Annals of Nuclear Energy 109 (2017) 548–556

Contents lists available at ScienceDirect

Annals of Nuclear Energy

journal homepage: www.elsevier.com/locate/anucene

Evaluation of spent fuel pool temperature and water level during SBO

Hiroyasu Mochizuki

Laboratory for Advanced Nuclear Energy, Institute of Innovative Research, Tokyo Institute of Technology, 2-12-1 Ookayama, Meguro-ku, Tokyo 152-8550, Japan

ARTICLE INFO

Article history:
Received 13 August 2016
Received in revised form 8 April 2017
Accepted 2 June 2017

Keywords:
Spent fuel pool
SBO
Boil-off
Dryout
RELAP5-3D
Hand calculation

ABSTRACT

The objective of the present study is to evaluate water level of a spent fuel pool during a station blackout (SBO) event which was really caused in the Fukushima-Daiichi (Fukushima-I) accident. The water level during the event can be calculated using a computer code based on the inventory of water in the spent fuel pool and decay heat of spent fuel assemblies. However, a calculation model should be prepared and a longer CPU time is required to obtain the result. If the water level change can be calculated by a hand calculation, it is fast and convenient to obtain the result. Therefore, the calculation results in terms of timings of saturated condition and boil-off are compared to the hand calculation results. It has been shown that the hand calculation results about the saturated and boil-off timings have good agreement with the calculated results using the RELAP5-3D code. The calculation model using the RELAP5-3D is verified using the water level data measured during the Fukushima-I accident. The spent fuel has a dryout phenomenon after the collapsed water level decreases below the top of the active fuel. The calculation model is verified using the measured data under an atmospheric pressure. The code can trace the collapsed water level to cause dryout at the top of the fuel assembly.

1. Introduction

During the Fukushima Daiichi (Fukushima-I) Accident on 11th March 2011, many people were anxious about the cooling of spent fuel pools (SFPs) implemented in the reactor buildings from Unit 1 to 4. Especially at the SFP of the Unit-4, all fuel assemblies of the reactor core were withdrawn and stored in the SFP in order to have a special maintenance of the reactor. They did not have alternative current (AC) power for 10 days. In a certain period of time in the Unit-1 and 2, they also lost direct current (DC) power due to flooding of seawater by the huge tsunami. Then after, the Unit 4 had caused hydrogen explosion inside the reactor building. The hydrogen was generated by the core melt of the Unit 3 and reversed into the Unit 4 through an exhaust pipe connected to a common stuck. Operators did not have any measures to cool down spent fuels and to keep the water level in the SFPs at the initial stage of the accident. Helicopters of the Self-Defense Forces poured seawater on the pool using a special bucket hanged beneath the helicopter in order to keep the water level above the top of the active fuel (TAF). The water level was observed visually during the flight. But we learned afterward that this action was not effective, and a most effective measure to keep the water level was seawater supply by a concrete pumping machine. Water in the pool was evaporated and water level was lowered gradually. However, nobody knew the correct water level and condition of the spent fuels for a long period of time. In some case, the Tokyo Electric Power Company (TEPCO) might think that they had to use a computer code to predict the timing of water evaporation when the fuel uncovery might occur.

After this accident, the importance of the cooling of the SFP is recognized and the International Panel on Fissile Materials made a report (Feiveson et al., 2011) to discuss the relevant issues about the management of the spent fuel. Before this accident, Collins and Hubbard (2001) pointed out potential risks of the SFP at a decommissioning nuclear power plant (NPP) because the SFP is not implemented in the containment vessel but in the reactor building which cannot endure an overpressure condition. The Nuclear Energy Agency Committee on the Safety of Nuclear Installations prepared a status report on SFPs under loss of cooling accident conditions (NEA, 2015). Studies relating passive cooling of the SFPs using heat pipes have also been conducted by several researchers (Miller, 2012), (Ye et al., 2013).

Temperature and water level of the SFP at the Fukushima-I nuclear power station have been studied by Yanagi (2013) using a computer code developed by himself. Good agreement was obtained in water level between the calculated and measured results after the Fukushima accident was temporary calmed down. There is a precedent study to predict the water level behavior of a PWR spent fuel pit (Yanagi et al., 2012). Yanagi (2013) investigated thermal-hydraulics of the SFP taking into account the decay heat

E-mail address: mochizuki.h@lane.iir.titech.ac.jp

http://dx.doi.org/10.1016/j.anucene.2017.06.006
0306-4549/

Nomenclature

A	constant	t_s	timing of saturated condition (s)
B	constant	t_{off}	timing of boil-off (s)
C	constant	τ_s	time period of reactor operation (s)
Cp	specific heat capacity (J/kg K)	V	total water inventory above top of fuel (m^3)
h_{fg}	latent heat of evaporation (J/kg)	V_T	total water inventory in the pool (m^3)
Q_d	decay power (kW)	ρ	density of subcooled water (kg/m^3)
Q_0	nominal reactor power (kW)	ρ_s	density of saturated water (kg/m^3)
T_i	initial water temperature (K)		
T_s	saturation water temperature (K)		
t	elapsed time from the time of reactor shutdown (s)		

and water evaporation rate under high temperature conditions. He also used a computational fluid dynamics (CFD) code to investigate temperature distribution in the pool during the accident. Park et al. (2013) also calculated temperature distribution in a SFP using a CFD code when a SFP cooling is lost in Korean NPP. However, the CFD calculation is usually a laborious work to obtain the long term temperature distribution and water level in the pool. Therefore, thermal-hydraulic calculation using a 1-D system code is realistic one. Franiewski et al. (2013) evaluated the consequences of fuel damage in a SPF after a loss-of-coolant event using the TRACE code. Kaliatka et al. (2013) evaluated the consequences of fuel melt in the pool during the similar event for the SFP of the Ignalina RBMK NPP using mainly the ATHLET-CD code. They used the ASTEK and RELAP5/SCDAPSIM codes in order to benchmark the same accident. Wu et al. (2014) also evaluated an accident of loss-of-pool-cooling of a PWR using the MAAP5 code. Kocar and Dagli (2015) calculated the thermal-hydraulics of the SFP of the Fukushima-I Unit 4 using the RELAP5/SCDAP code system to observe the water level reduction and fuel uncovery under an assumption that the boil off continues. Unfortunately, both timings of saturation and boil-off were too fast because total water inventory might not be correct. They concluded that natural circulation flow is stopped when the coolant level decreases below the top of fuel assemblies and the fuel cladding temperature starts to increase. However, it was confirmed that fuel uncovery occurs when the collapsed water level is below the TAF according to the experiment using a mock-up (Mochizuki, 2014). This behavior is discussed in the present study through the calculation with the RELAP5-3D code. Lee et al. (1994) calculated thermal-hydraulics of a SFP with rather simple method. Non-boiling water level is evaluated using their specific method which is a simplified flow network model like electrical circuits.

The thermal-hydraulics till the fuel is uncovered is seemed to be simple according to the results conducted by the above mentioned researchers, and the timings of reaching saturation temperature and the water level lowering due to evaporation may be estimated by the hand calculations. Therefore, one of the objectives of the present study is to compare the hand calculation results to the calculated results by RELAP5-3D. The other objective is to verify the calculation model with a measured result at the Unit 4 of the Fukushima-I.

2. Estimation of decay heat

Water level of the SFP is dependent on the decay heat of the spent fuels and water inventory in the pool during a loss of cooling accident. Therefore, the correlation to predict the decay heat is investigated in the present study. The aim of this investigation is to use the correlation which predict highest decay power.

Way and Wigner (1948) proposed an equation relating the decay power as follows.

$$\frac{Q_d}{Q_o} = C\left\{t^{-0.2} - (t+\tau_s)^{-0.2}\right\}, \tag{1}$$

where Q_d is the decay power, Q_0 is the nominal reactor power, τ_s is the time of reactor shutdown measured from the time of startup and t is the elapsed time from the time of reactor shutdown. C is a constant which is specific value for a fuel assembly.

Todreas and Kazimi (1990) give the following approximate decay power correlation based on Glasstone and Sesonske (1981) for beta heating as and the approximate decay power for gamma heating,

$$\frac{Q_d}{Q_o} = 0.066\left\{t^{-0.2} - (t+\tau_s)^{-0.2}\right\}. \tag{2}$$

Their correlation has the −0.2th power of time as well as the correlation of Way and Wigner. Todreas and Kazimi also proposed the following less simple expression in their textbook.

$$\frac{Q_d}{Q_o} = \left\{0.1(t+10)^{-0.2} - 0.087(t+2\times10^7)^{-0.2}\right\} - \left\{0.1(t+\tau_s+10)^{-0.2} - 0.087(t+\tau_s+2\times10^7)^{-0.2}\right\} \tag{3}$$

The American Nuclear Society proposed the following correlation in ANS (1973):

$$\frac{Q_d}{Q_o} = 0.005At^{-b}, \tag{4}$$

where constants A and b are defined as a function of the elapsed time as listed in Table 1.

These correlations are compared in Fig. 1. Since the decay heat power is large when the operating period of a reactor is short, one-month operation is assumed in the comparison. The correlation of Way and Wigner is highest among three correlations. The committee in the Atomic Energy Society in Japan proposed a correlation to predict decay heat using a complex way (Research Advisory Committee for Reactor Decay Heat Standard, 1989). However, the correlation has a trend slightly lower than the ANS correlation.

3. Calculation model

The calculation model of an SFP of the Advanced Boiling Water Reactor (ABWR) at Hamaoka NPP is illustrated in Fig. 2. The components in the model consist of two time-dependent volumes

Table 1
Constants of the ANS decay heat curve.

t (s)	$0 < t \le 10$	$10 < t \le 150$	$150 < t \le 8\times10^8$
A	12.05	15.31	27.43
b	0.0639	0.1807	0.2962