Analysis of fuel failure on beam transient of accelerator-driven system

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Abstract

The cladding failure analyses on transients and accidents of accelerator-driven system (ADS) were conducted in this study. The cladding failure was evaluated by ADSE code and the cladding failure analysis programme, which is based on the method of cumulative creep damage fraction (CDF), a kind of creep rupture evaluation method.

Various beam profile changes were analysed to a JAEA-designed ADS core as a beam transient. As a result, CDF values were far below the failure criterion and the claddings had very small damages on beam diameter expansion, beam flattening and beam hollowing events. However, CDF values of beam incident position change event exceeded the failure criterion in a short time and beam incident position change event was found to have a high risk for the cladding failure by creep.

As for an accident, beam over power (BOP) and unprotected loss of flow (ULOF) were analysed and their CDF values reached to the failure criterion in a very short time. As an example, the CDF reached to the failure criterion at 5.4 s on 200% beam power of BOP. Concerning ULOF, the shortest rupture time was 9.6 s on 5 s pump coast-down of ULOF. Beam power limitation on BOP and maximum beam shutdown time on ULOF were also investigated for the prevention of the cladding failures.

Introduction

An accelerator-driven system (ADS) is widely studied for the transmutation of minor actinides (MA) and long-lived fission products (LLFP) included in high-level radioactive wastes (HLW). An ADS consists of a high-intensity proton accelerator, a spallation target of a heavy metal such as lead-bismuth eutectic and a subcritical core. An ADS is continually driven by employing spallation neutrons that are generated by the incident of high-energy proton beam into a spallation target. An ADS has some advantages compared to conventional reactors – high security and high transmutability of HLW. An ADS can be shutdown easily by turning off an accelerator and has a high flexibility of a fuel loading because of the usage of a subcritical core.

There are many research and development topics for the establishment of an ADS technology. As for the safety study, a computational analysis by a calculation code is a centre of the study. However, there are few reports about the transients and accidents of ADS and most of studies are only focused on temperature variations. Especially, beam profiles such as a shape and a position is considered likely to be changed but there are no codes which can treat beam profile changes.

The ADSE code has been developed to research ADS dynamics including a beam profile change [1]. ADSE can calculate the neutronics and the thermo-hydraulics of ADS and consider the variations of accelerator parameters such as beam intensity, beam diameter and beam incident position. In addition, a cladding failure analysis program intended for the ADSE code was developed to evaluate a cladding failure from the viewpoint of a material strength [2]. This module can treat a high-temperature creep rupture analysis and employs the method of Cumulative Creep Damage Fraction (CDF). CDF is calculated from the following equation:

$$CDF = \sum_{i} \frac{\Delta t_i}{t_{r,i}} \tag{1}$$

where Δt_i is a calculation time step and $t_{r,i}$ is a creep rupture time on the condition i. A creep rupture time $t_{r,i}$ is calculated by using cladding temperatures, material data, sizes, burn-up condition and so on. In this study, various transients and accidents are analysed with this code and program. Transients are defined as the beam profile change when cooling systems work as usual and a beam stays the same power, and accidents as the event except for transients – that accompany with the power change or abnormal condition of cooling system.

ADS core model and failure evaluation method

ADS core model and analysis condition

This study was intended to 800 MWt ADS proposed by Japan Atomic Energy Agency (JAEA) [3,4]. This core employs (Pu+MA) + ZrN fuel and lead-bismuth for the coolant and the spallation target. The proton beam energy is 1.5 GeV and a linear accelerator is assumed. The core design is shown in Figure 1 and the main core parameters are summarised in Table 1. The parameters related to CDF calculation are described in Table 2. These parameters were set to strict values to consider the analyses on the safe side.

Failure evaluation method

A cladding failure was evaluated by whether CDF values exceed 0.5 or not. This value is employed on a normal operation of the lead-bismuth cooled fast reactor under contemplation by JAEA [5]. The failure criterion 1.0 is usually used for a CDF analysis but this study adopted 0.5 to evaluate a cladding failure severely. A time interval of CDF analysis was set to 1 000 s after a transient comes up. A creep rupture is normally analysed for some hours or more but temperature variations would show stable values after several tens of seconds because this study only treated instantaneous beam variations or a pump coast-down of several tens of second. Thus, this time interval was considered effective since CDF would not be changed on a large scale after the temperatures converged.

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Figure 1: ADS core model employed in the study

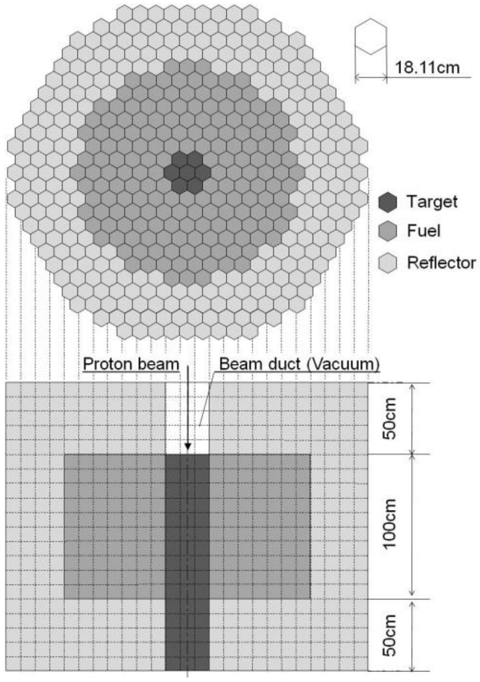


Table 1: Main parameters of the ADS model in the analysis

Thermal power	800 MWt
k_{eff}	0.95
Core height/diameter	1.00/2.50 m
Target height/diameter	1.50/0.50 m
Fuel	(MA+Pu)N + ZrN
Coolant and target	LBE
Coolant temperature (in/out)	603/703 K
Coolant velocity	2.0 m/s
Beam energy	1.5 GeV

Table 2: Parameters related to CDF analysis

Cladding material	T91 steel
Upper plenum length	1.2 m
Lower plenum length	0.5 m
Safety factor α_R	10
Burn-up condition	End of cycle
FP gas release rate	100%

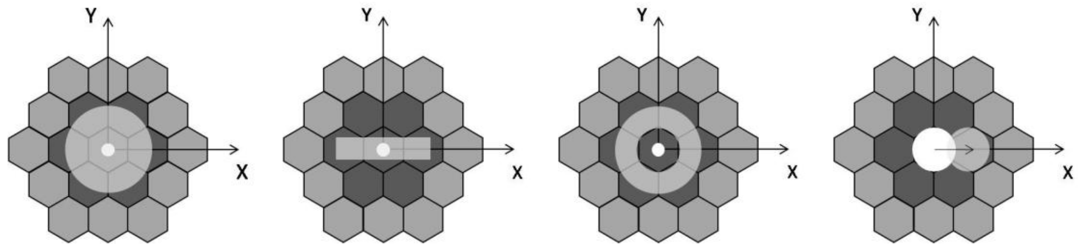
Cladding failure analysis on transient

Analysis event

Beam diameter expansion, beam flattening, beam hollowing and beam incident position change were analysed as transient. Figure 2 shows the schematics of beam transients. Beam shape and position was determined to be instantly changed in the range of the spallation target region. The details such as size and moving distance refer to each subject described in next section.

Figure 2: Conceptual diagram of beam variation

(a) Diameter expansion (b) Flattening (c) Hollowing (d) Incident position change



Analysis result and discussions

As for beam expansion event, a diameter of 1 cm up to 40 cm was analysed. An initial beam diameter was set to 1 cm because beam which inserts into reactor is supposed to be expanded from several millimetres or centimetres in actual ADS. Overall, 40 cm-diameter beam was the severest case but the maximum temperature node after the transient was only changed to 642.0°C from 625.7°C. Hence, maximum CDF value after 1 000 s from the transient was 1.30×10^{-5} and kept in very low value compared to the failure criterion. From this result, the influence of beam diameter expansion was found to be very small for the creep rupture of claddings.

On beam flattening event, a flattened beam was approximated by a rectangular beam with 20 cm and 40 cm-X direction width. Maximum Y direction width was 30 cm for 20 cm X-direction width and 20 cm for 40 cm X-direction width and an initial beam diameter was 1 cm which is the same as beam expansion. From the analysis results, the severest case was the case of 40 cm × 20 cm rectangular beam. The cladding temperature of the highest node was increased to 645.4°C after the transient. However, maximum CDF value after 1 000 s from the transient was 1.80×10^{-5} which is much lower than CDF failure criterion. Beam flattening was supposed to be acceptable transient for ADS.

Beam hollowing event treated a beam as 40 cm-diameter beam with hollow inside of it. A hollow diameter was changed from 0 cm to 35 cm to investigate how the difference of a hollow diameter affects. The temperatures showed the highest when there was no hollow and temperatures tended to decrease as hollow diameter becomes larger. As a result, beam hollowing event was found to have little influence on the cladding.

Concerning beam incident position change event, a beam diameter was set to 1 cm, 10 cm, 20 cm and 30 cm to investigate the influence of diameter differences in this analysis. The maximum move distance of beam centre position was 25 cm for 1 cm diameter beam, 20 cm for 10 cm diameter beam, 15 cm for 20 cm diameter beam and 5 cm for 30 cm diameter beam. In all cases of analysis, temperatures rose drastically when the beam centre position moved. For example, the temperature of the highest node soared to 887.4°C from 631.8°C as shown in Figure 3 when 20 cm-diameter beam moved 15 cm. CDF exceeded the failure criterion when the centre position of the beam moved over 15 cm with 1 cm- and 10 cm-diameter beam, 10 cm with 20 cm-diameter beam. The shortest time until the failure was 6.1 s with 20 cm-diameter beam of 15 cm move as presented in Figure 4 and maximum CDF value after 1 000 s from the transient start was 2 507.8. The cladding failed region is described in Figure 5.

These results revealed that beam incident position change event have a very high risk to cause creep failures of claddings. Therefore, some measures such as a review of design should be taken for the prevention of the failures.

Figure 3: Time variation of cladding temperature in 20 cm diameter beam moved 15 cm

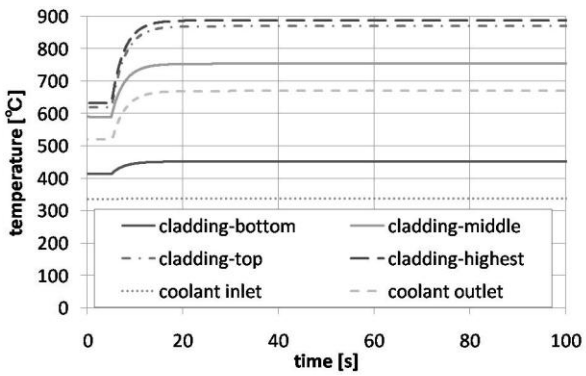


Figure 4: Time variation of cladding CDF in 20 cm diameter beam moved 15 cm

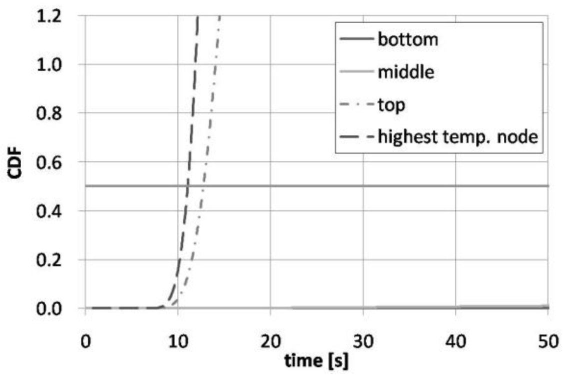
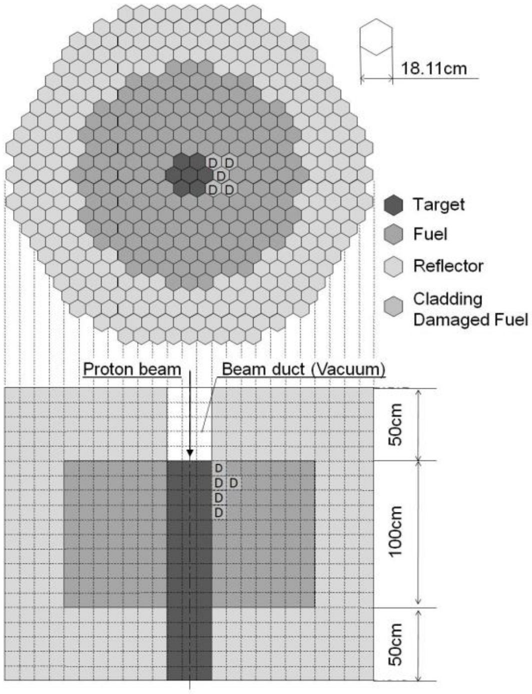


Figure 5: Cladding damaged region in 20 cm diameter beam moved 15 cm



Cladding failure analysis on accident

Analysis event

As mentioned in the first section, the accident was defined as the events which accompany with the beam over power or abnormal condition of cooling system. In this section, beam over power (BOP) was selected as the event which accompany with power change, unprotected loss of flow (ULOF) as abnormal condition of cooling system. Detailed beam power of BOP and pump coast-down time of ULOF refer to each subject described in following section.

Analysis result and discussion

Beam over power (BOP)

An instantaneous beam power increase was analysed and maximum beam power is set to 200% because the beam current ranges from 15 mA to 28 mA on the case of the ADS employed here. Besides, 125%, 150%, 175% beam power analyses are conducted to examine how much beam power causes a cladding failure.

Figure 6 shows the axial distributions of cladding temperatures after the transient with different beam power. The temperatures were extremely increased as the beam power becomes bigger. The maximum temperature before the transient was 631.4°C but it was increased to 702.1°C for 125% power, 771.7°C for 150%, 840.0°C for 175% and 907.3°C for 200% after the transient. CDF values also remarkably increased in response to temperature increases. As shown in Figure 7, the range of damaged cladding was spread with increasing beam power. In addition, the shortest rupture time is 516 s for 150% power, 12.8 s for 175% power and 5.4 s for 200% power (see Figure 8).

BOP caused the cladding failure in a short time. Beam injection into the spallation target should be interrupted by the introduction of some feedback circuit for the prevention of the failure when the excess beam intensity is detected in the beam line. Since the rupture threshold power was thought to range from 125 to 150% in this core, beam injection should be cut in the case over 125% beam power was detected to consider on the safe side.

Unprotected loss of flow (ULOF)

Pump coast-down times of 5 s, 10 s and 15s were analysed in this study. 5 s pump coast-down is the severest time in a previous study [6] and 10 s and 15 s pump coast-down were selected to investigate how the coast-down time difference influences results.

The time variation of the cladding temperatures on 5 s pump coast-down is shown in Figure 9 as an example of ULOF. The accident started at 5 s on this figure. Temperature increased to 1 081.2°C at a maximum on 5 s pump coast-down, which was the severest case. But the differences of maximum temperature were small since maximum cladding temperature was 1 077.1°C for 10 s coast-down and 1 059.2 for 15 s coast-down. These large temperature rises made the great increases of CDF at all of the nodes and wide cladding ruptures occurred on the all cases (see Figure 10). The ranges of cladding failed nodes were the same at all cases. The shortest rupture time was 9.6 s for 5 s coast-down, 13.4 s for 10 s coast-down and 17.1 s for 15 s coast-down as shown in Figure 11 of the CDF variations of the highest temperature node.

There is a little difference in the rupture time and temperature elevations but the huge scales of the cladding failure arise by all cases of ULOF. It is considered that safety beam shutdown before the rupture is the only way to prevent the cladding failure. The dependency between CDF and beam shutdown time was analysed and maximum beam shutdown time for the safety reactor shutdown was derived in regard to the severest case of the 5 s pump coast-down. As a result, maximum beam shutdown time was found to be within 9.2 s (see Figure 12).

Figure 6: Axial distributions of cladding temperatures after beam over power

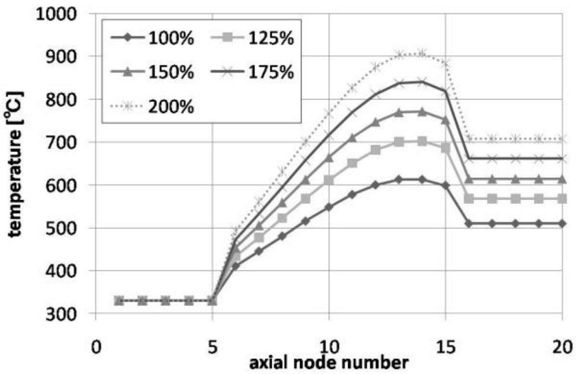


Figure 7: Axial distributions of cladding CDF after 1 000 s from beam over power

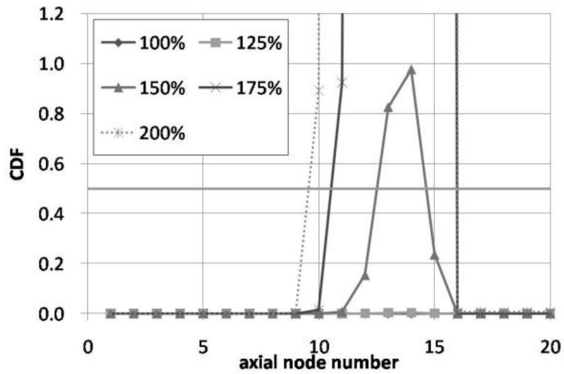
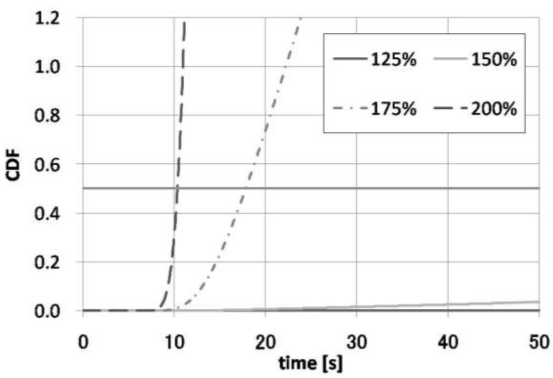


Figure 8: CDF variations of highest temperature node on beam over power

a) 10 s order

b) 100 s order



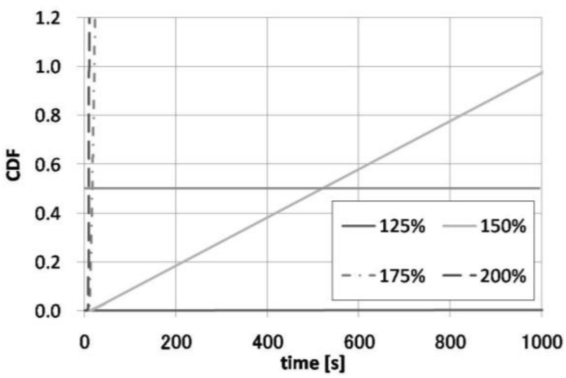


Figure 9: Time variations of cladding temperatures on 5 s pump coast-down with initial design core

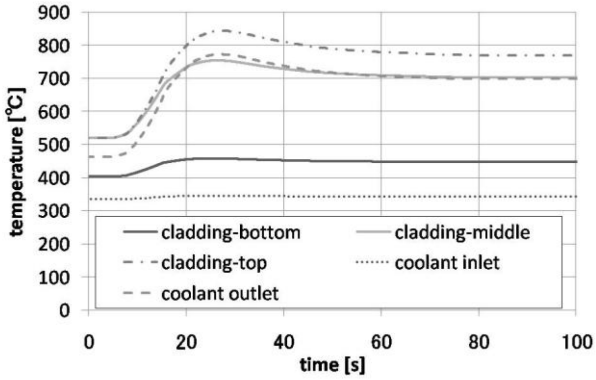


Figure 10: Time variations of cladding CDF on 5 s pump coast-down with initial design core

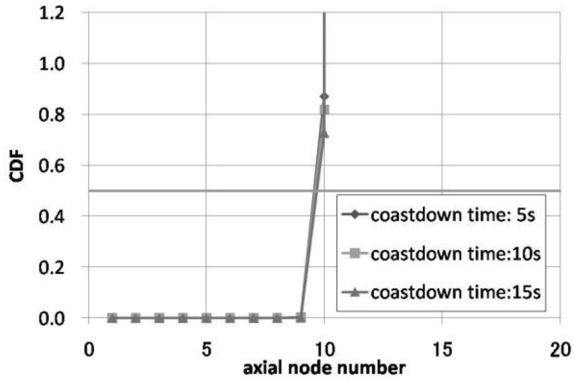


Figure 11: CDF variations of highest temperature node on unprotected loss of flow

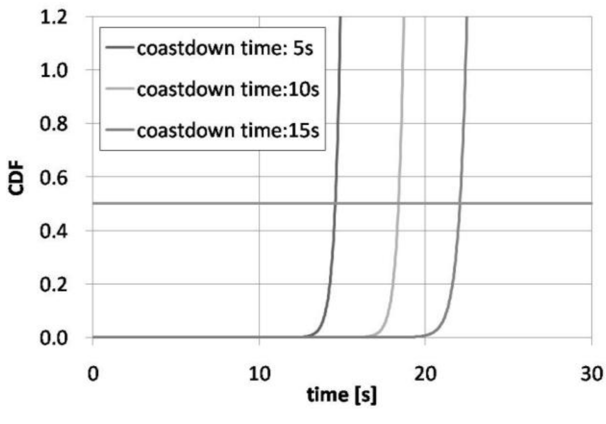
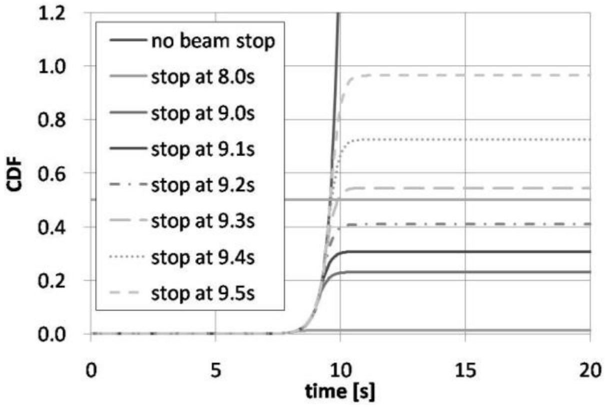


Figure 12: CDF variations of different beam shutdown time on 5 s pump coast-down



Conclusion

The cladding failure analyses on the transient and accident of ADS were conducted in this study by the method of CDF calculation. In the transient analysis, there were no failures by creep on beam diameter expansion, beam flattening and beam hollowing. However, beam incident position event increased cladding temperatures to 887.4°C and CDF values exceeded the failure criterion at 6.1 s. Since beam incident position change has a high risk to cause cladding failures by creep, some measures are essential for the prevention of cladding failure.

As for the accident, beam over power (BOP) was analysed and drastically increased the cladding temperatures. In the severest case of 200% power, the maximum temperature after the transient was about 270 K higher than that before the transient. CDF values also increased rapidly and claddings were failed over 150% beam power. Since BOP has a high probability to cause failures, beam power limitation is necessary for the prevention of the failure. From the analysis results, the limitation was determined to be 125%. In unprotected loss of flow (ULOF) analysis, cladding temperatures were increased extraordinarily. The maximum cladding temperature was 1 081.2°C and CDF value reached to the failure criterion at 9.6 s on the case of 5 s pump coast-down. ULOF have very high risk to fail the claddings at the large area of the core regardless of the pump coast-down time. Beam injection should be cut off before ruptures came up for the prevention of the failure and maximum beam shutdown time was investigated by changing the beam shutdown time for 5 s pump coast-down. Consequently, it is found that beam should be shut down within 9.2 s.

However, this study only deals with the creep rupture and does not consider other rupture modes such as a ductile rupture. The analysis by other method is essential for the detailed study of the cladding failure on the transient and accident of ADS.

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