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A Study on the Applicability of MELCOR to Molten Core-Concrete Interaction Under Severe Accidents

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Abstract

It has been an essential part for the safety assessment of nuclear power plants to understand various phenomena associated with the molten core-concrete interaction(MCCI) under severe accidents. In this study, the severe accident analysis code MELCOR was used to simulate the MCCI experiments such as SWISS and SURC test series which had been performed in Sandia National Laboratories(SNL). The calculation results were compared with corresponding experimental data such as melt temperature, concrete ablation distance, gas generation rate, and aerosol release rate. Good agreements were observed between MELCOR calculation and experimental data. The melt pool was sustained within the range of high temperature and the concrete ablation occurred continuously. The gas generation and aerosol release were under the influence of melt temperature and overlying water pool, respectively.

Key Words : molten core-concrete interaction(MCCI), MELCOR, severe accidents, concrete ablation, melt temperature, gas generation, aerosol release

1. Introduction

Under severe accidents of light water reactors (LWRs), losses of normal and emergency cooling systems would lead to melting and slumping of the core. If uninterrupted, this would be followed by failure of the pressure vessel and deposition of molten core onto the concrete floor of the reactor cavity. For this molten core-concrete interaction(MCCI), the temperature of debris would be so high as to decompose and ablate the concrete, and finally the failure of containment would occur. The large amount of water vapor and carbon dioxide produced by the decomposition of concrete, which could react with metals to produce hydrogen and carbon monoxide, would lead to the overpressurization of containment. Also, radioactive aerosols that evolve as a result of MCCI could enhance radiological consequences of containment failure.

The MELCOR1.8.3[1] code is a fully integrated, relatively fast running code that models the progression of severe accidents in LWRs. It was developed at Sandia National Laboratories(SNL) for the U.S. Nuclear Regulatory Commission (NRC). The entire spectrum of severe accidents can be treated in a unified code framework of MELCOR. The MELCOR code is composed of a number of different packages, each of which models a different portion of the accident phenomenology. The CORCON-MOD3[2] that could be indirectly accessed by means of running MELCOR1.8.3 was developed to mechanistically model the MCCI.

Various experimental and theoretical investigations have been performed as a part of making an effort to understand the MCCI[3,4,5,6,7,8,9]. The previous work was brought into focus on the minute examination of separate effect in the process of MCCI, which might cause the discontinuous interrelations among the complex phenomena of MCCI. This study was performed to comprehensively analyze the MCCI with MELCOR. The experiments chosen for this study were the SWISS-1[3], SWISS-2[3], SURC-1[4], and SURC-4[5] tests which had been conducted at Sandia National Laboratories(SNL). The calculation results were compared with the overall experimental data including melt temperature, concrete ablation distance, gas generation rate, and aerosol release rate all together.

2. Description of Experiments

2.1. SWISS(Sustained Water Interaction with Stainless Steel)

SWISS program consisted of two experiments aimed at the investigation of the influence of an overlying water pool on melt quenching and aerosol scrubbing. In both tests high temperature and induction heated stainless steel was used as a melt simulant. After heat-up, the melt was poured into MgO crucible of 21.6cm inner diameter. Its bottom was made of limestone common sand concrete. During the test, the melt was flooded with water that was continuously renewed to sustain constant levels of subcooling and hydrostatic water head. The two SWISS tests mainly differed from each other in the timing of water addition. In case of SWISS-1, no water was added until concrete of 12cm had been eroded and concrete slag had started to form a crust on top of the melt. To the contrary, the flooding in SWISS-2 was initiated immediately after the onset of test. In both tests no fragmentation occurred at the surface. Instead, a solid crust formed and isolated MCCI from the water on top. Consequently, there was no reduction of the concrete ablation rate in response to the flooding, and the final extent of ablation was found to be almost identical despite different histories of water addition.

2.2. SURC(Sustained Urania Reacting with Concrete)

The SURC test series were designed to extend the existing database of MCCI and to produce the associated aerosol source term. The SURC-1 was large scale test which gave important result for axial concrete ablation by oxidic melt of UO_2-ZrO_2. The basemat of 40cm diameter was made of limestone concrete. In SURC-4, zirconium was added to the stainless steel pool in order to investigate the effect of zirconium oxidation on MCCI. The effects of zirconium addition on concrete ablation and on gas release rates were observed. The basaltic concrete slug was 40cm in diameter and was surrounded by MgO cylinder that limited the ablation to the downward direction. The experiment started with 200kg stainless steel charge in the crucible and at an initial temperature of 25℃. At 119 minutes, 20kg of zirconium cylinders were dropped into the melt. Upon the addition of the zirconium, the melt temperature was observed to increase over several minutes and the volumetric gas flow increased accordingly.

3. MELCOR Calculation and Results

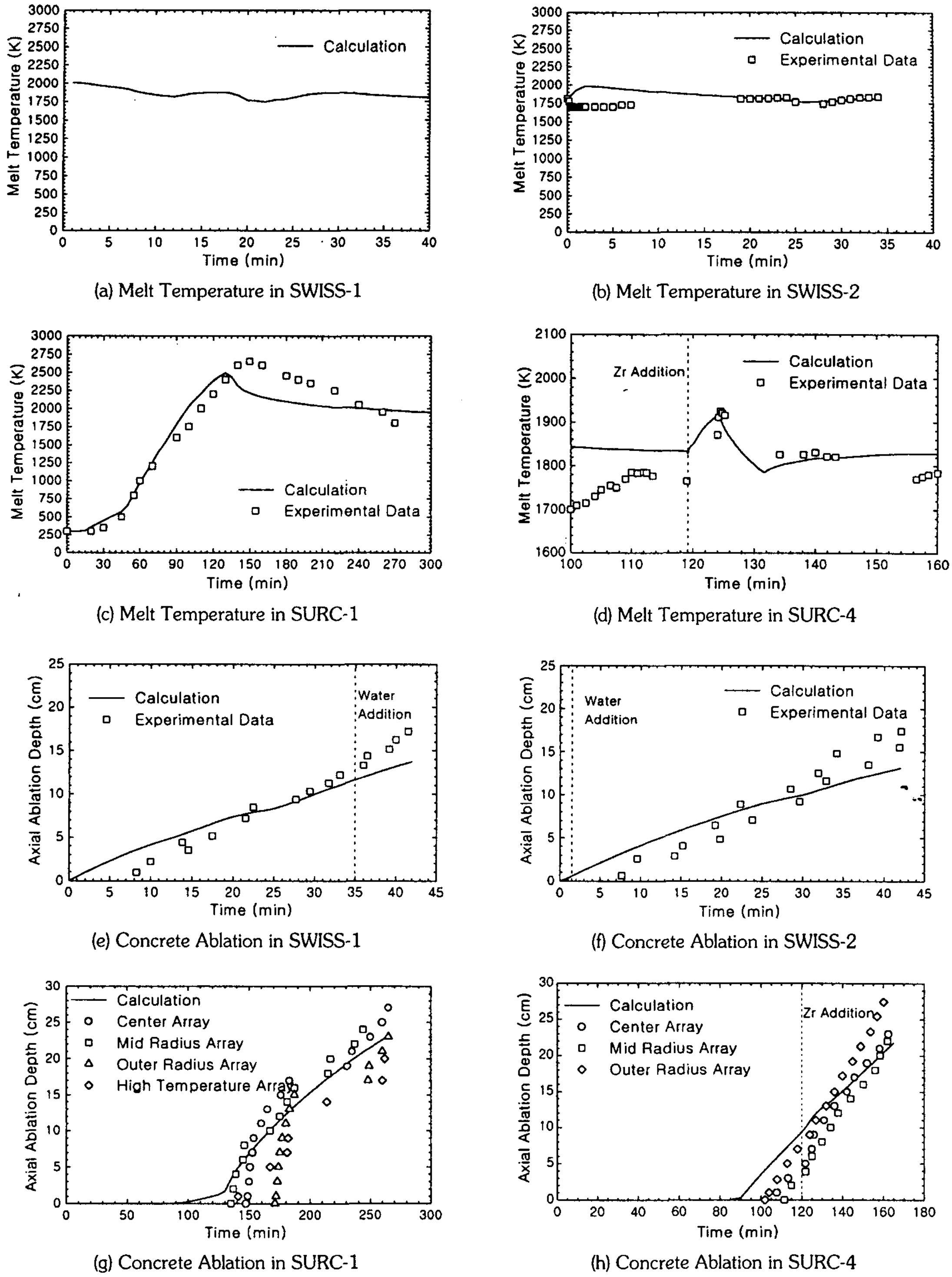
3.1. Melt Temperature

The calculated melt temperature of SWISS-1 was shown in Fig. 1(a). The comparison of calculation results with experimental data was not made because the temperature data of SWISS-1 was not available. It was observed that the melt pool was sustained within the range of high temperature and the melt temperature decreased slowly. Fig. 1(b) showed the melt temperature history of SWISS-2. MELCOR predicted results were in good agreements with experimental data. In SWISS-2, a thick crust formed on the surface of the melt soon after the contact by water. The crust adhered to the walls of the crucible and remained in place as the molten steel continued to penetrate the concrete. Because the upper surface of the melt was not in contact with the coolant due to interfacial crust, upward heat loss was controlled by conduction rather than by convection. Therefore, it was assumed that water would simply boil on the molten steel due to film boiling, and that unless the molten steel was spread quite thinly, insufficient heat would be removed by coolant. If a coolant layer was present, MELCOR calculated the heat transfer between melt and coolant on the basis of standard pool boiling correlations. Because the crust modelling was not included in MELCOR, the substitutive film boiling model was used. From the Fig. 1(b), it was found that the melt temperature decreased very slowly and overlying water hardly had influence on melt coolability. This fact was supported by other experiments such as WETCOR[10] and MACE [11].

Temperature data of SURC-1 were shown in Fig. 1(c). In this test, about 200kg of UO_2 containing 25wt% of ZrO_2 and 10wt% of Zr was inductively heated using tungsten ring susceptors and brought into contact with limestone concrete. Once the zirconium inventory was consumed and large amounts of molten concrete were incorporated into the melt, temperatures dropped sharply but remained above the liquidus temperature of concrete(1750K) until 300 minutes. The melt temperature predicted by the MELCOR code together with the SURC-4 experimental results was shown in Fig. 1(d). The experimental results shown in the figure were the peak temperatures prior to failures of thermocouples during the test. The measured melt temperature continuously increased after the initiation of concrete attack at 105 minutes. This upward trend of melt temperature leveled off around 110 minutes. It was also shown that the addition of zirconium into melt pool had a very strong and prompt positive impact on the melt temperature. An abrupt transient increase of temperature could be explained by exothermal chemical reactions of zirconium with the condensed oxide of concrete decomposition products.

3.2. Concrete Ablation Distance

Each of the SWISS and SURC tests involved molten prototypic materials interacting with concrete surrounded by the crucible of magnesia sidewalls. This crucible design limited the MCCI to



(a) Melt Temperature in SWISS-1

(b) Melt Temperature in SWISS-2

(c) Melt Temperature in SURC-1

(d) Melt Temperature in SURC-4

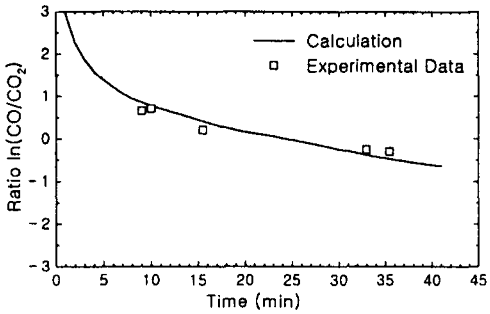
(e) Concrete Ablation in SWISS-1

(f) Concrete Ablation in SWISS-2

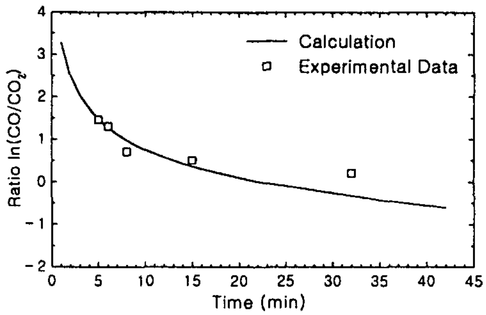
(g) Concrete Ablation in SURC-1

(h) Concrete Ablation in SURC-4

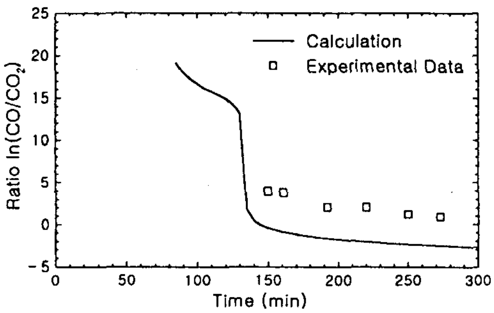
Fig. 1. Comparison of Calculation with Experimental Data



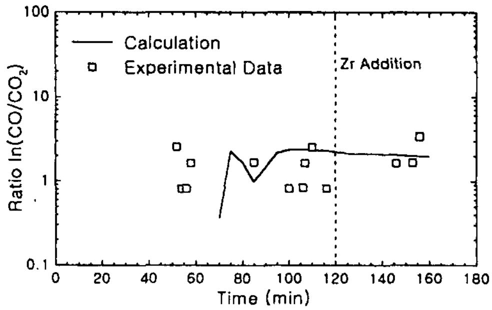
(i) Ratio ln(CO/CO_2) in SWISS-1



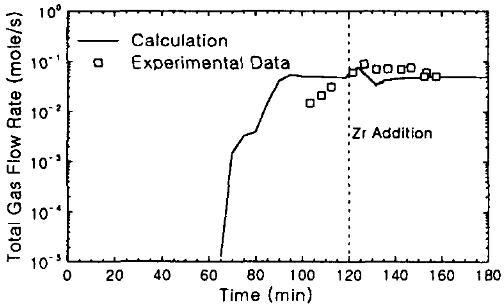
(j) Ratio ln(CO/CO_2) in SWISS-2



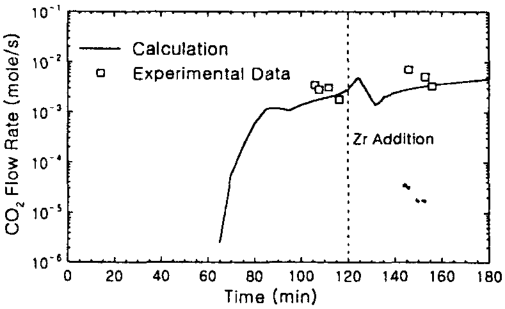
(k) Ratio ln(CO/CO_2) in SURC-1



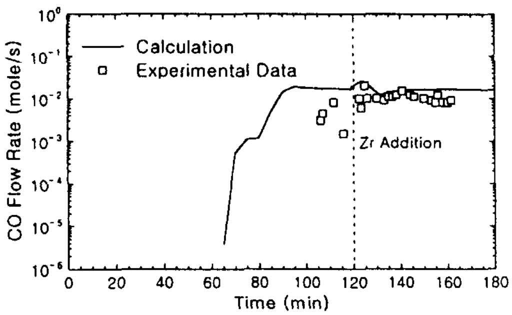
(l) Ratio ln(CO/CO_2) in SURC-4



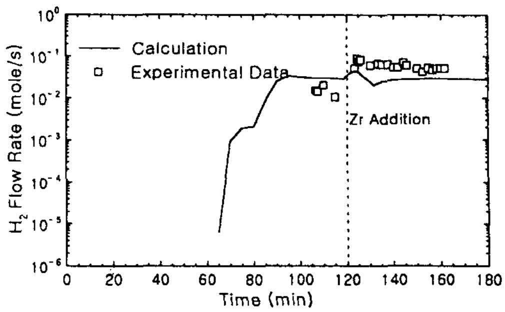
(m) Total Gas Flow Rate in SURC-4



(n) CO_2 Flow Rate in SURC-4

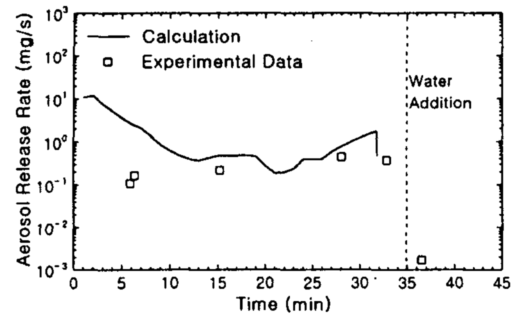


(o) CO Flow Rate in SURC-4

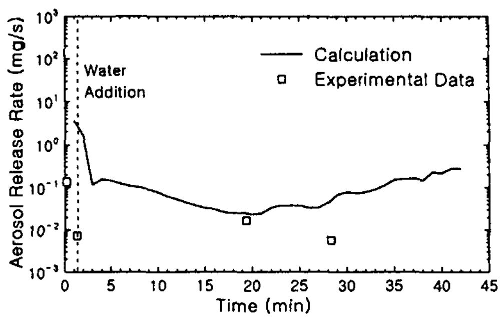


(p) H_2 Flow Rate in SURC-4

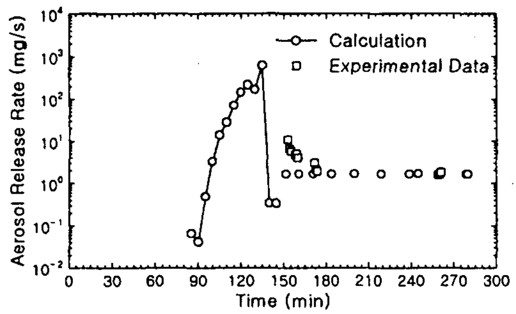
Fig. 1. Comparison of Calculation with Experimental Data(continued)



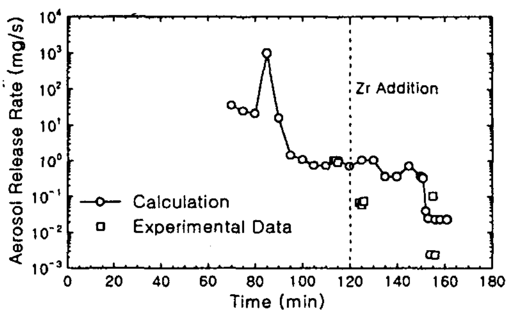
(q) Aerosol Release Rate in SWISS-1



(r) Aerosol Release Rate in SWISS-2



(s) Aerosol Release Rate in SURC-1



(t) Aerosol Release Rate in SURC-4

Fig. 1. Comparison of Calculation with Experimental Data(continued)

the axial(downward) direction. Therefore it permitted one-dimensional MCCI analysis. Since the thermocouples embedded in concrete failed when they were in contact with the melt, the failure of these thermocouples indicated the extent of concrete ablation.

The objective of SWISS tests was to investigate the coolability of melts by overlying water pools. In SWISS-1 and SWISS-2, the steel melts of 46kg and 44.2kg, respectively, were poured on concrete with a diameter of 21.6 cm. In SWISS-1, the melt was flooded after the concrete ablation of 12cm, while in SWISS-2 the water was injected about 1 minute after the start of concrete ablation. In both cases, the cooling of melt was prevented by a stable surface crust, which limited upward heat removal so that downward concrete ablation remained nearly unaffected as shown in Fig. 1(e) and 1(f). The one-dimensional model of concrete ablation in MELCOR predicted the experimental results quite well as shown in Fig. 1(g). It was also observed that the ablation rate based on the central array thermocouples increased by a factor of 2 after the addition of zirconium metal as shown in Fig. 1(h).

3.3. Gas Generation Rate

Besides the concrete penetration, MCCI had a great influence on the pressure load of containment and the aerosol concentration in the containment atmosphere. Chemical reactions between concrete decomposition gases and molten pool were important because they provided a source of combustible gases such as H_2 and CO and the transport of fission products out of the molten pool. For SWISS and SURC-1, only ratios of CO/CO_2 could be compared with calculation results due to data deficiency. For SURC-4, calculated gas generation rates were compared with experimental data for major four gases such as H_2, H_2O, CO, and CO_2. In general, gas analysis technique was very difficult so that gas data of MCCI experiments had large uncertainties. The ratios of CO/CO_2 in SWISS-1, SWISS-2, SURC-1 and SURC-4 were shown in Fig. 1(i), 1(j), 1(k) and 1(l). An examination of data showed that the CO content decreased steadily after the initiation of MCCI because the melt cooled down slowly. The ratio of CO/CO_2 indicated the reduction rate of CO_2 evolved from the decomposing concrete and the extent of steel oxidation.

Fig. 1(m) through 1(p) compared the gas flow rates including H_2, CO, and CO_2. As shown in these figures, the measured gas flow rates increased after the addition of zirconium metal. In SURC-4, the gas compositions were measured at an equilibrium temperature of 300K. But the gas compositions predicted by MELCOR were at a much higher temperature, i.e., around the melt temperature. In these figures, no adjustment was made to account for this difference.

3.4. Aerosol Release Rate

The aerosol release from MCCI was important because it represented a major mechanism through which fission products could be released to the containment atmosphere. In addition, inert aerosols composed of the concrete decomposition products such as CaO, SiO_2 and Al_2O_3 could be released. Both types of aerosols could be produced by the condensation of vaporized chemical species when they encountered cold gas or by other mechanical means.

Besides decreasing the decay heat source from the molten debris, overlying water pools could also reduce the gas and aerosol release during the MCCI. Experimental results showed that water would attenuate the aerosol production associated with MCCI. This fact was proved in calculation results. Total aerosol release rates of SWISS-1 and SWISS-2 were displayed in Fig. 1(q) and 1(r). It was shown that total aerosol release rate was reduced by a factor from 10 to 100 after the water addition. The aerosol release rates of SURC-1 and SURC-4 were displayed in Fig. 1(s) and 1(t). As shown in these figures, the initial large peak of aerosol was attributed to the initial violent interactions between the melt and the concrete.

4. Conclusions

MELCOR calculations were performed to comprehensively investigate the MCCI phenomena focusing on the melt temperature, concrete ablation distance, gas generation rate, and aerosol release rate. The experimental data were well predicted by the code in all cases. The melt pool was sustained within the range of high temperature and the melt temperature decreased slowly regardless of the presence of overlying coolant so that downward concrete ablation remained nearly unaffected. It was also observed that the addition of zirconium into melt pool had a great influence on the melt temperature and concrete ablation. The gas generation rates were dependent on melt temperature and decreased steadily as the melt cooled down slowly. The addition of water was considered as an important mechanism to reduce the aerosol release rates.

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