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Structural Integrity Assessment of an Educational Reactor Module under Postulated Oil Fire Conditions

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1. Introduction

Loss of integrity in nuclear components and facilities may lead to radiation leakage accidents and subsequent environmental contaminations. To ensure the delivery of required safety functions and operator actions, Structures, Systems and Components (SSCs) should be adequately protected against internal and external hazards [1]. Especially, fire accidents in Nuclear Power Plants (NPPs) have been gradually increased in the recent.

The fire hazard analyses have been carried out according to strengthened international and domestic requirements [2]. Because these studies have been rigorously addressed in commercial NPPs, the relevant researches should be also performed in research/educational reactor. Among several ignition sources such as electricity, pumps, batteries, oil and transients, the oil fire has the largest heat release rates [3].

In this study, structural integrity assessment of an Aerojet General Nucleonics (AGN) educational reactor module is evaluated under postulated oil fire conditions. The four fire scenarios were assumed by considering fire area, height and fire type. The Computational Fluid Dynamics (CFD) analyses are implemented and the subsequent Finite Element (FE) analyses are carried out by calculating the von-Mises stress. Finally, the effects of parameters are also checked, of which details and key findings are discussed.

2. Analysis methods and conditions

2.1 Fire scenarios

The educational reactor which has licensed power of 10 W, the reactor module is located in reactor room as depicted in Fig. 1. In this research, the reactor module is made of several components. However, the only exterior parts such as reactor tank, water shielding tank, upper shielding material and reactor support were decided and simplified because of conservative assessment.

Fig. 1 depicts schematic of the educational reactor module and ignition sources. To evaluate influences of parameters, the four postulated oil fire scenarios were assumed with ignition source by taking into account fire area, height of ignition source and fire type as summarized in Table I. Furthermore, the ignition sources had same volume as 0.05 m^3 by combining fire area and height in fire scenarios.

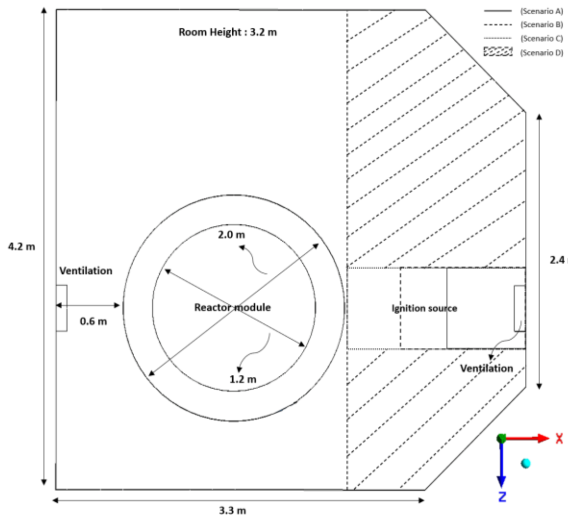


Fig. 1. Schematic of educational reactor module and ignition source upon fire scenarios

Table I: Postulated fire scenarios

Scenario	Fire area (m^2)	Height (m)	Fire type
A	0.25	0.2	Confined
B	0.5	0.1	Confined
C	0.8	0.0625	Confined
D	5.0	0.01	Unconfined

2.2 Analyses conditions and models

With regard to the oil fire, the heat release rates of ignition source were derived by Eq. (1) [4].

$$\dot{Q} = \dot{m}\Delta H_{c,eff} A_f \left(1 - e^{-k\beta D}\right) \quad (1)$$

In this equation, $\dot{Q}$ is heat release rate (kW), $\dot{m}$ is burning or mass loss rate per unit area per unit time (kg/m^2-sec), $\Delta H_{c,eff}$ is effective heat of combustion (kJ/kg), A_f is horizontal burning area of the fuel (m^2), $k\beta$ is empirical constant (m^{-1}) and D is diameter of burning area (m). Therefore, the values were calculated according to fire area under Scenarios A, B, C and D.

The initial temperature was set to room temperature and ventilation condition was applied to 0.67 m^3/s [5]. Also, fire duration time was categorized with 60 sec, 180 sec and 300 sec by regarding fire detector's time [6] and operator's reaction time [5]. The fire suppression system was not considered for more conservative assessment. The reactor module was made of SS304 stainless steel and its temperature dependent material properties [7] were taken into account.

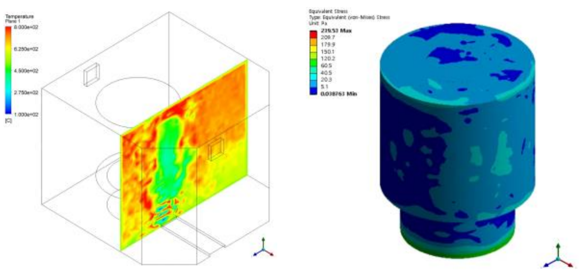
Integrity assessment was performed by ANSYS CFX and Mechanical. The CFD analyses were implemented with Smagorinsky turbulence model through previous verification and grid sensitivity studies [6]. Meanwhile, the number of nodes was 181,967 and the number of elements was 97,430 based on FE mesh sensitivity analyses. And then, bottom of the reactor module was fully fixed.

3. Analysis results

3.1 Structural integrity assessment

Structural integrity of the reactor module was evaluated based on sequential CFD analyses and FE analyses. Particularly, calculated effective stresses were compared with the corresponding criterion such as yield strength. As results, among confined fire scenarios, the maximum temperature and von-Mises stress were estimated as 822 ^{o}C and 240 MPa respectively when Scenario C was considered as shown in Fig. 2.

The reactor module sustained integrity under Scenarios A and B. However, the maximum stress value under Scenario C was 13 % higher than the corresponding criterion at the bottom of the reactor module due to close distance between ignition source and target. Otherwise, under the unconfined fire scenario, as soon as fire was started, the reactor module lost integrity because of high heat release rate upon large fire area.



(a) Temperature distribution (b) von-Mises stress distribution

Fig. 2. Temperature and von-Mises stress distributions at 300 sec under Scenario C

3.2 Parametric evaluation

To investigate contributions of fire area and duration time, a parametric evaluation was analyzed with only confined fire scenarios by comparing with three conditions respectively. Fig. 3 represents the tendency of these parameters based on von-Mises stress values. As results, the fire area which was relevant with heat release rate of ignition source was more effective than the duration time.

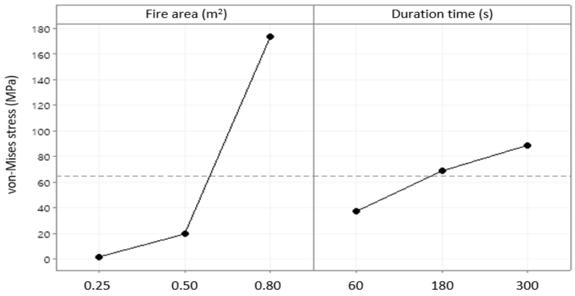


Fig. 3. Parametric evaluation based on stress values

4. Conclusions

In the present study, structural integrity assessment and parametric evaluation of the educational reactor module were carried out by systematic numerical analyses and the following conclusions were derived.

(1) In confined fire scenarios, the maximum von-Mises stress value under Scenario C was 13 % higher than the corresponding criterion because of close distance between ignition source and target.

(2) From the point of oil fire type, unconfined fire was more vulnerable to integrity of the reactor module than confined fire due to high heat release rate upon large fire area.

(3) As results of parametric evaluation, the fire area based on heat release rate of ignition source was more influential than the duration time.

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