MELCOR Model of the Spent Fuel Pool of Fukushima Dai-ichi Unit 4

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INTRODUCTION

Unit 4 of the Fukushima Dai-ichi Nuclear Power Plant suffered a hydrogen explosion at 6:00 am on March 15, 2011, exactly 3.64 days after the earthquake hit the plant and the off-site power was lost. The earthquake occurred on March 11 at 2:47 pm. Since the reactor of this Unit 4 was defueled on November 29, 2010, and all its fuel was stored in the spent fuel pool (SFP4), it was first believed that the explosion was caused by hydrogen generated by the spent fuel, in particular, by the recently discharged core. The hypothetical scenario was as follows: power was lost, cooling to the SFP4 water was lost, pool water heated/boiled, water level decreased, fuel was uncovered, hot Zircaloy (Zr) reacted with steam, hydrogen was generated and accumulated above the pool, and the explosion occurred.

Recent analyses of the radioisotopes present in the water of the SFP4 and underwater video indicated that this scenario did not occur. The spent fuel in this pool was never uncovered nor damaged. The hydrogen causing the explosion was apparently generated in Unit 3 and transported through exhaust ducts that shared the same chimney with Unit 4.

This paper will try to answer the following questions: Could that hypothetical scenario in the SFP4 have occurred? Could the spent fuel in the SPF4 generate enough hydrogen to produce the explosion that occurred 3.64 days after the earthquake? Based on the damage of the explosion, it was estimated that at least 150 kg of hydrogen had to be generated.

DESCRIPTION OF MODEL

As part of the investigations of this accident, MELCOR models of the SFP4 were prepared and a series of calculations were completed. Two different versions of MELCOR were employed, version 1.8.6 and the latest version, version 2.1 [1]. The spent fuel pool option for boiling water reactor (BWR) fuel was selected in MELCOR.

The MELCOR model of the SFP4 consists of a total of 1535 fuel assemblies, out of which 548 assemblies are from the core defueled on November 29, 2010, 783 assemblies are older assemblies, and 204 are new/fresh assemblies. The total decay heat of the fuel in the pool was, at the time of the accident, 2.284 MWt, of which 1.87 MWt was from the 548 assemblies of the last core discharged and 0.41 MWt was from the older 783 assemblies. These decay heat values were calculated at Oak Ridge National Laboratory using the ORIGEN2.2 code [2], and they agree with values reported elsewhere[3]. The pool dimensions are 9.9 m × 12.2 m × 11.8 m (height). With the water level at 11.5 m, the pool volume is 1389 m3, of which only 1240 m3 is water, as some volume is taken up by the fuel and the fuel racks. The initial water temperature of the SFP4 was assumed to be 301 K. The fuel racks are made of stainless steel and are modeled in MELCOR with stainless steel and B4C.

RESULTS

MELCOR calculations were completed for different initial water levels: 11.5 m (pool almost full, water is only 0.3 m below the top rim), 4.457 m (top of the racks), 4.2 m, and 4.02 m (top of the active fuel). A calculation was also completed assuming a rapid loss of water due to a leak at the bottom of the pool, with the pool drained in 20 minutes, the fuel rapidly uncovered and oxidized in air. Results of these calculations are shown in Table I.

Table I. MELCOR Calculations for Fukushima Spent Fuel Pool - Unit 4

Initial Water Level (m)	Time to dry pool (days)	Time to 150 kg H_2 (days)	Total H_2 generated (kg)
11.5 – leak	0.014	–	10
11.5	19	14.65	1800
4.457	8.0	4.17	1980
4.2	7.8	3.86	2050
4.02	6.6	**3.63**	2000

The calculation with the initial water level at 11.5 m (full pool) takes 11 days for the water to boil down to the top of the fuel racks, 11.5 days for the fuel to be uncovered, 14.65 days to generate 150 kg of hydrogen, and 19 days for the pool to be completely dry. The calculation with the initial water level at 4.457 m takes 1.1 days to uncover the fuel and 4.17 days to generate 150 kg of hydrogen.

The calculation with the initial water level at 4.02 m takes 3.63 days to generate 150 kg of hydrogen, which is close to the time when the actual explosion occurred in Unit 4. Finally, fuel oxidation in air, after the pool drained the water in 20 minutes, generates only 10 kg of hydrogen. This is because very little steam is available, and Zr oxidation with

the oxygen of the air does not generate hydrogen. MELCOR calculated water levels and hydrogen generated in the SFP4 as a function of time for initial water levels of 4.457 m, 4.2 m, and 4.02 m are shown in Figs. 1 and 2, respectively.

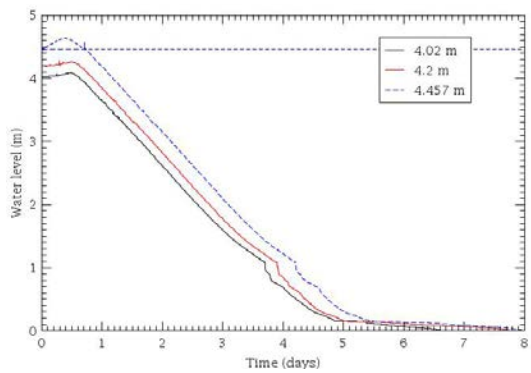

Fig. 1. Water levels as function of time in the spent fuel pool of Fukushima Unit 4.

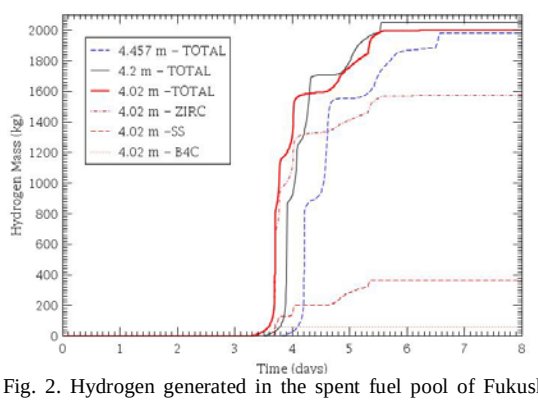

Fig. 2. Hydrogen generated in the spent fuel pool of Fukushima Unit 4.

Water levels increase at the beginning due to the expansion of the water during the heat-up from 301 K to 373 K. MELCOR did not calculate water evaporation. Pool water level decreases by boiling that occurs after the water temperature reaches saturation. The total amount of hydrogen generated is ~2000 kg; this amount includes hydrogen generated from Zr, which is the largest amount (~1580 kg), from stainless steel (~360 kg), and from B4C (~60 kg). In theory, it is possible to generate up to 3.4 kg of hydrogen per assembly (from oxidation of Zr in the fuel cladding and box), or a total of 4,525 kg from the hot 1331 assemblies stored in the SFP4. The hydrogen generated from oxidation of steel and B4C in the racks will be additional.

CONCLUSIONS

So the answers to the questions posed in the Introduction are – YES – according to these MELCOR calculations of hypothetical scenarios at the SPF4, enough hydrogen (150 kg) could be generated in the SFP4 3.64 days after the earthquake to produce an explosion. The initial water level has to be only 4.02 m, barely covering the top of the active fuel. If the water level is higher than 4.02 m, the time to generate enough hydrogen for an explosion will be longer than 3.64 days after the earthquake. If the pool is full of water, it takes 14.65 days to generate 150 kg of hydrogen. Total amounts of hydrogen generated from the spent fuel in the pool are ~2000 kg, except for fuel oxidation in air, which generates only 10 kg (Table I).

Source term releases from severe accidents are very different from fuel inside the vessel and from fuel inside spent fuel pools. With the appropriate source terms and release factors, these MELCOR models could be used to calculate radioactive releases from uncovered spent fuel in storage pools and to develop severe accident management strategies in spent fuel pools.

REFERENCES

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