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Drop Impact Analysis of Control Rod Assembly for Sodium-Cooled Fast Reactor

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1. Introduction

The Korea Atomic Energy Research Institute (KAERI) has been developing Prototype Gen-IV Sodium-cooled Fast Reactor (SFR). Only 0.72% (uranium-235) of natural uranium is fissile. For nuclear power to be sustainable it is essential we make better use of the natural resource. SFR fuel technology can resolve both the drain of fossil and limit Uranium resource in the world so that it can stably provide the energy resources to the public. In addition, the reprocessing technology of the SFR fuel and Pyro-processing can alleviate the storage problem of spent nuclear fuel. To provide a metal fuel for SFR constructed in 2028, it is necessary to develop a fuel and non-fuel assemblies (Control Assembly, Reflector Assembly and Shield Assembly). Control Assembly includes primary and secondary control rods. Primary and secondary control rods are made of B_4C (boron carbide). The purpose of primary control assemblies is two-fold: to provide neutronic start-up and shutdown, and control over the neutron population during normal operation. Secondary control assemblies are intended for rapid shut-down in emergency situations. Control assembly has a Control Rod Assembly with inner duct and control rod. Control rod assembly falls into a duct of control assembly due to gravity. Drop time and impact velocity of a control rod assembly are important parameters with respect to reactivity insertion time and the structural integrity of the Control Assembly. Drop time and velocity of Control Rod Assembly in normal condition were derived from CFD analysis.

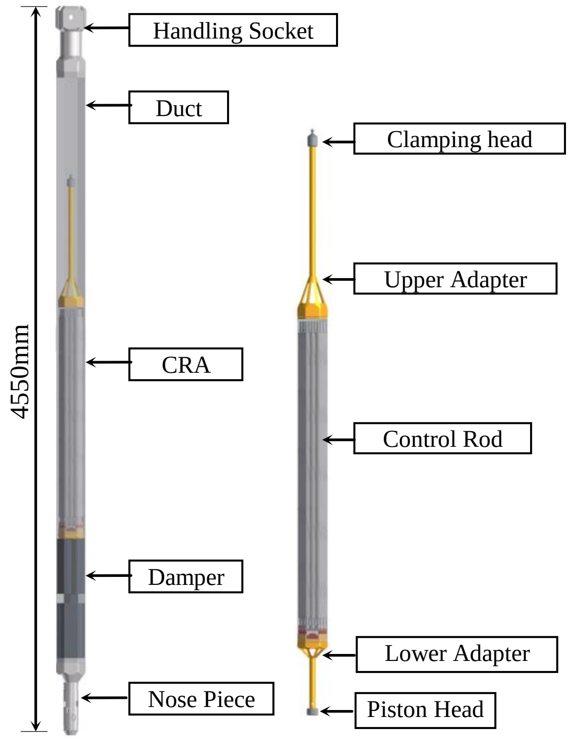
The objective of this study is to investigate the dynamic behavior and integrity evaluation of the Control Rod Assembly due to drop impact.

2. Control Assembly

The Control Assembly includes a Handling Socket, Duct, Control Rod Assembly, Damper and Nose Piece. Main components of Control Rod Assembly are Clamping head, Upper adapter, Control rod, Lower adapter, Piston head and Inner duct. Fig. 1 shows configuration of CA (Control Assembly) and CRA (Control Rod Assembly) for PGSFR.

Damper for the protection against drop impact of the CRA has a flow hole that reduces the velocity of CRA by using the fluid resistance between the piston head.

Therefore, CRA have the two types of velocity at the normal condition. Terminal velocity is the highest velocity attainable by CRA as it falls through sodium before the inserted into the damper. Impact velocity is a reduced velocity by a damper's flow hole. Drop height and velocity are summarized in table I.



(a) CA (Control Assembly) (b) CRA (Control Rod Assembly)

Fig. 1. Configuration of CA (Control Assembly) for PGSFR

Table I: Drop condition of CRA at normal condition

Drop height	Terminal velocity	Impact velocity
1 m	1.33 m/s	0.37 m/s

Table II: Material properties of 316 SS

Material (316SS)	Young's Modulus (GPa)	Poisson' s ratio	Yield Strength (MPa)
Room Temp.	193	0.29	290
545 ℃	161.5	0.31	162

The material of CA was 316SS that is an austenitic chromium-nickel stainless steel containing molybdenum. It provides increased strength at elevated temperatures. Material properties of 316SS are given in Table II.

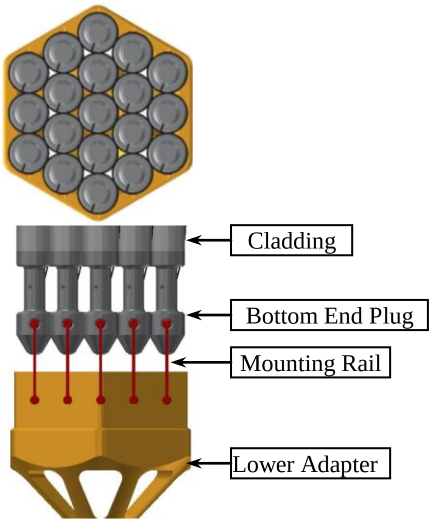


Fig. 2. Check point of CRA under impact load

Main components of CRA under impact load were shown in Fig. 2. Control rod and Lower adapter were connected by the Mounting rail that is subjected to impact load of control rod. Therefore, the Mounting rail is a check point in the drop impact analysis.

3. Finite element model

A finite element modeling for drop impact analysis was carried out using Hypermesh 11.0. Fig. 3 shows FE-model of external part of CA.

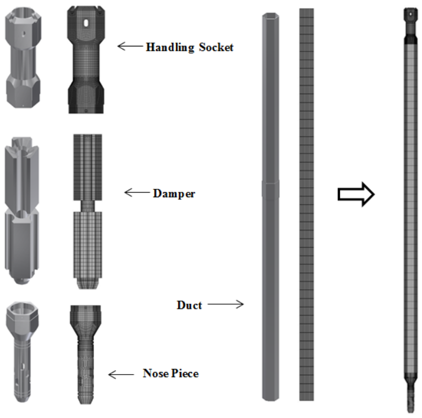


Fig. 3. FE-model of external part of CA

Table III: Summary of FE-model of external part of CA

Part	Type	Nodes	Elements
Handling socket	C3D8 & C3D6	26,824	19,822
Duct		4,512	2,208
Damper		56,570	54,084
Nose piece		14,718	10,608
External parts of CA		102,624	86,722

The element type of external part used Solid C3D8 that is a general purpose linear brick element with fully integrated (2x2x2 integration points). The accuracy of the analysis is higher than C3D8R with 1 integration point. Information on FE-model of external part is summarized in table III.

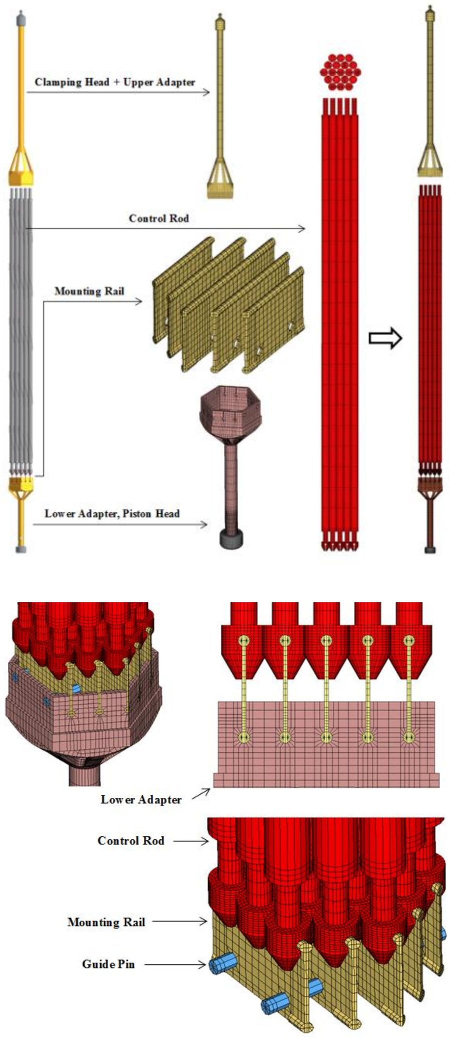


Fig. 4. FE-model of CRA for drop impact analysis

Table IV: Summary of FE-model of CRA

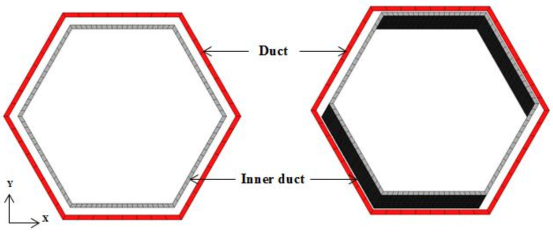
Part	Type	Nodes	Elements
Upper adapter	C3D8 & C3D6	7,951	4,784
Control rod		70,813	50,236
Mounting rail		5,685	3,480
Guide pin		450	384
Lower adapter		8,808	5008
Piston head		7,290	6,640
Inner duct		5,408	2,600
CRA		104,971	73,132

A finite element model of the CRA is a more detailed than external part of CA. Finite element model of CRA was shown in Fig. 4. Table IV shows summary of FE-model of CRA.

4. Drop impact analysis

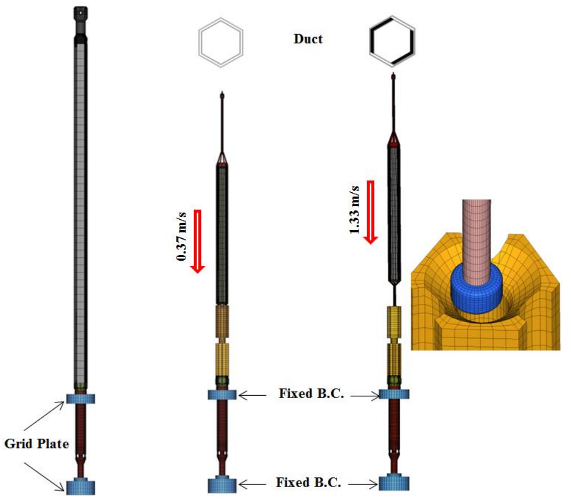
4.1 Boundary conditions

The boundary condition for impact analysis is different from according drop angle of CRA. Normal condition is inserted into the flow hole of Damper. Thus, the initial impact occurs between the Lower adapter of CRA and Damper. But, abnormal condition has 0.4 degree drop angle of CRA. Therefore, initial impact occurs between Piston head of CRA and Damper. Fig. 5 shows two different position of inner duct.



(a) Normal condition (b) Abnormal condition

Fig. 5. Position of inner duct according to drop angle



(a) Impact analysis-1 (b) Impact analysis-2

Fig. 6. Boundary conditions of impact analysis according drop angle

The boundary condition of impact analysis shows Fig. 6. Impact analysis-1 has initial velocity 0.37 m/s that is reduced velocity by the damper's flow hole. Impact analysis-2 has initial velocity 1.33 m/s. It selected the Terminal velocity in the conservative point.

4.2 Results of impact analysis

Impact analysis was carried out using a LS-DYNA that is a general–purpose finite element program capable of simulating complex real problems.

Fig. 7 shows results of Impact analysis-1 with normal condition. Maximum stress 140 MPa was occurred in Lower adapter and Mounting rail. But, it is lower than yield strength of 316SS at 545℃ and the stress was rapidly removed. Therefore, CRA maintained structural integrity in normal condition.

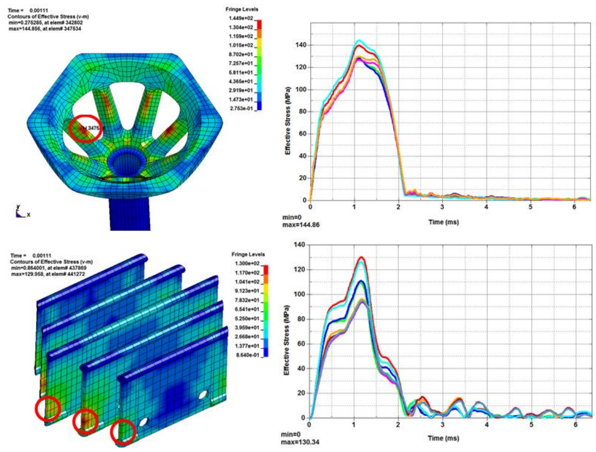


Fig. 7. Results of Impact analysis-1 with normal condition

Dynamic behavior of piston head of CRA with 0.4 degree drop angle was shown in Fig. 8. The CRA slides down an inclined surface on the Damper, and then that is normally inserted into the flow hole. Fig. 9 shows Diagram of location of check-point on Piston head. Check-point tend to converge toward center of flow hole.

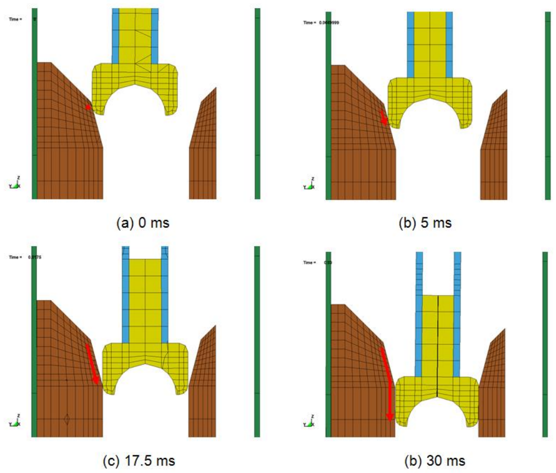


Fig. 8. Dynamic behavior of Piston head of CRA with abnormal conditions

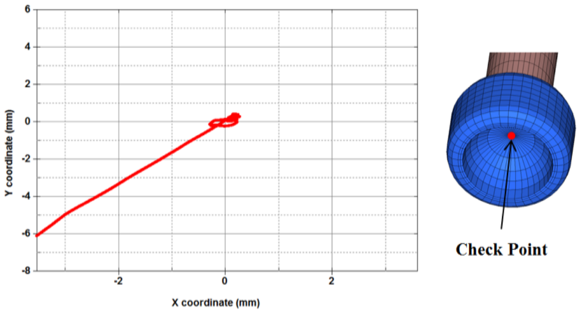


Fig. 9. Diagram of location of check-point on Piston head

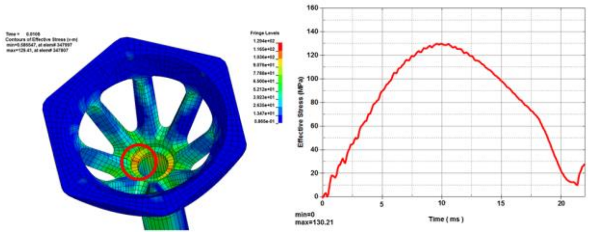


Fig. 10. Maximum stress of Lower adapter of CRA with abnormal conditions

Fig. 10 shows maximum stress of Impact analysis-2 with abnormal condition. Maximum stress 130 MPa was occurred in Lower adapter. The maximum stress is lower than yield strength of 316SS at 545℃ and the stress was removed. Therefore, CRA maintained structural integrity in abnormal condition.

5. Conclusions

Drop impact analysis of CRA with normal/abnormal drop condition was carried out to investigate the dynamic behavior and integrity evaluation. The results were as follows: The maximum stress was lower than yield strength and it was rapidly removed. Therefore, CRA maintained structural integrity and it is normally inserted into the flow hole of damper at abnormal condition.

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