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Interaction and Penetration of Heated UO_2 with Limestone Concrete

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To safeguard the environment against radiological releases, the major question of concern in PAHR safety assessment, following an HCDA, involves confinement and dilution of the molten core-debris. Significant to the study is the directional growth of the core-debris in the concrete foundation of the reactor building or the concrete below the reactor cavity. Concrete poses an excellent core-debris confinement and dilution medium, since its molten phase is lighter than and miscible with the core-debris. Nevertheless, contact between the core-debris and concrete is accompanied by violent interaction and a considerable amount of gas release. This is expected to greatly affect the molten pool heat transfer and directional melting heat transfer into the bounding concrete surfaces. Accordingly, real material experiments are being conducted to investigate various phenomena associated with core-debris/concrete interaction.

The real material experiments were carried out in the test apparatus shown in Fig. 1. Casts of CRBRP limestone concrete [2,3] were prepared in graphite cylinders, each having an internal diameter of 8.9 cm and a depth of 30.5 cm. The 17.8-cm-deep concrete samples were allowed to cure for at least 28 days. Experiments were conducted within two months of curing time. Embedded in each concrete sample were six thermocouples, 1.2 cm apart, located along the axis of concrete, with the first thermocouple being ~ .3 cm below the initial surface of the concrete. The graphite cylinder containing the concrete was inserted into a graphite block, such that the concrete surface and bottom of the block were in a common plane. The graphite block and a tungsten rod placed in the center of the cylinder were connected to a 300-kw a-c power supply. A displacement transducer was used to measure the radial expansion of the concrete in the plane of the No. 6 thermocouple.

The cavity above concrete was packed with 3 kg of pure UO_2 particles (1-3 mm). A uranothermic mixture was placed on the top of UO_2 powder. The top of the test section was sealed and the system was connected to a gas/aerosol sampling device. The test section was then entirely insulated to reduce radial heat losses as much as possible. The test section was isolated in a radioactive cave and all the experimental operations thereon were conducted remotely.

Heating and possible melting of UO_2 was achieved resistively after the ignition of the thermite. Total experimental time was about 60 minutes, during which time a maximum electrical power input of 1.8 watts/gr was applied to the UO_2. Termination of the experiment was brought about by the discontinuity in the electrical current path. An automatic data acquisition system was utilized to record the relevant data at regular time intervals.

Three gas samples were taken at temperatures of 100, 600, and 950°C, measured in the plane of the #2 thermocouple. Selection of these temperatures were to study the amount and the type of gases released from different phases of concrete.

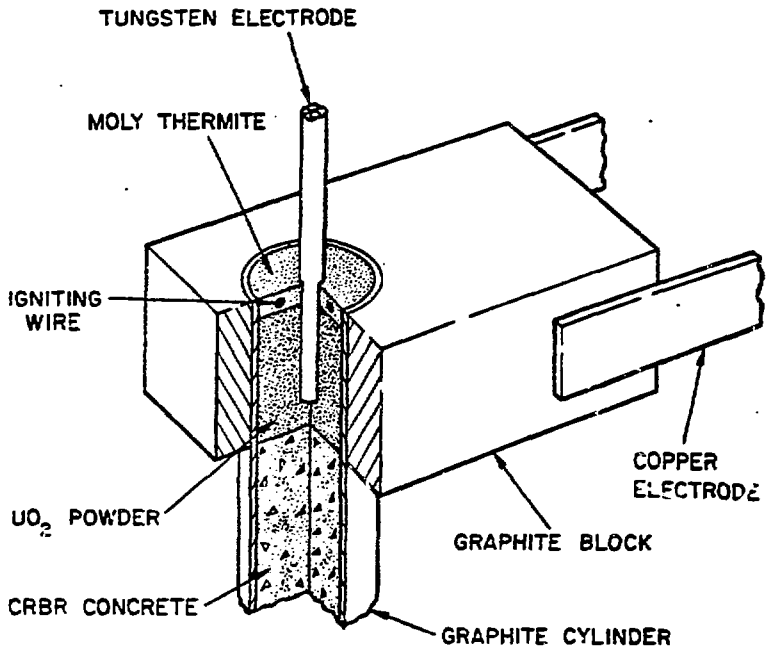

Figure 1. Schematic Drawing of the Test Appartus.

Table 1 gives the chemical composition, percentage and flow rate of each composition in the sampled gases. As is evident, each sample contained H_2, CH_4, H_2O, N_2, CO, O_2, Ar, and CO_2. Limestone concrete contains 43% by wt H_2O and CO_2, which are released at elevated temperatures. H_2 results from H_2O dissociation. CH_4 and CO result from reaction of H_2 and CO_2 with very hot graphite. Furthermore, reaction of water vapor with graphite, dissociation of CO_2, as well as reaction of UO_2 with calcite could contribute to a high volume % of CO. N_2 and some of the O_2 could be the excess air left in the system and Ar is the purged gas. Volume % of different gases in each sample is dependent on the concrete temperature at the time the sample was taken. As expected, rates of water vapor and H_2 in the first sample is large. The small amount of CO and CO_2 is due to reaction of H_2O vapor with graphite. In the second sample, H_2 has decreased but CO and CO_2 has increased. H_2 in the third sample, for all practical reasons, has approached zero whereas CO has attained maximum value. Nevertheless, the type of chemical composition that comprises any sample beyond 1200°C resembles the result of sample #3 until the experiment is terminated. In relation to reactor technology, once the initial heating phase of concrete is overcome, presence of H_2 is expected to be minute. However, considerable amounts of CO and CO_2 can be present in the containment building which can safely enter into the atmosphere, in the event the breach of the containment building is encountered.

The aerosol sampling device did not show any detectable radioactive particles. In the process of melting, penetration and gas release, the gases did not carry any UO_2 particles. The detectable aerosol particles were mostly C and very minute concrete constituents.

Radial expansion measurements of concrete by the displacement transducer is given in Fig. 2 in terms of time, and in Fig. 3 in

Table 1. Analyzed Sampled Gases and Their Respective Rates

Samples	H_2 % Vol. (cc/min)	CH_4 % Vol. (cc/min)	H_2O % Vol. (cc/min)	CO % Vol. (cc/min)	CO_2 % Vol. (cc/min)	N_2 % Vol. (cc/min)	O_2 % Vol. (cc/min)	Ar % Vol. (cc/min)
#1	82. (713.4)	.3 (2.61)	.5 (4.35)	3.9 (33.93)	3.1 (26.97)	1.7 (14.79)	.3 (2.61)	8.2 (71.34)
#2	26.5 (429.3)	.2 (3.24)	.6 (9.72)	28.1 (455.22)	21.9 (354.78)	7.9 (127.98)	2.0 (32.4)	12.8 (207.36)
#3	.4 (20.4)	< .02 (< 1.02)	.4 (20.4)	83.2 (4243.2)	.7 (35.7)	9.0 (45.9)	2.4 (122.4)	3.9 (198.9)

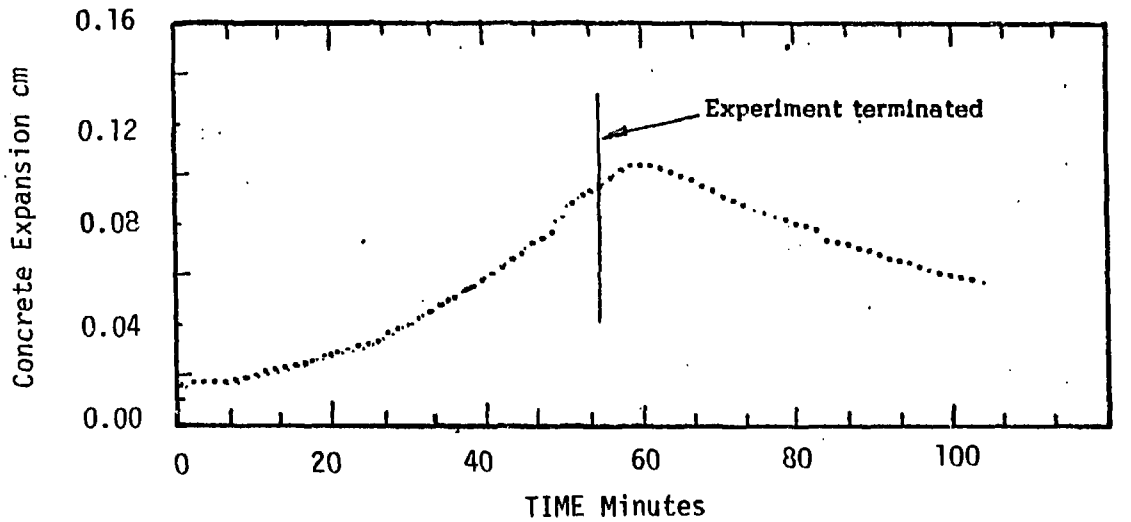

Figure 2. Concrete Expansion as a Function of Time.

terms of temperature. Radial expansion of concrete at the #6 thermocouple reaches a maxmimum of 0.087 cm about 5 minutes after the experiment is terminated. Referring to Fig. 3, it is evident that this maximum does not occur at the maximum temperature of 700°C. At the maximum temperature concrete has gone through slight compression, 0.054 cm. Accordingly, expansion of concrete can be attributed solely to pore pressure established by migrating water. Reversal in the expansion of concrete can be due to removal of the water from concrete and the drying of the concrete which in turn contributes to the relief of stresses caused by pore pressure. The failure time and distance of the two consecutive thermocouples is used in calculating the penetration rate of UO_2 into concrete. This amounted to about .23 cm/min. Using radiograph of Fig. 4 and experimental time of 30 min similar rate is obtained. Furthermore, the radiograph clearly indicates the uniform downward heat transfer into concrete and relatively small heat loss in the radial direction, about 20%.

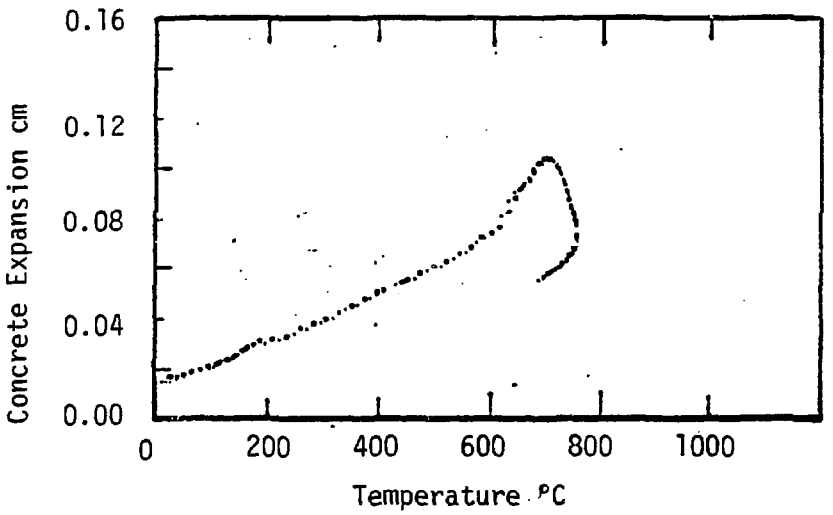

Figure 3. Concrete Expansion as a Function of Temperature.

Post-experimental analysis of the sample indicated more or less similar results as were described by Farhadieh and Gunther.[1] The solid mass of UO_2/concrete mixture, that resulted from the penetration of UO_2 into concrete, had a porous, volcanic appearance and was relatively brittle. The top surface of the mass, looking into the overlying cavity, contained random holes 3-7 mm in diameter, which were indicative of gas release sites through the once-molten mixture (Fig. 5). It is likely that gas pockets were locally formed between the molten mass and top surface of the solid concrete which were removed by Rayleigh Taylor instability mechanism. Similar phenomenology was observed in melting of an immiscible system, but the melt film was continuous.

Electron probe analysis of selected UO_2/concrete samples showed more or less uniform distribution of UO_2 and concrete constituents. X-ray analysis of similar samples indicated formation of CaU_2O_6 and $Ca_2U_2O_7$ chemical compounds between UO_2 and concrete constituents.

Inspection of the post-experimental concrete samples indicated presence of about 5-mm-thick white powder, mostly CaO, at the interface of concrete and UO_2/concrete solidified mass. The underlying concrete mass, though not decomposed, was heavily dehydrated. Inspection of the concrete sample two days later revealed that the dehydrated region of concrete, extending about 3 cm below the surface, had swollen considerably, with virtually no strength.

Plans are to include some typical fission particles in the experiments to study the airborne capability of the particles upon penetration, gas release, and aerosol formation, and to carry out similar experiments with basalt and magnetite type concrete for comparison with the limestone concrete. It should be mentioned that the first test on basalt concrete was successfully carried out.

References

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3. T. Z. Harmathy, "Thermal Properties of Concrete at Elevated Temperatures," J. Mater., 5, 2, 47 (1970).

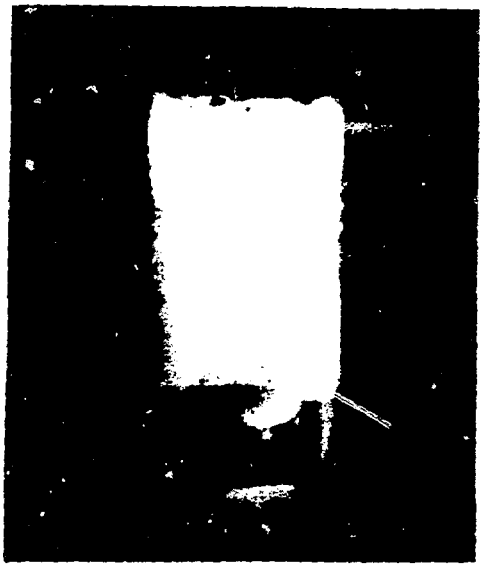

Figure 4. Posttest Radiograph of the Test Section Depicting UO_2 Penetration into Concrete.

Figure 5. Posttest Photograph Surface of UO_2/Concrete Mixture Depicting the Gas Release Sites.

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