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RECOMMENDED HPI RATES FOR THE TMI-2 ANALYSIS EXERCISE (0-300 MINUTES)

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EG&G Idaho

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ABSTRACT

An international analysis exercise has been organized to evaluate the ability of nuclear reactor severe accident computer codes to predict the TMI-2 accident sequence and core damage progression during the first 300 minutes of the accident. A required boundary condition for the analysis exercise is the High Pressure Injection or make-up rates into the primary system during the accident. Recommended injection rates for the first 300 minutes of the accident are presented. Recommendations for several sensitivity studies are also presented.

SUMMARY

An international analysis exercise has been organized to evaluate the ability of nuclear reactor severe accident computer codes to predict the TMI-2 accident sequence and core damage progression during the first 300 minutes of the accident. A requirement for code calculation of the accident is specified boundary conditions. One of the required boundary conditions is High Pressure Injection (HPI) or make-up rates during the accident. Unfortunately, these rates were not recorded during the accident. Estimates of these rates have been made based upon analysis of the HPI systems and analysis of the known accident progression. However, these analyses only result in possible ranges of HPI rates. The period of perhaps greatest uncertainty is during the core uncovery and initial core damage period of 100-174 minutes. During this period the recommended HPI rate is 4 kg/s average injection. It is recommended that the base case calculation be performed using a constant injection rate of 4 kg/s during the 100-174 min period, starting from an initial collapsed liquid level at the top of the heated core length following shutdown of the A-loop pumps at 100 min.

To evaluate the effects of differing average injection rates, it is recommended that a sensitivity study be performed in which constant injection rates of 3 and 5 kg/s also be used. To evaluate the effects of a changing injection rate during this period, it is further recommended that calculations be performed using two step changes in flow rate which result in the base case average injection rate of 4 kg/s. The first step change case would be an injection rate of 6 kg/s for 100-125 min and 3 kg/s for 126-174 min.[a] The second step change case would be for an injection rate of 8 kg/s for 100-125 min and 2 kg/s for 126-174 min. Since the time chosen for performing the step change is somewhat arbitrary, another recommended calculation is to evaluate the effect of the time at which the

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a. The time of 126 minutes for a step change is based upon the observed dramatic decrease in the steam condensation in the A-loop steam generator at this time.[1]

step change occurs. The recommended HPI rate is 8 kg/s for 100-137 min and 0 kg/s for 138-174 min. These rates result in an average injection rate of 4 kg/s, the base case rate.

The final recommended calculation (to study the sensitivity of the calculated results on the HPI rates) is to evaluate the effect of an increasing HPI rate after the minimum core level has been reached. This scenario may result in the observed end-state condition of a crucible-shaped lower crust zone, with the bottom at 0.6 m and the sides at about 1.2 m. The first recommended set of HPI rates are 7 kg/s from 100-125 min, 1 kg/s from 125-160 min, and 11 kg/s from 160-174 min. The second set of recommended rates are 8.4 kg/s from 100-125 min, 0 kg/s from 125-160 min, and 11 kg/s from 160-174 min. Both of these HPI scenarios result in a minimum core level of 0.6 m (2 ft) at 160 min, and an increase in core level to 1.2 m (4 ft) by 174 min.

The seven recommended sensitivity studies, in addition to the recommended base case, should provide sufficient calculational results to adequately evaluate the effects of different assumed HPI rates within the possible HPI bounds established from previous analysis efforts.

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RECOMMENDED HPI RATES FOR THE TMI-2 ANALYSIS EXERCISE (0-300 MINUTES)

1. INTRODUCTION

The TMI-2 accident on March 28, 1979 provides the only full-scale integrated facility data for a severe nuclear power reactor accident which can at this time be used to bench mark severe accident computer codes. In order to fully utilize the existing TMI-2 data base, an international analysis exercise was organized to evaluate the capabilities of the severe accident computer codes such as RELAP/SCDAP.[2] The events on March 28, 1979 were not planned to provide a bench mark data set; the plant instrumentation was intended for normal operations, not experiments, and many critical parameters were not recorded. One of the critical parameters not recorded was the make-up or High Pressure Injection (HPI) rates during the accident. This is a critical boundary condition, for which estimates have been made based upon core end-state conditions and analysis independent of the severe accident analysis codes. This document presents the recommended HPI rates for use in the analysis exercise during the period of 100-174 minutes after accident initiation, during which time initial core damage occurred. For completeness, the recommended HPI rates during the remainder of the first 300 min of the accident are also provided. Because the recommended HPI rates are estimates, alternate HPI rates for the 100-174 min period are also recommended in order to evaluate the sensitivity of the calculated results to this critical parameter.

2. HPI ESTIMATION TECHNIQUE

The rates at which liquid was injected into the primary system during the TMI-2 accident were not recorded. For certain time periods, reasonably accurate estimates of the injection rates can be made from knowledge of actuation of the Safety Injection (SI) system. Unfortunately, during the period of current interest (100-174 min) there are no records of an SI actuation. As a result, the HPI rates must be estimated using other information such as knowledge of the end state of the core, observation of superheated steam temperatures in the A-loop hot leg at 112 min, and calculation of the system void fraction at 100 min based upon the Source Range Monitor (SRM) neutron count rates external to the vessel. These items, combined with mass balance analysis, were used to obtain the HPI estimates.

From the end-state condition of the core, the lowest level[a] of observed damage in the core region is about 0.6 m (2 ft).[3] It is believed that the minimum water level in the core during the accident was at this level. It is further believed that this minimum level occurred during the 100-174 min period. Therefore, the estimated HPI rates during this period must result in a minimum liquid level of about 0.6 m.

An estimate of the coolant level at 100 min, immediately following trip of the A-loop pumps, was obtained from analysis of the SRM output recorded on the reactimeter system. This has two useful analysis results. First, the average void fraction in the downcomer/core region can be calculated from the increasing neutron count rate during the 20-100 min period,[4] in which it is assumed that a homogeneous two-phase mixture was flowing through the A-loop and the vessel. The core void fraction of 45% (calculated at 100 min, just before shutdown of the pumps) allows calculation of the coolant level through use of a mass balance at that time. Analysis of the SRM data after 100 min results in a collapsed liquid

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a. All levels are referenced to the bottom of the fuel pellets in the core, which corresponds to a reference elevation 298.75 ft above sea level. For comparison, the center of the vessel nozzles (hot and cold legs) are at an elevation of 315.5 ft.

level near the top of the core heated region. Both of these analyses result in an estimate of collapsed liquid level near the top of the core. It is therefore recommended that a collapsed liquid level of 3.67 m (12 ft) be used as an initial condition for start of phase 2 of the analysis exercise (immediately following shutdown of the A-loop pumps at 100+ min).

At 112 min, the temperature recorded in the A-loop hot leg began increasing above the saturation temperature corresponding to the recorded pressure. From this observation, it can be concluded that core uncovery had occurred before this time (the two-phase mixture level below the top of the fuel pellets in the core). Because the existence of droplets in the core outlet would tend to eliminate superheat, it can be further concluded that the mixture level was significantly below the top of the core, probably resulting in 0.3-1.3 m (1-4 ft) of the core being uncovered. This conclusion provides another bench mark for evaluation of the core liquid level, and thus HPI rates, during the 100-174 min period.

The aforementioned analyses and observations can be summarized to provide the following bench marks during the 100-174 min period.

1. The collapsed liquid level at 100+ min was at the top of the heated core, 3.7 m (12 ft).

2. Core uncovery occurred before 112 min, with a two-phase interface level of about 3.0-3.4 m (10-11 ft).

3. The lowest two-phase interface level occurring in the core during the 100-174 min period was about 0.6 m (2 ft).

2.1 Mass Balance Analysis

To evaluate the effects of different HPI rates during the 100-174 min period, a computer program was developed to perform a mass balance analysis of the TMI-2 primary system. Where data on primary parameters was available, these data were used to drive the computer program as boundary conditions. This included the primary pressure and hot and cold leg temperatures recorded on the reactimeter and strip charts (the qualified composite data included in the ICBC data base). Results of other analysis efforts were also used as boundary conditions in the mass balance analysis. These included the letdown flowrate calculated from the letdown coolers analysis,[5] the PORV critical flowrate calculated from the pressurizer analysis, and the energy transfer into the two Once Through Steam Generators (OTSG).[1] Use of these results permitted calculation of the total primary mass, in addition to the mass distribution within the primary system. By varying the assumed HPI rates, and comparing the resulting calculated coolant level to the required bench marks presented previously, a best estimate of the HPI rates can be obtained. These rates are summarized in Table 1 for the 300 min of the analysis exercise. The resulting injection rate for the 100-174 min period is 4 kg/s (8.8 lbm/s) averaged over the period.

The estimated injection rate of 4 kg/s results in the coolant two-phase interface levels shown in Fig. 1. The interface level was obtained from the collapsed liquid level resulting from the mass distribution analysis, using the core decay power and the void distribution model of Cunningham and Yeh.[6] This injection rate results in core uncovery beginning at 106 min, with a level at 2.7 m (9 ft) by 112 min, which is perhaps slightly low. The coolant level rapidly decreases between 100 and 125 min due to boiling in the core and condensation in the A-loop steam generator. The analysis of the steam generators[1] indicates that the heat transfer into the steam generator, and thus condensation on the primary side, abruptly decreased by a factor of approximately 7 at about 125 min. This may have been due to blockage of the steam generator by fission product gases or hydrogen. In any case, the decreased condensation reflects the decreased boildown of the core, resulting in the fairly constant level of 1 m (3 ft) shown in Fig. 1 from about 130 to 170 min. The 4 kg/s injection rate results in a minimum core level of 0.6 m (2 ft) at 174 min, just before the restart of the 2B reactor coolant pump.

TABLE 1. DATA LISTING FOR HPI/MAKE-UP

Time (min)	HPI (kg/s)
0.0	5.4
0.683	5.4
0.683	25.0
2.0	25.0
2.0	61.0
3.25	61.0
3.25	6.0
10.40	6.0
10.40	0.0
11.717	0.0
11.717	6.5
100.0	6.5
100.0	4.0
173.0	4.0
173.0	4.0
200.2	4.0
200.2	60.5
217.00	60.5
217.00	9.50
236.1	9.50
236.1	61.7
257.3	61.7
257.3	0.00
262.0	0.00
262.0	10.0
267.0	10.0
267.0	64.0
300.0	64.0

3. RECOMMENDATIONS

The best estimate of the average HPI rate during the 100-174 min period is 4 kg/s. This is an estimate based upon the mass balance analysis, which is independent of the severe accident analysis code calculations. Therefore, results from the severe accident analysis codes may differ slightly from the mass balance analysis results. Because of possible variations in results between different analysis codes, it is important to perform sensitivity studies. One of the largest unknowns in the boundary conditions, probably the largest unknown, is the HPI rate during 100-174 min. It is therefore important to perform calculations with different HPI rates for this period.

The recommended base case is to use an average HPI rate of 4 kg/s during 100-174 min. To evaluate the sensitivity of the calculations to the average injection rate, two other calculations are recommended with average injection rates of 3 and 5 kg/s. The results of the mass balance calculation for the core interface level using these two injection rates are compared to the results from the recommended injection rate of 4 kg/s in Fig. 2. The 3 kg/s injection rate results in a level of 0.5 m (1.5 ft) after about 135 min, and decreases to below the bottom of the core by 174 min. This rate results in an unrealistically low minimum core level. The 5 kg/s injection rate results in a minimum level of about 1.2 m (4 ft) at 135 min. This resulting level is higher than the minimum observed damage level of 0.6 m (2 ft).

Another unknown is how the HPI rates may have varied during the 100-174 min period. There is some evidence, based on operator interviews, that coolant injection may have started at a higher rate and then was decreased later in the period. To evaluate possible effects, several simulations were performed in which a step change occurred in the HPI rate at 125 min.[a] The injection rates before and after 125 min were varied in

a. The time of 125 min was chosen because this was the time at which the steam generator analysis indicated that the heat transfer rate into the A-loop steam generator abruptly decreased by approximately a factor of 7.

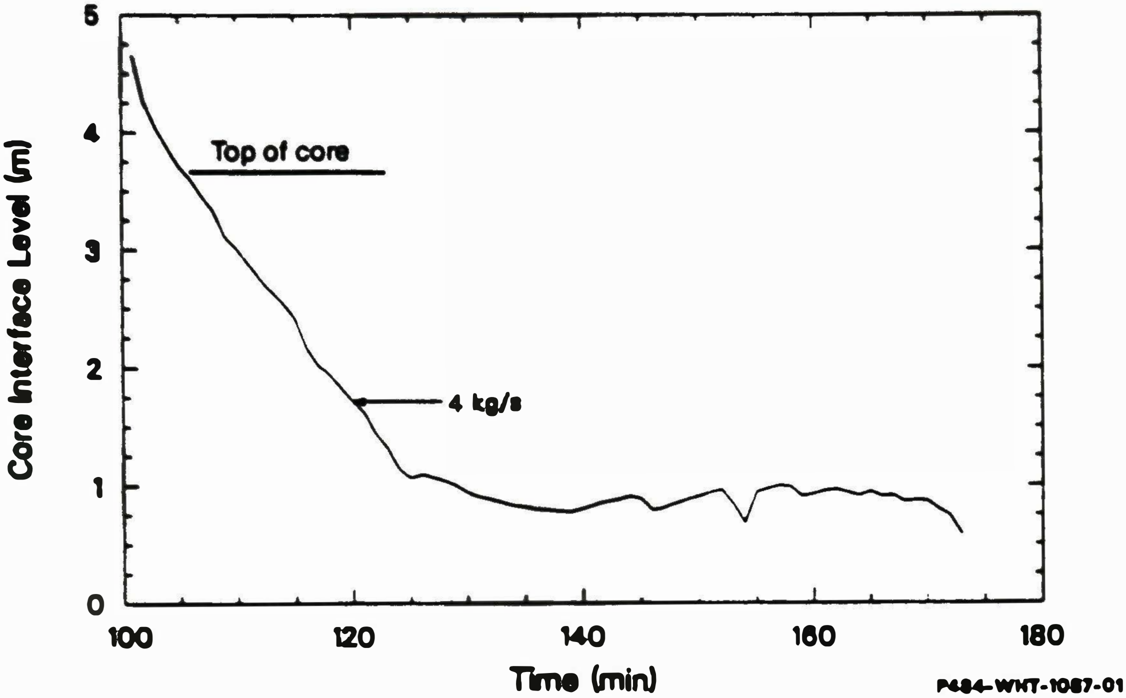

Figure 1. Nominal HPI rate - base case.

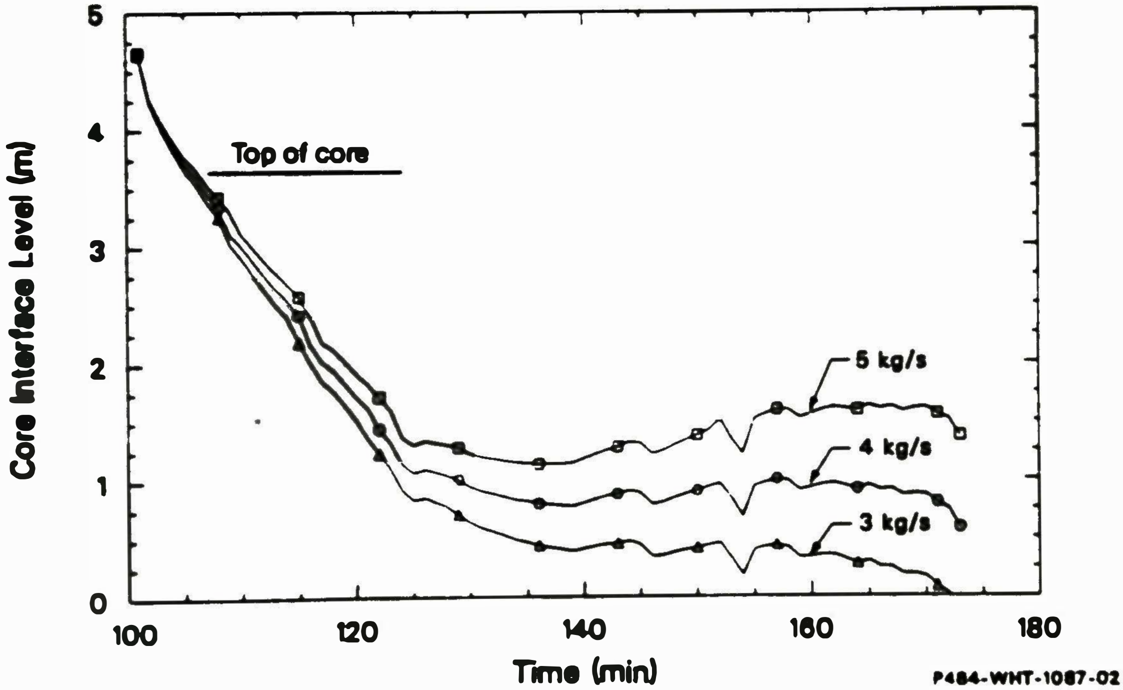

Figure 2. Constant HPI rates.

order to maintain a average injection rate of 4 kg/s, the recommended base case injection rate. The core interface levels resulting from three different step changes in HPI rates are compared to the base case calculation in Fig. 3. The three cases used were step changes of 6/3, 8/2, and 10/1 kg/s. Each of these cases started from the same initial collapsed liquid level at the top of the core, and resulted in the same level at 174 min. As the initial injection rate (before 125 min) was increased, the period to core uncovery was also increased. In addition, the level at which the core stabilized after 125 min was higher for each higher initial injection rate. The case of 8/2 kg/s results in what may be the most reasonable core uncovery timing, in which the interface level was at 3.3 m (11 ft) at 112 min. The case of 10/1 kg/s results in a late core uncovery, and should provide an upper bound on the initial HPI rate. It is therefore recommended that sensitivity calculations be performed using three injection scenarios utilizing a step change in the HPI rate at 125 min. The three recommended rates are 6/3, 8/2, and 10/1 kg/s.

The choice of the time for the recommended step change is somewhat arbitrary, based only on the observation that the steam generator heat transfer significantly decreased at this time. As a result, it is recommended that a further calculation be performed in which the timing of the step change be a variable. It is recommended that the initial injection rate of 8 kg/s be continued until 137 min, and then terminate HPI. This will result in a average injection rate of 4 kg/s during the 100-174 min time period. The results of the mass balance analysis from this injection rate scenario is compared in Fig. 4 to the base case rate and the 8/2 kg/s step at 125 min. The step change at 137 min results in an increase in level between 125 and 137 min before decreasing to a minimum level of 0.6 m (2 ft) at 174 min. This extended injection at 8 kg/s may result in more steam being available for hydrogen generation during this period.

The observed end-state condition of the lower crust of the core is a crucible shaped crust, with the bottom center at a level of about 0.6 m (2 ft) and the outer bottom at a level of about 1.2 m (4 ft). A possible explanation for this configuration is that the water level in the core

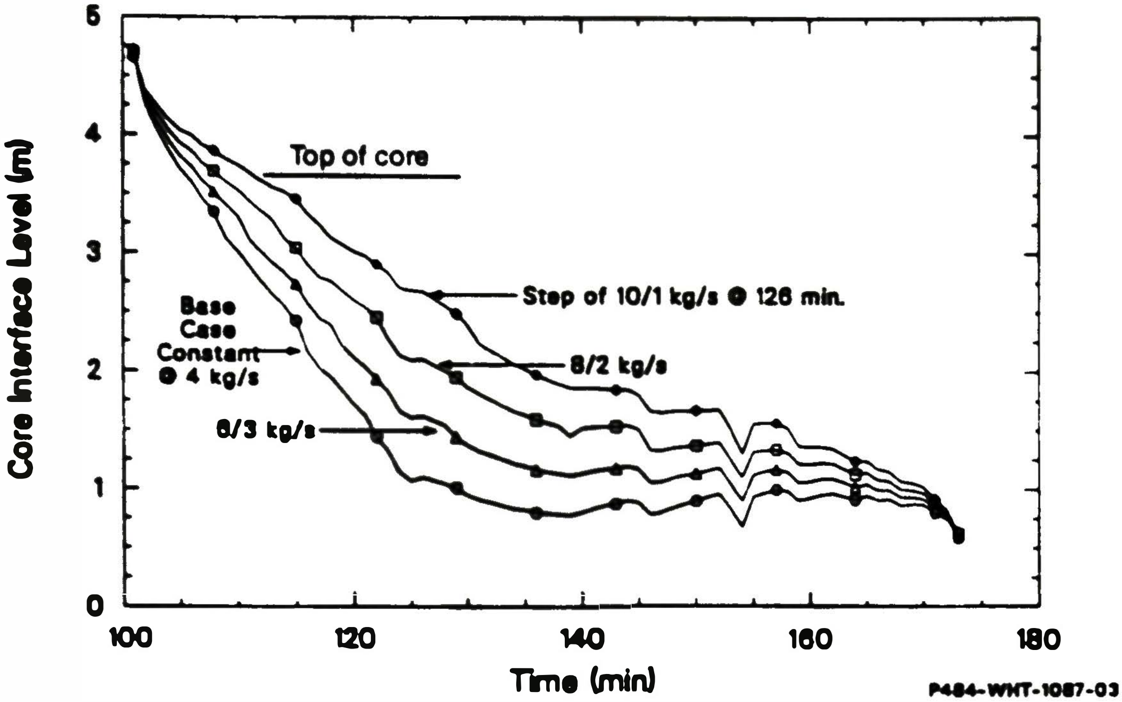

Figure 3. Step change HPI rates.

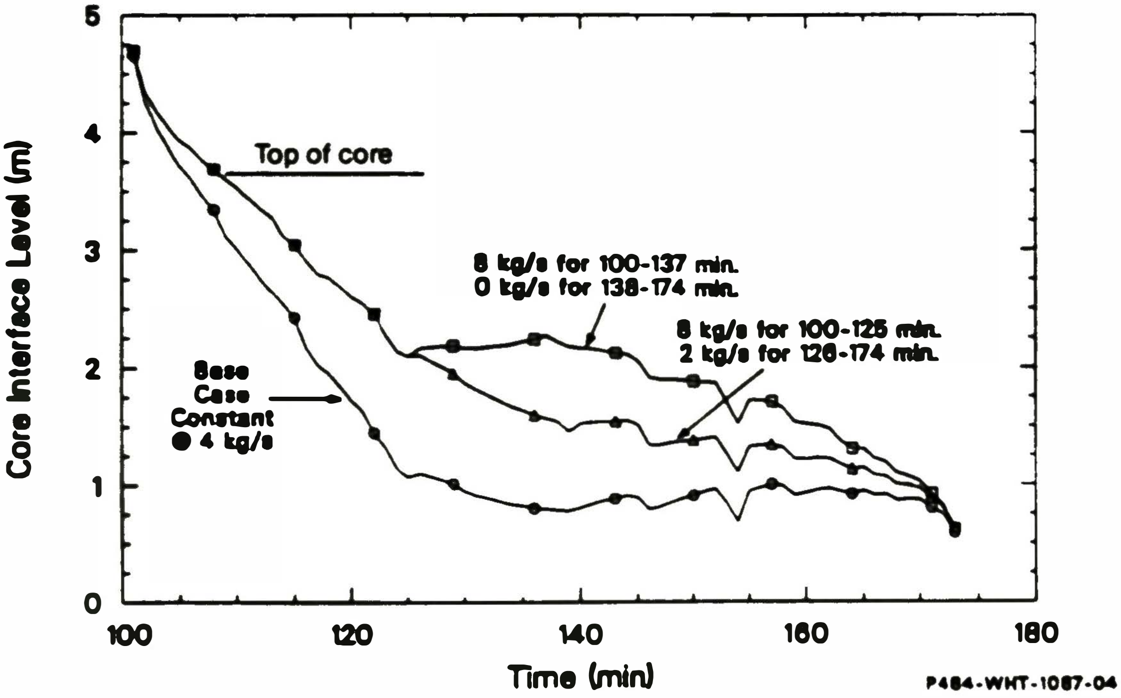

Figure 4. Step in HPI at two times.

increased after reaching a minimum level of 0.6 m (2 ft), reaching a level of 1.2 m (4 ft) before the start of the 2B reactor coolant pump at 174 min. This level increase could have occurred as the melt front progressed radially, with the water level stopping the melt front from progressing downward and thereby creating the observed shape of the outer crust. In order to evaluate this scenario, two additional sets of HPI rates are recommended for sensitivity studies. The first recommended set of HPI rates are 7 kg/s from 100-125 min, 1 kg/s from 125-160 min, and 11 kg/s from 160-174 min. The second set of recommended rates are 8.4 kg/s from 100-125 min, 0 kg/s from 125-160 min, and 11 kg/s from 160-174 min. The core interface levels for these two scenarios are compared to the base case level in Fig. 5. Both of these HPI scenarios result in a minimum core level of 0.6 m (2 ft) at 160 min, and an increase in core level to 120 cm (4 ft) by 174 min. The different injection rates from 100-125 min result in slightly different core uncovery times [the 7 kg/s rate results in a slightly more reasonable level of 3.1 m (10.2 ft) at 112 min], and may provide insight into the effect of the HPI rates during this period on the oxidation rates in the core.

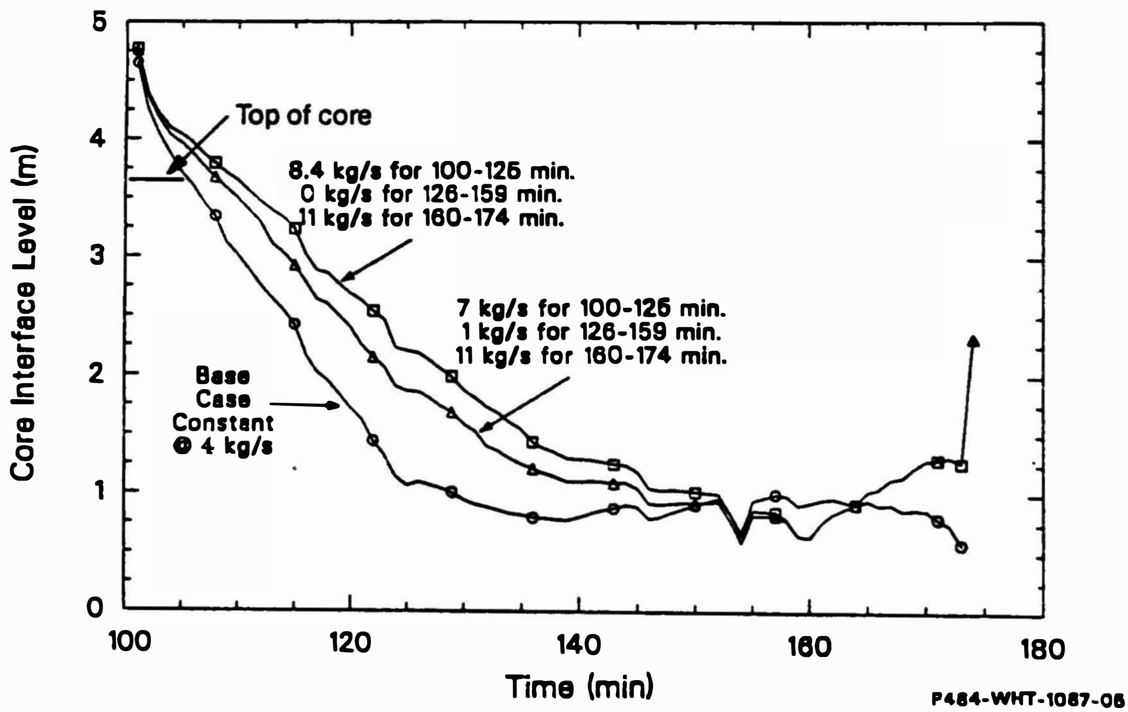

Figure 5. HPI rates with 3 steps.

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