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FFTF CONTAINMENT OF HYPOTHETICAL ACCIDENTS

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ABSTRACT

The FFTF facility was evaluated for the consequences of an HCDA followed by failure of in-vessel post-accident heat removal, reactor vessel melt-through, and release of core debris and sodium coolant to the reactor cavity. Two cases are presented based on parameters considered to represent upper limits for rates of chemical and thermal attack of the reactor cavity concrete containment structure. The reactor containment building temperature, pressure, and leak rate histories were computed with the CACECO code which provided input into the HAA-3C code for prediction of aerosol behavior, and to the COMRADEX-H code for prediction of radioactivity dispersion. The resultant 30-day doses at the site boundary were judged to be acceptable considering the conservatism in the analysis and the low probability of the event.

Introduction

This paper analyzes the accommodation provided by the FFTF reactor containment building (RCB) to a hypothetical core disruptive accident (HCDA) followed by failure of all emergency cooling provisions and subsequent melt-through of the reactor and guard vessels so that core debris and reactor sodium spill out of the vessels into the reactor cavity. This accident is more severe than any design-basis accident because its occurrence depends on low-probability multiple failures which cannot be mechanistically justified. Nevertheless, this accident was postulated for the purposes of evaluating FFTF containment margins.

Two cases were analyzed. The first case investigated the consequences of a sodium-concrete reaction attack of the reactor cavity floor by using an algorithm which was intended to conservatively bound available test data from HEDL and other laboratories and provide margin for scale-up-uncertainties. The second case investigated the consequences of a core debris melting attack of the cavity floor by using an algorithm which was intended to conservatively bound the concrete penetration rate. These two cases are identified in this paper as the chemical and thermal attack cases respectively.

The calculations reported here differ from the RCB transients reported previously[1] by the use of maximum rates for the attack of structural concrete by sodium coolant and core debris.

Containment Models

The FFTF consists of the Fast Test Reactor, the closed loop systems, and supporting facilities. The reactor uses Pu-U oxide fuel and sodium coolant and has a power rating of 400 Mwt. The heat transport system has primary and secondary loops and dump heat exchangers to reject reactor thermal energy to atmosphere. Figure 1 identifies the following components which are important to this study.

1. The reactor containment building (RCB) is a steel enclosure with an air volume of approximately 4×10^4 m^3 above grade.

2. The head access compartment is a square room just above the reactor vessel head with an air volume of approximately 450 m^3.

3. The reactor cavity is a cylindrical cell which encloses the reactor vessel and has an inerted atmosphere volume of approximately 620 m^3. Its concrete roof, walls, and floor are lined with steel plate for protection in the event of a sodium spill.

4. The reactor building subcavity is the empty space below the reactor cavity floor with an air volume of approximately 100 m^3.

5. The H&V cooler room contains heating and ventilating equipment for the reactor cavity and other spaces and has an air volume of approximately 1800 m^3. It fills the bottom regions of the RCB and surrounds the subcavity and lower part of the reactor cavity. This cooler room is important because the spaces behind the liners of the cavity vent to this area. That is, the postulated accident conditions will heat the cavity concrete and release its water which vents as steam through the liner vent system to the H&V cooler room. In turn, the cooler room vents through stairways to the RCB air space.

The foregoing containment figuration was used in both the chemical attack and thermal attack case.

Both cases were analyzed by using the CACECO[2], HAA-3C[3] and COMRADEX-H[4] codes in sequence. The RCB temperature, pressure and leak rate histories were computed with the CACECO code which provided input to the HAA-3 code for prediction of aerosol behavior, and to the COMRADEX code for prediction of radioactivity release and resultant exposures. The modeling of the reactor vessel, reactor cavity and subcavity for the CACECO analyses are shown in Figures 2 and 3. Figure 2 shows these before the HCDA when the sodium is in the reactor vessel. The HCDA was assumed to expel 450 kg of sodium into the head access compartment, directly above the reactor head, along with one percent of the core debris including fuel, actinides and fission products and 100 percent of the noble gas fission products. Figure 3 shows the result of the core debris melt-through when the sodium forms a pool in the reactor cavity with a depth of about 5.0 m.

Chemical Attack Case

The purpose of the chemical attack case was to evaluate containment response based on an upper bound for the sodium-concrete reaction rate. The available test data indicate that: (1) the initial attack rate is relatively rapid, and (2) the attack depth is limited by accumulation of reaction products.

These considerations suggest the following differential equation for the attack rate:

$$dX/dt = a_1 a_2 - a_2 X \qquad [1]$$

with X as the attack depth at time t and with a_1 and a_2 as parameters to fit the experimental data. The initial attack rate was taken as 0.15 m/hr to reflect the rates suggested by the P Tests[5] and the limiting attack depth was taken as 0.30 m to obtain a factor of four for scale-up uncertainties on the maximum penetration measured in the SC Tests.[6] The parameters were then: $a_1 = 0.30$ m and $a_2 = 0.5$/hr. The chemical attack defined by this algorithm is compared to the experimental data in Figure 4.

The CACECO code analysis using this chemical attack algorithm assumed that the HCDA core debris and sodium spilled onto the cavity floor at three hours, the steel liner failed, and the sodium attacked the concrete under the failed liner. The sodium-concrete reaction was self-limited by the algorithm and the attendant concrete water release, hydrogen generation and hydrogen concentration in the RCB were limited also. The sodium pool in the cavity did not heat to boiling. The RCB gradually pressurized by the accumulations of hydrogen from the reactor cavity and water vapor from the H&V cooler room. At 170 hours the RCB pressure was 69 kPa gauge. The atmosphere included 30.9 percent water vapor from the 25,100 kg leaked from the H&V cooler room, which in turn, had received 63,300 kg of water vapor vented from the heated concrete of the cavity roof, walls, and outer floor. The RCB was vented at 170 hours to prevent overpressurization. The ventdown effects are shown in Figure 5: in the top curve by the sharp fall in temperature from 82°C to 73°C; in the middle curve by the sharp fall in pressure from 60 kPa gauge to zero; and in the bottom curve by the sharp rise in concentrations of hydrogen and water vapor. The ventdown released 45 percent of the RCB atmosphere to the outside. At 720 hours, the end of the analysis, 99.8 percent of the sodium remained in the reactor cavity. Of this 99.8 percent, 2.0 percent had reacted with the concrete of the cavity floor and 4.4 percent had reacted with the water released from the concrete of this floor.

The HAA-3C code analysis began with the aerosol formed from the HCDA expulsion of 1 percent of core debris and 450 kg sodium into the head access compartment. The Pu-U oxide of the core debris mixed with sodium oxide (13 percent of the sodium immediately reacted to oxide) which, in turn, mixed as an aerosol with the RCB air. The sodium oxide aerosol was augmented by new oxide from cavity leakage and was diminished by RCB leakage and fallout.

The COMRADEX-H code analysis began with the HCDA expulsion of core debris and associated fission products and sodium into the RCB. The halogen and noble gas fission products of the initial expulsion were diminished by radioactive decay and by RCB leakage, additionally other species were diminished by fallout. The sodium soluble fission products (As, Br, Cd, Cs, I, Rb, and Se) left in the reactor cavity were released from the sodium according to their partition coefficients to follow the hydrogen and sodium leakage into the RCB where they were diminished by radioactive decay, fallout, and leakage. The RCB atmosphere together with fuel, coolant, and fission products suspended in it leaked to the outside at the constant rate of 0.1 percent/day until RCB ventdown and thereafter at the rate predicted by the CACECO results. The meteorology model for activity dispersion used stability classes and wind speeds which fitted the diffusion factors (X/Q values) recommended by the Nuclear Regulatory Commission from local weather data. COMRADEX-H predicted 30-day doses at the FFTF site boundary (7,242 m from the RCB) were: whole body, 1 REM; lung, 5 REM; thyroid, 66 REM; and bone, 46 REM.

Thermal Attack by Core Debris Heating

The LAYER code,[7] INTER code,[8] and GROWS-II code[9] provide mechanistic and phenomenological analyses of the core debris melting attack of concrete, but each code has particular modeling and numerical features which have not been validated. This analysis used a non-mechanistic core debris melting attack model intended to conservatively bound the expected concrete penetration. The melting attack model has the following features:

1. The core debris attack began with the debris spread across the available floor.

2. The melting attack proceeds with 50 percent of the core decay power. The other 50 percent is transferred to the sodium that covers the debris and to the accumulating pool of debris and concrete that results from this melting attack.

3. The melting attack rate in the lateral direction is equal to the attack rate in the downward direction.

4. The concrete water released by this melting attack goes into the sodium pool where it reacts to form hydrogen.

The CACECO code analysis using this thermal attack algorithm assumed that the HCDA core debris and sodium spilled onto the cavity floor at three hours where the debris, confined to 12.8 m^2 area by partitions, began a melting attack into the concrete. This attack in the center and the assumed intact liner over the remainder of the floor precluded sodium-concrete reactions. At 30.5 hours the melting attack had penetrated 0.76 m into the floor and the remaining, unmelted 0.20 m of floor collapsed which spilled the pool of debris-molten concrete into the empty subcavity. The sequence of events for this melting attack and collapse are portrayed in Figure 6: in (A) the core debris starts the attack at three hours, in (B) the pool of debris-molten concrete has reached the collapse point, and in (C) the collapse has cast the debris-molten concrete into a layer on the subcavity floor. The reactor vessel, reactor cavity and subcavity model for CACECO analysis after the spill is shown in Figure 7: The sodium fills the subcavity completely and the cavity to a depth of about 2.0 m above the original level of the cavity floor. The CACECO analysis continued with sodium-concrete reaction attacks on the remaining cavity floor and on the bare subcavity walls in addition to the core debris melting of the cast on the subcavity floor. At 37 hours the reaction attacks were completed according to their attack algorithm and had consumed 18 percent of the sodium. At 49 hours the core debris had melted the cast of debris and concrete materials on the subcavity floor and began the melting attack of this floor. At 667 hours this attack had penetrated the 2.0 m thickness of subcavity floor-RCB foundation concrete and began melting the underlying earth and basalt rock. Our attention now switches to the RCB conditions.

The CACECO analysis of the RCB conditions showed a gradual pressurization by accumulation of water vapor, mainly from reaction of hydrogen leakage from the reactor cavity with RCB atmospheric oxygen according to the natural, sodium aerosol catalyzed hydrogen-oxygen recombination reaction.[10] The cavity floor collapse and sodium flooding of the subcavity promoted very rapid concrete water release into the sodium and attendant hydrogen leakage and RCB pressurization. Very shortly after the floor collapse the RCB was vented to prevent overpressurization. This ventdown released approximately 32 percent of the RCB atmosphere to the outside and then the RCB oxygen concentration was too low to sustain the recombination reaction. The hydrogen accumulated and by 31.6 hours, the hydrogen/oxygen concentration ratio (18 percent/9.1 percent) approximated the 2/1 ratio for stoichiometric deflagration and the CACECO analysis was triggered to cause deflagration in one time step. The deflagration consumed all of the oxygen and raised the RCB pressure to 127 kPa, but this overpressure vented quickly and then, as the atmosphere cooled, air flowed back into the RCB and the oxygen concentration increased to the level to support another deflagration. The analysis followed three deflagrations, but these merge together in Figure 8: in the top curve into the spike in temperature, in the middle curve into the spike in pressure, and in the bottom curves into step changes in hydrogen, oxygen, and water vapor concentrations. The first deflagration caused the venting of approximately 59 percent of the RCB atmosphere before the inhale of air; the second deflagration vented 10 percent; and the third deflagration vented 14 percent, but the inhale of air was small and thereafter the oxygen concentration remained below the low flammable limit. These deflagrations are, of course, speculative. Hydrogen will burn at lower concentrations and the resultant pressure build-up and RCB release would be lower. By 302 hours the sodium pool was gone from the reactor cavity and subcavity because 67 percent had reacted with concrete and with water from concrete (the reaction products remained, of course) and 33 percent had leaked into the RCB and formed a sodium hydroxide deposit about 6 cm deep over the floor. Thereafter, the RCB cooled.

The HAA-3C code analysis began with the aerosol formed from the HCDA expulsion as described above for the first case. This aerosol was augmented by new oxide from the 9.3×10^4 kg of sodium leakage from the cavity after the cavity floor collapsed.

The COMRADEX-H code analysis method was the same as for the earlier case only the vent rates and fallout rates were different. In this case the ventdown occurred early, at 30.5 hrs., and was followed by the venting of three hydrogen deflagrations. Discharge of hydrogen from the cavity and of water vapor from the H&V cooler room increased the ventage from the RCB. COMRADEX-H predicted 30 day doses at the site boundary were: whole body, 13 REM; lung, 11 REM; thyroid, 1260 REM; and bone, 94 REM. The dramatic increase in the thyroid dose had two causes: First, the initial expulsion was assumed to contain "free" iodine which was not diminishing by fallout prior to the ventdown when most of it was released during a period of relatively poor atmospheric diffusion; four times as much iodine was released at ventdown as in the first case altogether. Secondly, the subsequent boiloff of sodium iodide from the cavity because the sodium pool boiled dry, released 2.7 times as much iodine from the RCB as during the ventdown.

Conclusions

In the course of extensive studies of containment margins, the FFTF facility was evaluated for consequences of an HCDA followed by reactor vessel melt-through and spill of core debris and sodium into the reactor cavity. The two cases presented in this paper were based on parameters considered to represent upper limits for the rates of chemical and thermal attack of the reactor cavity floor by the sodium and core debris. Those parameters were used in calculation of containment transients and potential site radiological exposures, using the CACECO, HAA and COMRADEX computer codes. The resultant 30-day doses at the site boundary were judged to be acceptable considering the conservatism in the analysis and the low probability of the event.

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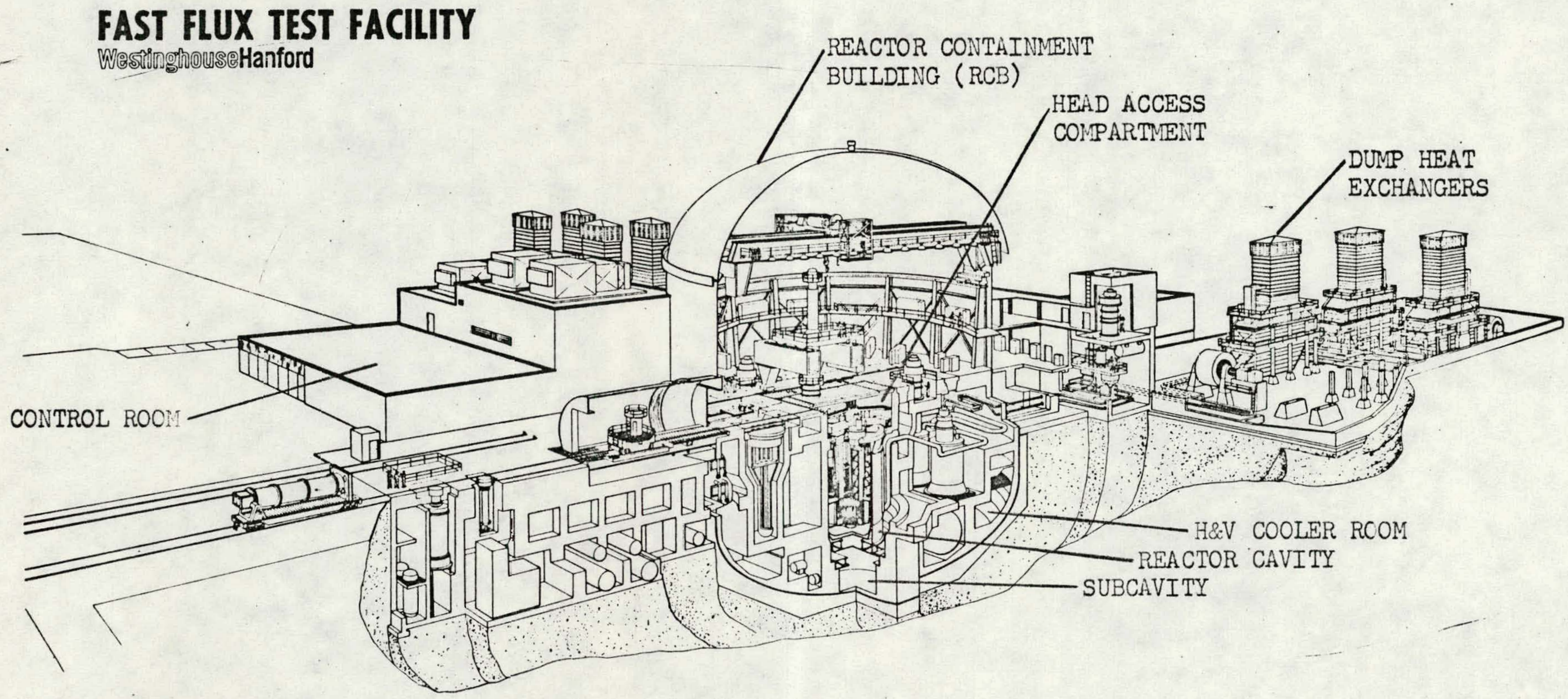


FIGURE 1. FAST FLUX TEST FACILITY

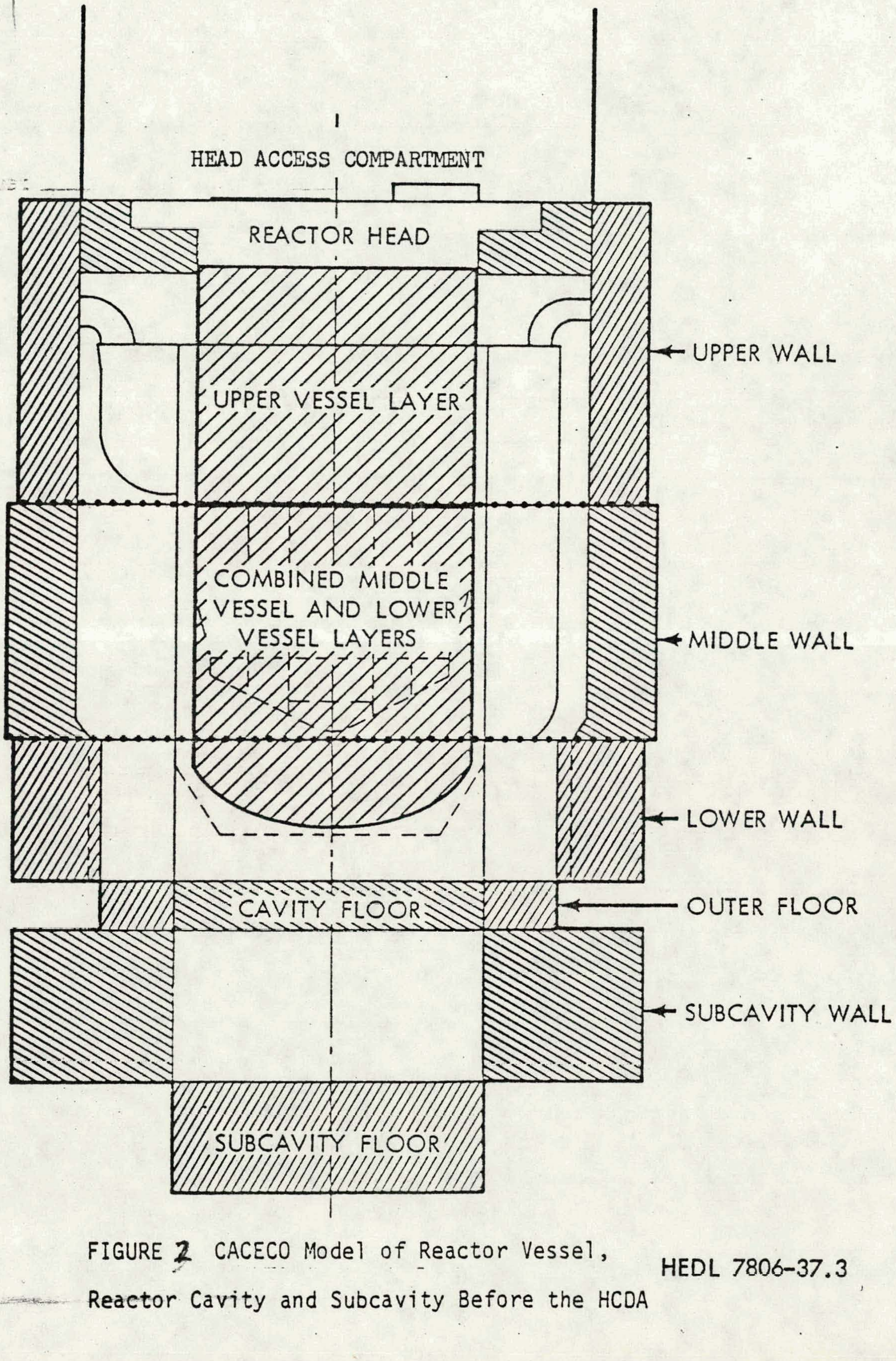


FIGURE 2 CACECO Model of Reactor Vessel, Reactor Cavity and Subcavity Before the HCDA

HEDL 7806-37.3

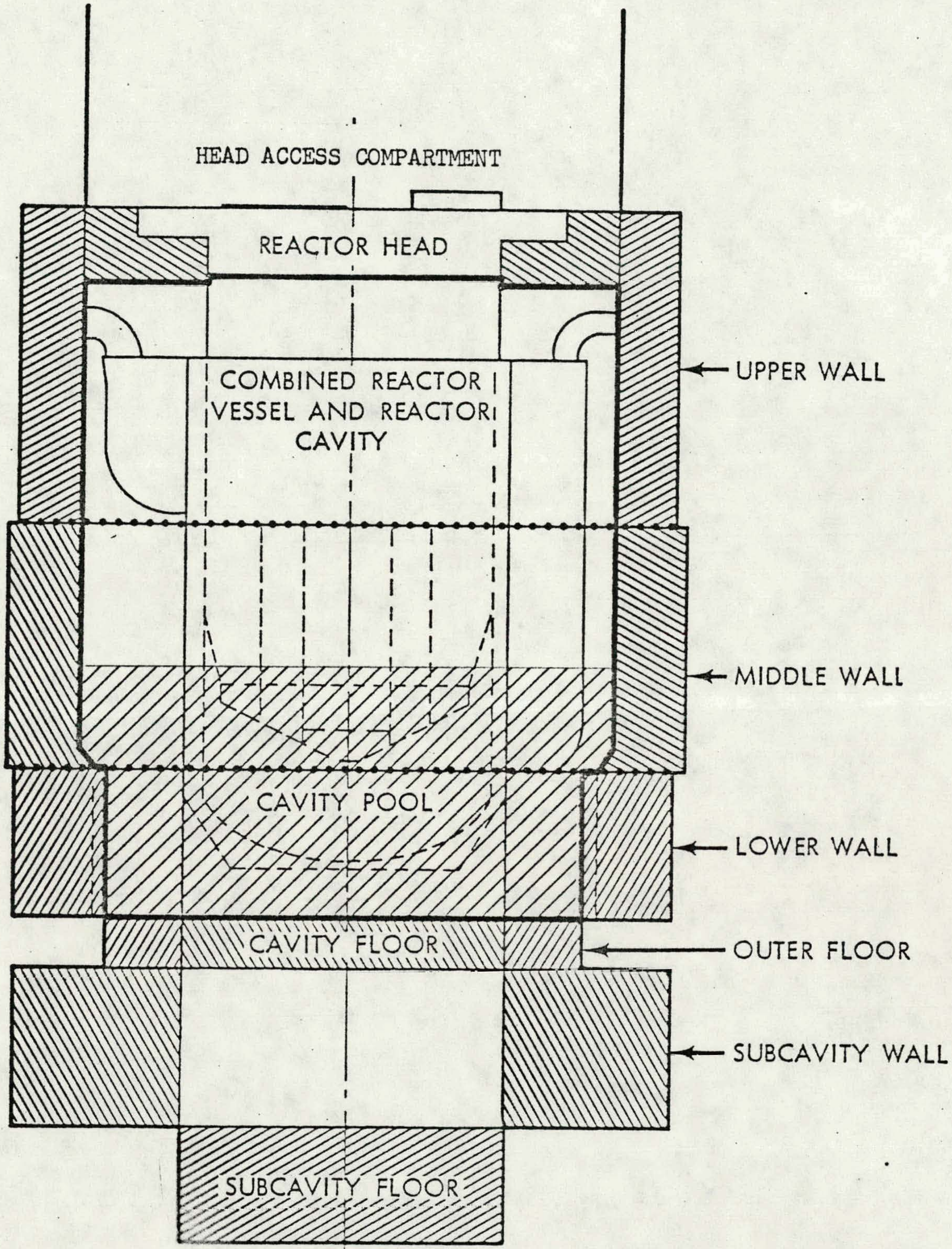


FIGURE 3 CACECO Model of Reactor Vessel, Cavity and Subcavity Following Core Debris Melt Through at 3 Hours

HEDL 7806-37.2

K+E LOGARITHMIC 359-112
KEUFFEL & ESSER CO. MADE IN U.S.A.
2 X 3 CYCLES

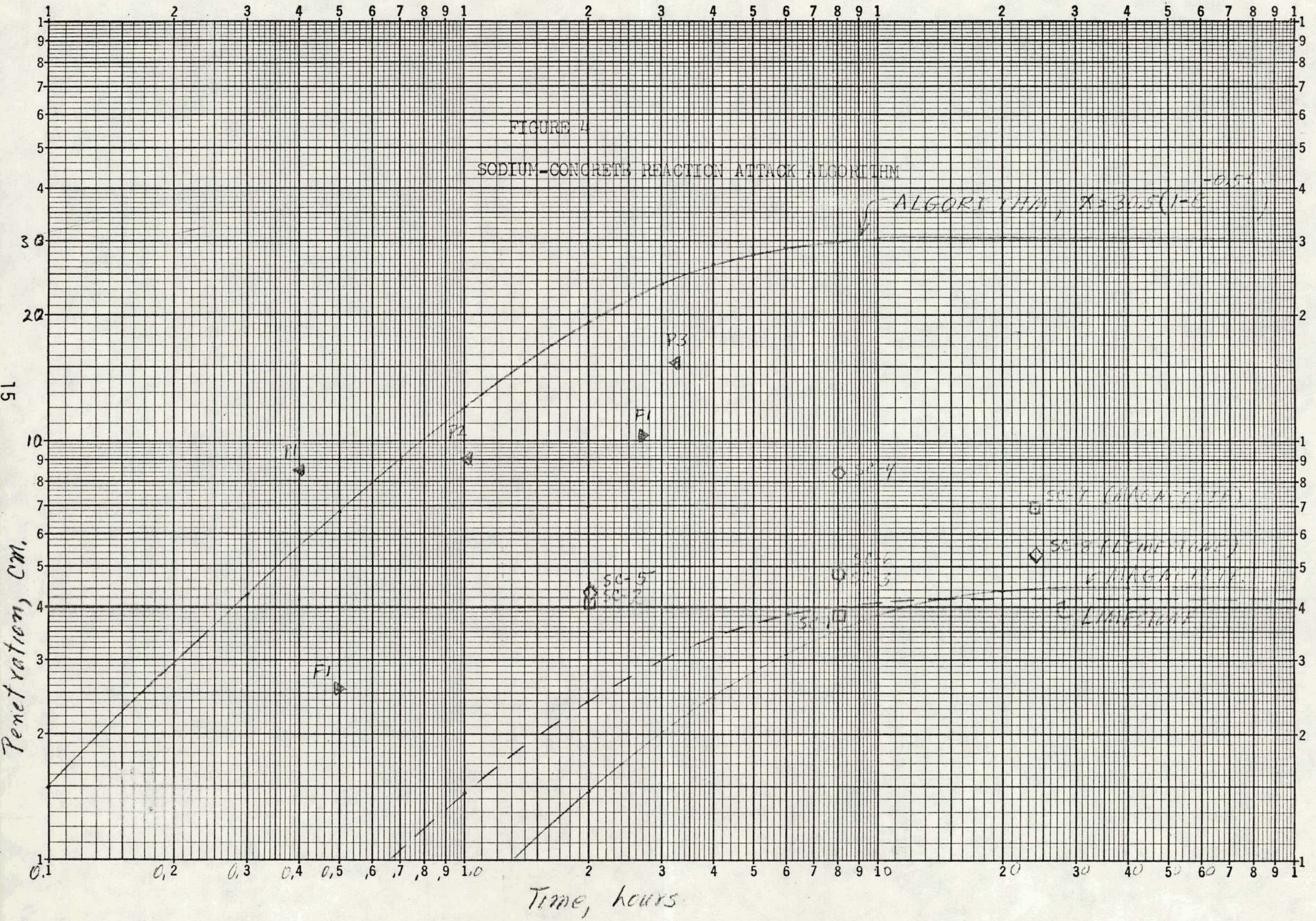


FIGURE 4

SODIUM-CONCRETE REACTION ATTACK ALGORITHM

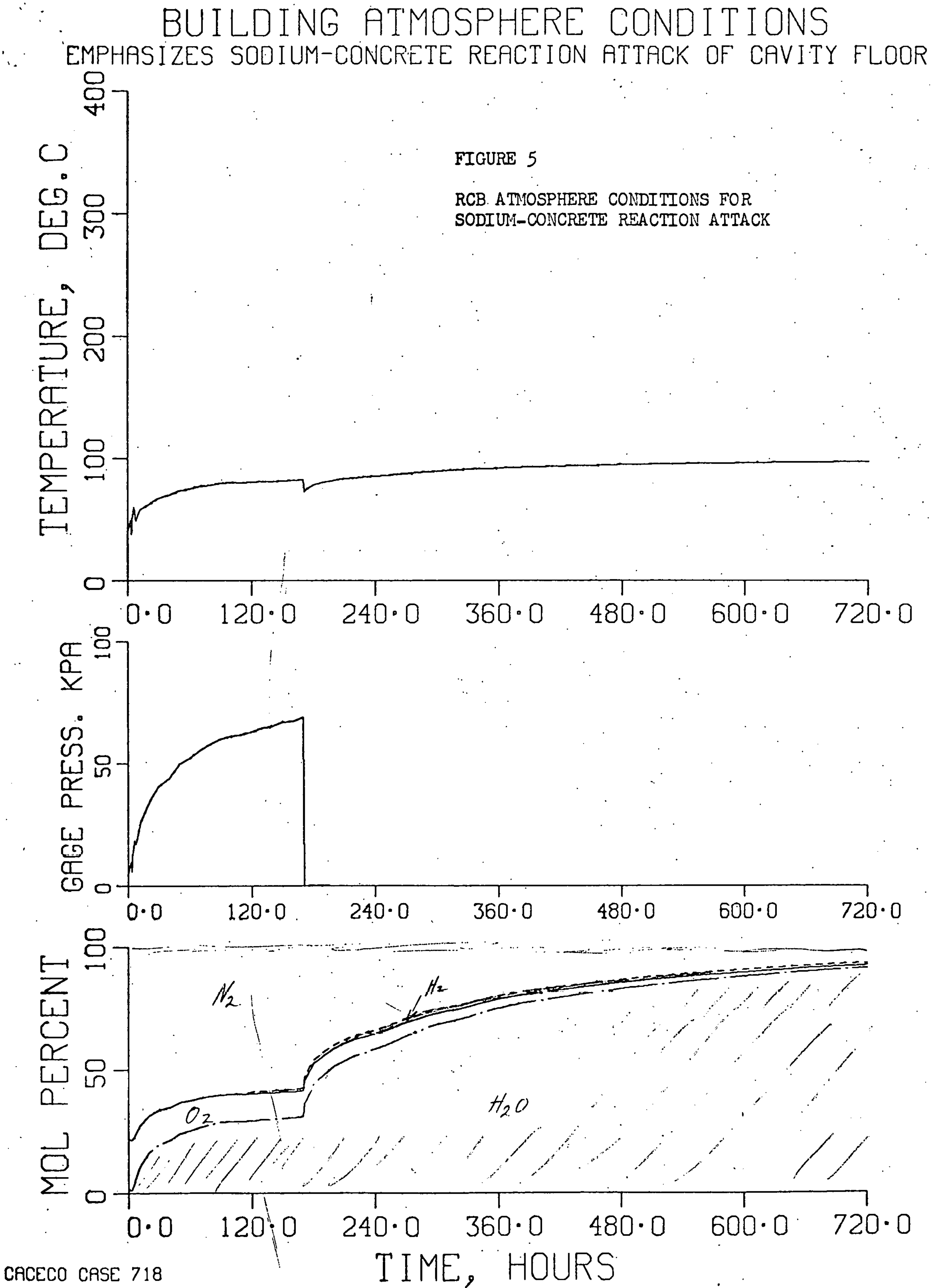
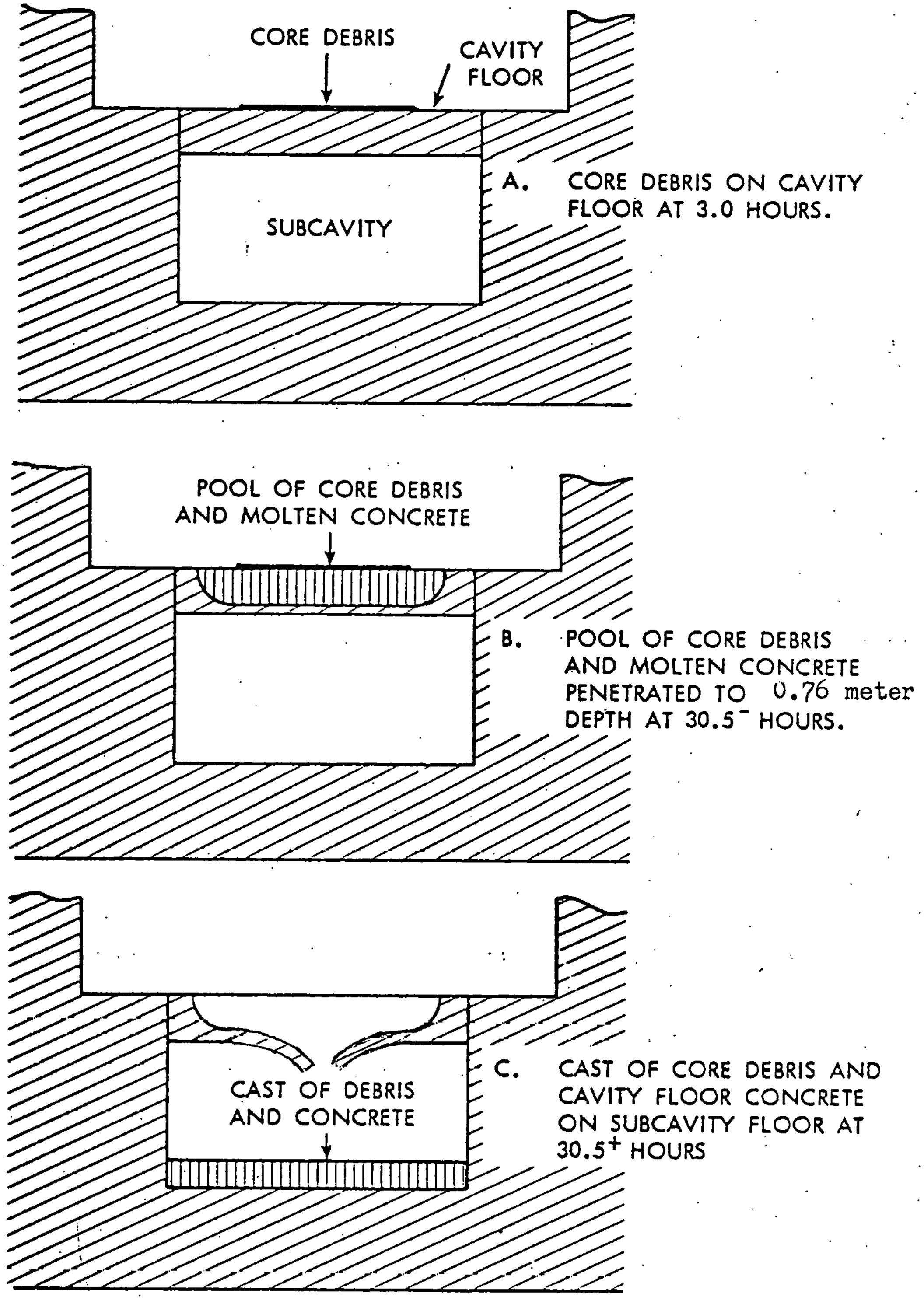


FIGURE 5

RCB ATMOSPHERE CONDITIONS FOR SODIUM-CONCRETE REACTION ATTACK



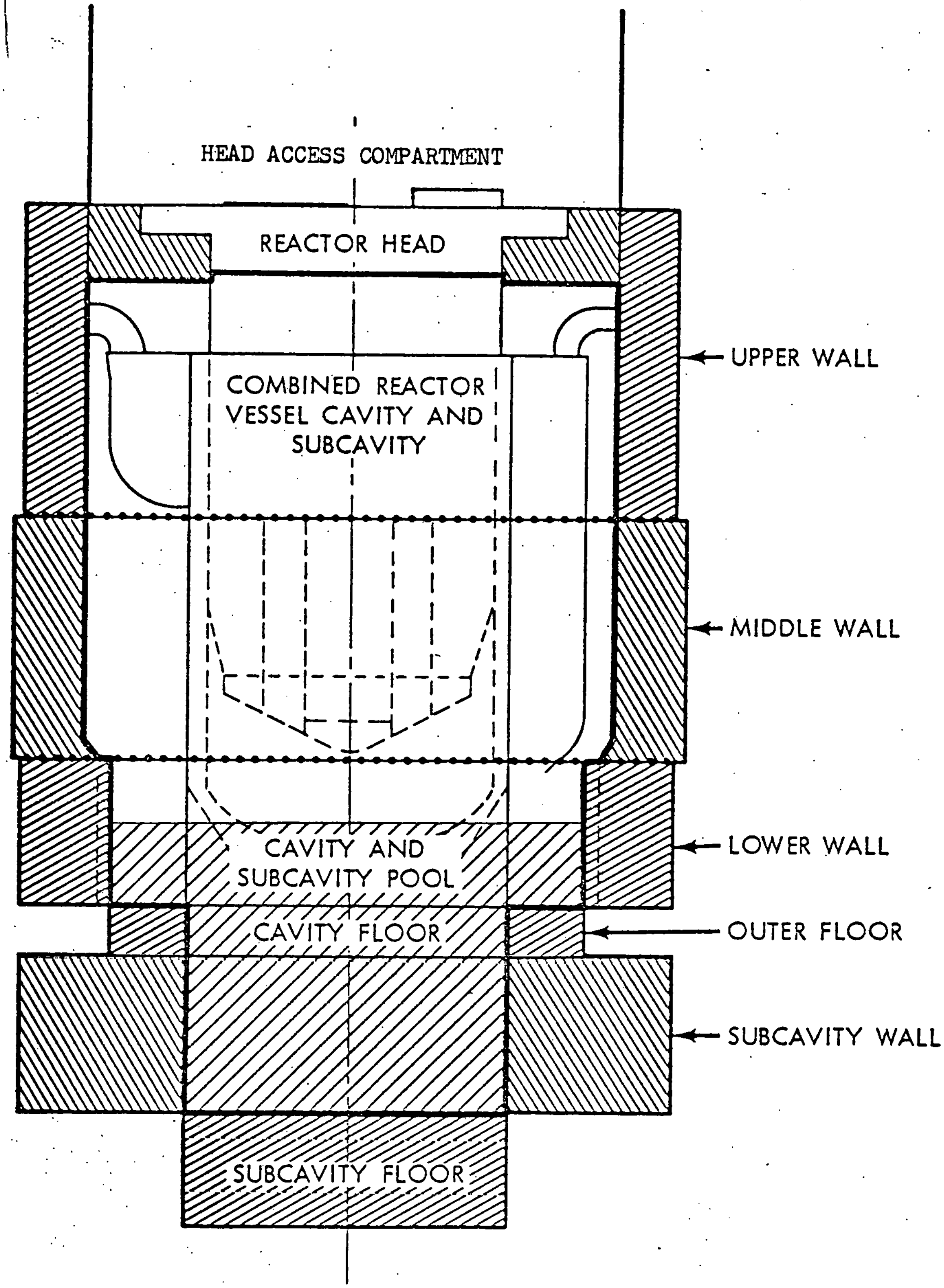
A. CORE DEBRIS ON CAVITY FLOOR AT 3.0 HOURS.

B. POOL OF CORE DEBRIS AND MOLTEN CONCRETE PENETRATED TO 0.76 meter DEPTH AT 30.5^- HOURS.

C. CAST OF CORE DEBRIS AND CAVITY FLOOR CONCRETE ON SUBCAVITY FLOOR AT 30.5^+ HOURS

FIGURE 6 MELTING ATTACK AND COLLAPSE OF CAVITY FLOOR

HEDL 7806-37.6



HEDL 7806-37.1

FIGURE 7 CACECO Model of Reactor Vessel, Cavity and Subcavity Following Cavity Floor Collapse at 30.5 Hours

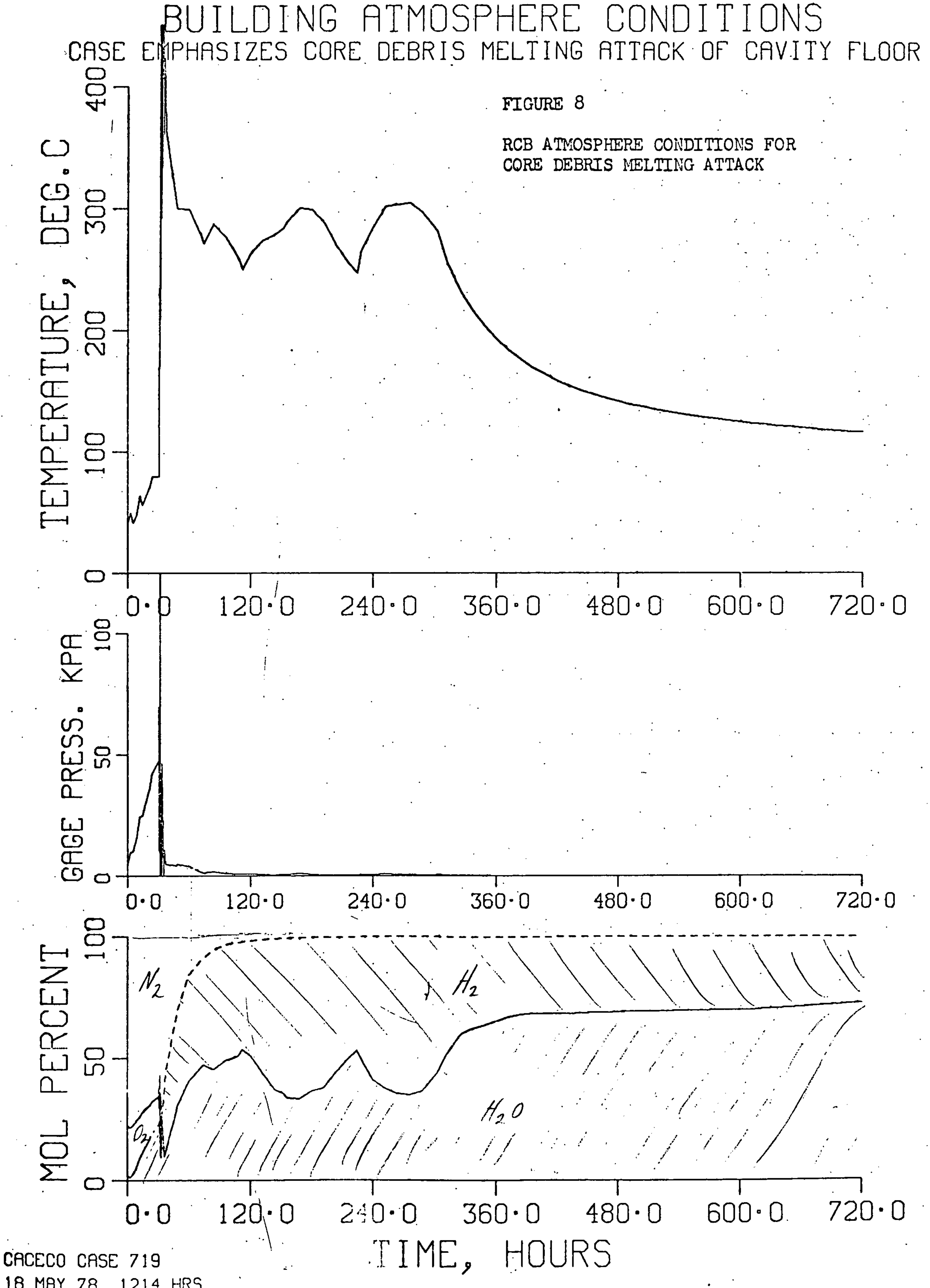


FIGURE 8

RCB ATMOSPHERE CONDITIONS FOR CORE DEBRIS MELTING ATTACK