+03
10.0	**1.248E+03**	**1.244E+03**	**1.242E+03**
30.0	8.163E+02	8.158E+02	8.156E+02
50.0	6.071E+02	6.073E+02	6.074E+02
70.0	4.714E+02	4.719E+02	4.722E+02
90.0	3.805E+02	3.812E+02	3.816E+02
100.0	3.466E+02	3.473E+02	3.477E+02
110.0	3.183E+02	3.190E+02	3.195E+02
200.0	1.930E+02	1.935E+02	1.938E+02

After that, the DH values for small outage time are lower than for other large outage time. Nevertheless, this small change does not affect the dry management of the SF. The interpretation of the dependence of DH on the refueling outage times is beyond the paper scope and is subject to future study.

- *CP versus EPR DH*

The fitting tool was used to find a relation between CP and EPR DH. Given EPR DH, the CP can calculated in years by

$$\mathrm{CP}(\mathrm{DH}) = \sum_{i=0}^{7} a_i \mathrm{DH}^i. \qquad (1)$$

Where $a_0 = 388.09$, $a_1 = -1.7256$, $a_2 = 0.0041$, $a_3 = -5.6564\times10^{-6}$, $a_4 = 4.6808\times10^{-9}$, $a_5 = -2.2497\times10^{-12}$, $a_6 = 5.7908\times10^{-16}$, and $a_7 = -6.1709\times10^{-20}$.

The maximum residual (0.077) and 0.0063 values are added to Eq. (1) as a safety margin. Eq. (1) should be used in the DH range from 2100 to 400 W/assembly.

- *PCT versus EPR DH*

The fitted PCT is shown in fig. 3, *a*, and is given by

$$\mathrm{PCT}(\mathrm{DH}) = -9.359\times10^{-12}\mathrm{DH}^4 + 9.836\times10^{-8}\,\mathrm{DH}^3 - 0.000373\mathrm{DH}^2 + 0.6431\mathrm{DH} - 59{,}39. \qquad (2)$$

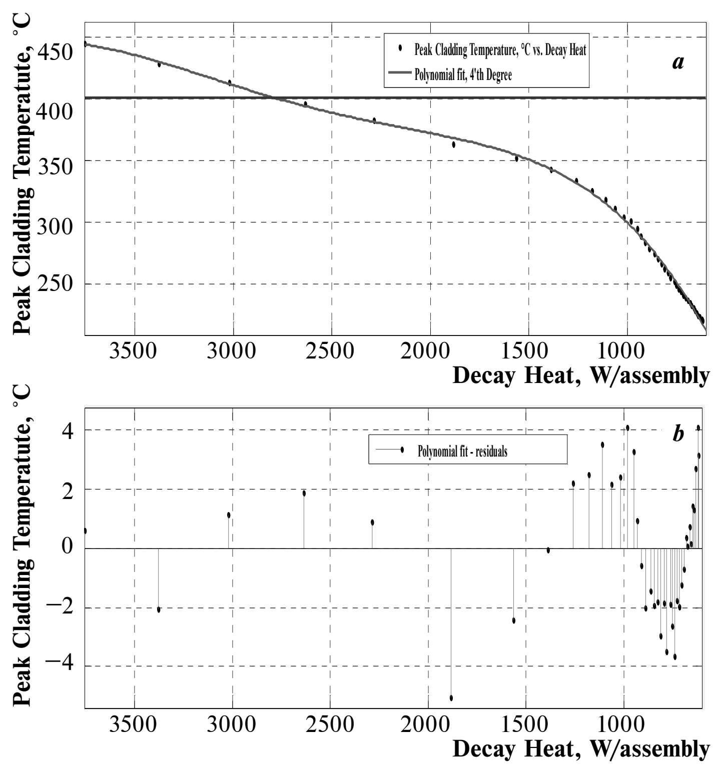


Fig. 3. PCT vs. DH Fitting:
a — Cladding Temperature; *b* — Residual Values

Eq. (2) should be used in the range of DH from 3750 to 400 W/assembly. The difference between PCT calculated by Eq. (2) and the true PCT is about ±4 °C, as shown in Fig.3*b*. The error-free PCT is given by adding +4 °C (which is maximum positive residual) to Eq. (2) values.

For conservatism, the thermal analysis should be performed not for the real value of PCT, but for larger one which is given by adding a positive value as a safety margin to each PCT value. Fig. 4, *a* shows the real PCT and the PCT used by EPRI [12] analysis. The difference between 2 curves was about 19°C in the given data set and is about 15 °C in the extrapolated range due to the linear extrapolation. The predicted PCT (positive error free) for EPR SF that was calculated using Eq. (2) is shown in Fig. 4*b*. Also, it shows the PCT which is selected in the following analysis for DPCs and MPCs.

Discussions

SF is loaded in casks through its life. The key parameter in the SF loading is the thermal load. The SF thermal load is restricted to satisfy the PCT limit. The PCT shall be limited to 400°C for normal conditions of SF loading and storage operations [13]. The DH of EPR SF changes from 13700 W/assembly to about 350 W/assembly in the period from 0.5 year to 110 years respectively. There are many types of casks/canisters according to their functions and thermal load [14]. The following section will show the CP conditions that satisfy the dry management safety of EPR SF. Table 2 shows some types of casks which can be used for EPR SF dry management. The PCT values are provided according to the analysis of PCT values in Fig. 4, *b*.

• *Transportation*

The NAC-LWT and TN-12 casks are approved for SF transportation, loaded with 1 and 12 fuel assemblies respectively. Their thermal loads are 11.5 and 51.6KW, respectively. So the EPR SF can be safely transported after being cooled in a pool for about **220** and **804** days in these casks, respectively.

• *Storage*

CASTOR-V/19 and TN24E are DPC casks with heat loads of 39 and 40 KW loaded by 19 and 21 fuel assemblies, respectively, so the EPR SF can be safely transported and stored after being cooled in a pool for about **4.741** and **5.088** years.

For the MPC used in HI-STORM-100 system with 24 assemblies per cask, the EPR SF can be safely loaded in MPC-24 after **17.342** years of SFP cooling where the total heat loads about 24.5KW [15]. Another option arises from using NUHOMS-24P cask after **10.01** years of EPR SF cooling where the assembly DH is about 1250 W.

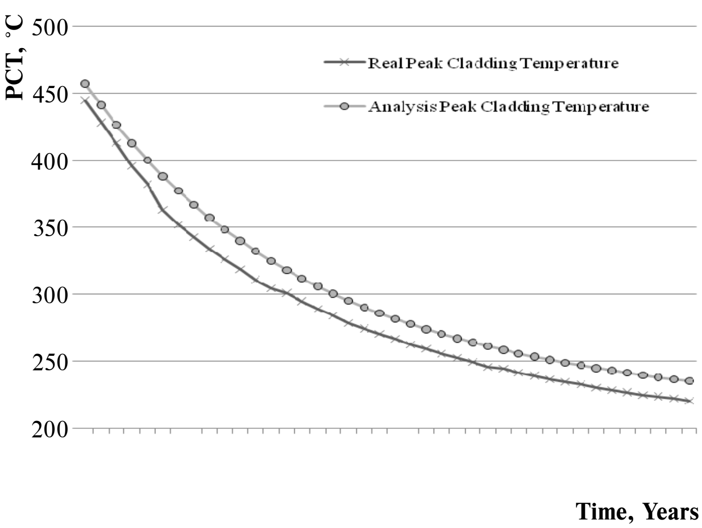
• *Repository*

The results show that the EPR SF can be placed in a geological disposal environment using new-design 4 assemblies MPC [10] after a CP of **96.677** years, where the maximum disposal canister heat load is 1430 Watts.

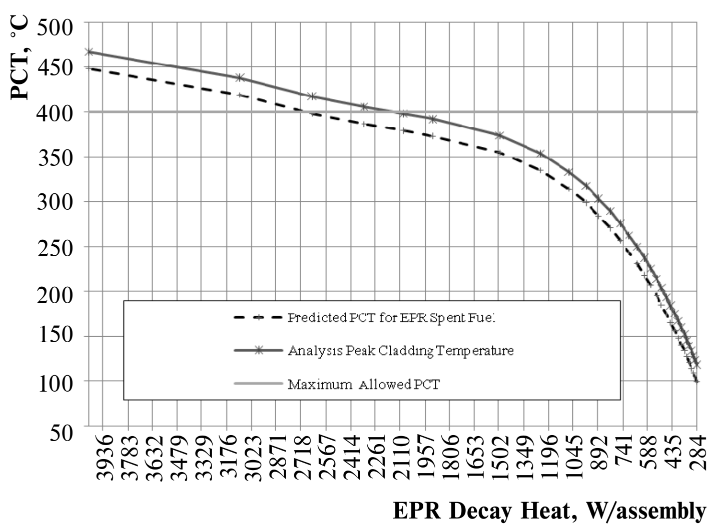
Also, EPR SF can be placed in a real repository as the Olkiluoto site in Finland by cooling the SF **71.68** years before disposal compared to 62.9 years in Kari Ikonen analysis [16]. The difference is because ORIGEN is more conservative than other codes and is due to the added safety margin and the low decrease rate of DH after 60 years.

Conclusions

DH is an important factor in SF dry management. The objective of this study was to conservatively evaluate the EPR SF thermal conditions for dry management by CP calculation. Hence, the DH of EPR SF was calculated by the ORIGEN code based on the EPR 1600 MW parameters. In this study, the DH depends on the time step used in ORIGEN input file and the refueling outage period. The EPR can satisfy the BU up to 62 MWD/MTU in only 3 cycles instead of a large number of cycles for other reactors; this is due to the M5 cladding material. From the calculations, it is noted that the EPR SF can be safely transported, stored and finally deposited in the repository in the dry passive cooling system such as a transport cask, DPC and MPC. The CP of the SF depends on the type of the used cask system. In general, the SF of EPR should stay in the SFP for at least 4.75 years before being loaded to DPC or MPC in order to maintain the PCT less than 400 °C in normal operation.



a



b

Fig. 4. PCT Curves of EPR SF:
a — PCT for real and analysis values; *b* — PCTs of EPR SF for DH analysis

Table 2. Parameters and Predicted Values for EPR SF Uniformly Loaded Casks

Cask Type	Cask Model	Thermal Load (KW)	Capacity (Assem-blies)	Cooling Period, years	Predicted PC/ Analysis PCT***, °C
DPC*	CASTOR-V/19	39 (2052.632 W/assembly)	19	4.741	377.61/396.61
	TN24E	40 (1904.762 W/assembly)	21	5.088	372.82/391.82
	NUHOMS-24P	24–30–40.8 (1250 W/assembly)	24	10.01	334.93/353.93
MPC**	HI-STORM 100 (MPC-24)	20–24.5–28.2 (1020.833 W/assembly)	24	17.342	306.88/325.88
		21.5 (895.833 W/assembly)	24	24.376	286.07/305.07

*DPC — dual purpose cask

**MPC — multipurpose cask

***PCT — peak cladding temperature

Particularly looking at the obtained results, it is noted that the curve fitting tool should be used to overcome the complexity and the limitation of nuclear code calculations for determining relations between CP given DH and PCT given DH.

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