THE 4TH INTERNATIONAL TOPICAL MEETING ON
NUCLEAR THERMAL HYDRAULICS, OPERATIONS AND SAFETY
April 6-8, 1994, Taipei, Taiwan

A PC Mathcad-Based Computational Aid for Severe Accident Analysis and Its Application to a BWR Small LOCA Sequence

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ABSTRACT

A PC-based Mathcad program is used to develop a computational aid for analyzing severe accident phenomena. This computational aid uses simple engineering expressions and empirical correlations to estimate key quantities and timings at various stages of accident progressions. In this paper, the computational aid is applied to analyze an early phase of a BWR small LOCA sequence. The accident phenomena analyzed include: break flow rates, boiled-up water level in the core, core uncovery time, depressurization of the reactor pressure vessel, core heatup, onset of clad oxidation, hydrogen generation, and onset of fuel relocation. The results are compared with those obtained running the MAAP 3.0B code. This PC-based computational aid can be used to train plant personnel in understanding severe accident phenomena and to assist them in managing severe accidents.

INTRODUCTION

During a severe accident in a nuclear power plant, the operators and technical staff must make timely judgements regarding the status of the plant and on the mitigative actions to be taken, often with limited information available. In this case, a simple tool for estimating plant response is useful. "Back of the envelope" calculations, although they lack precision, can provide fast bounding estimates and insights on the effect of key phenomena on the progression of the accident. In fact, it will be shown in this paper that simple engineering calculations can be applied to such complex phenomena as core heatup and hydrogen generation.

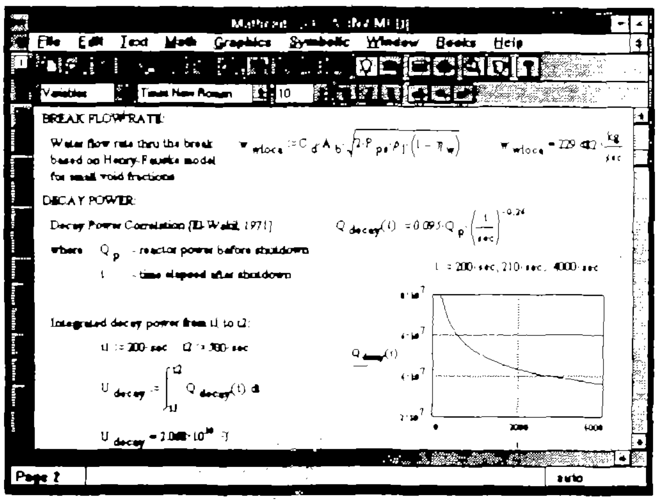
Such "back of the envelope" calculations related to severe accident phenomena were automated using a battery-powered, notebook PC. Mathcad, a commercially available PC software, which evaluates symbolic expressions typed on the computer screen and displays or plots the results, provides a convenient platform on which engineering expressions can be built. Once the expressions are typed onto the computer screen, the screen can be saved in a file and retrieved later. Expressions can be re-evaluated using different input values. The advantages of this computational aid are:

1. The aid is portable and self-powered since it is ported on a battery-powered, notebook personal computer.
2. The computational aid is self-explanatory because engineering expressions shown on the screen are literally evaluated on sight. Variables used are clearly defined on the screen. There is no hidden computer program lines being executed. Moreover, units are normally incorporated in the expressions, making the interpretation of expressions readily transparent to the user.
3. The aid is self-contained. A brief description of the topic, models used, and assumptions made appear on the top screen of each topic. There is no separate written manual the user has to resort to. The expressions themselves describe the detail of the models. The versatile graphic function allows the user to plot and examine the behavior of the expressions displayed on the screen.

This paper demonstrates how a set of engineering expressions implemented on Mathcad can be used to estimate key timings leading to the onset of fuel relocation, as well as key quantities of interest during a small LOCA accident. The phenomena considered are break flow, boiled-up water level in the core and core uncovery, depressurization of the reactor pressure vessel (RPV), fuel heatup, and hydrogen generation. The results obtained from this simple calculation are compared with the MAAP 3.0B results.[1] The MAAP 3.0B code was benchmarked against experiments and has been widely used to evaluate plant responses to severe accidents.[2,3,4] The computational aid described herein is not meant to provide an accurate prediction of accident progression. It is intended to be used for quick scoping or bounding calculations to check other more detailed and accurate calculations or for accident progression. The advantage of the tool lies in simplicity and clarity of the assumptions and expressions such that the user knows precisely how and what things are being calculated. Therefore, this paper places less emphasis on the technical detail of the calculation. The paper intends to describe the form of the tool and its sample application in general terms.

DEVELOPMENT OF COMPUTATIONAL AID USING MATHCAD

Mathcad is a commercially available PC software package for solving and manipulating equations symbolically or numerically. The user types in mathematical expressions containing symbols and literal equations are displayed on the screen. Then, the user may ask for evaluation of the equation for given values of the symbols. Alternatively, the equation can be integrated or differentiated symbolically. Numerical-integration of an expression is also available. Hence, Mathcad provides a versatile tool with which a set of mathematical expressions relating to severe accident phenomena can be constructed. Figure 1 shows an example of the screen display of Mathcad. These sets of expressions can be stored in a file. The user can invoke the desired expressions and alter the values of the symbols to represent a particular plant characteristic or to do sensitivity studies. The advantage of such Mathcad-based computational aids is that the user can see the equations which get evaluated. Brief explanations annotated with each expression helps the user appreciate the underlying physics, assumptions, and limitations of the expression.



BREAK FLOWRATE:

Water flow rate thru the break based on Henry-Fauske model for small void fractions $w_{wloca} := C_d \cdot A_b \cdot \sqrt{2 \cdot P_{pe} \cdot \rho_l \cdot (1 - \bar{\alpha}_w)}$ $w_{wloca} = 229.402 \cdot \frac{kg}{sec}$

DECAY POWER:

Decay Power Correlation (El-Wakil, 1971) $Q_{decay}(t) := 0.095 \cdot Q_p \cdot \left(\frac{t}{sec}\right)^{-0.26}$

where Q_p - reactor power before shutdown

t - time elapsed after shutdown

$t := 200 \cdot sec, 210 \cdot sec .. 4000 \cdot sec$

Integrated decay power from t1 to t2:

$t1 := 200 \cdot sec \quad t2 := 300 \cdot sec$

$U_{decay} := \int_{t1}^{t2} Q_{decay}(t)\, dt$

$U_{decay} = 2.0$[illegible]$\cdot 10^{10} \cdot J$

Figure 1 - Sample Screen Display of the Computational Aid.

APPLICATION OF THE DEVELOPED COMPUTATION AID FOR A BWR SMALL LOCA SEQUENCE

This computational aid is applied to analyze a BWR small LOCA sequence with no injection or operator action during an early phase of the accident up to the first onset of fuel relocation. The break is assumed to be a 4" break on the return line of the recirculation pipe. When a postulated LOCA sequence occurs and the reactor is scrammed, the feedwater pumps will be tripped and the MSIVs will be closed automatically. If all injections to the vessel are lost, the reactor water inventory is diminished due to water lost through the break and steaming in the core by the decay power. Eventually, the core will become uncovered and the fuel will start to heatup. When the fuel clad is highly heated, it starts to react with surrounding steam and generate hydrogen gas. The exothermic reaction will accelerate the fuel heatup leading to core damage.

This computation aid is designed so that all plant data and accident initiation conditions are displayed on the first page. They are categorized as primary system data, LOCA data, and plant geometry data. The sequence is analyzed chronologically so that the break flow rate, the steam generation rate, etc. calculated first can be used to provide the subsequent phenomena calculations such as core uncovery, RPV depressurization, core water level, and hydrogen generation.

A. <u>Break Flow Rate</u>

When a postulated LOCA sequence occurs and the reactor is scrammed, the mass flow rate through a break is calculated using the Henry-Fauske critical flow model.[5] The flow rate, with the steam generation rate due to decay power discussed below, is then used to calculate the water level decreasing rate in the vessel and to estimate the core uncovery time and the break uncovery time. While the break is covered, the primary system pressure remains at the relief valve set point because the volumetric discharge rate of the liquid through the break is less than the volumetric steaming rate due to decay heat. Therefore, the vessel starts to depressurize only after the break is uncovered.

Once the break is uncovered, gas starts to go out the break (the brief discharge of two-phase mixture is ignored) and its large volumetric flow rate initiates vessel depressurization. During the depressurization, the steam properties and the gas volume in the vessel are assumed to stay constant. In fact, steam properties vary considerably over the pressure range but their combined effect is benign as shown in the calculation result (see figure 2).

B. <u>Steam Generation Rate due to Decay Power</u>

After the reactor is scrammed, the decay power is the dominant heat source which is continuously released to the water, structures, and gas space after the core is uncovered. El-Wakil[6] provided a simple correlation for the rate of decay heat generation, which is a func-

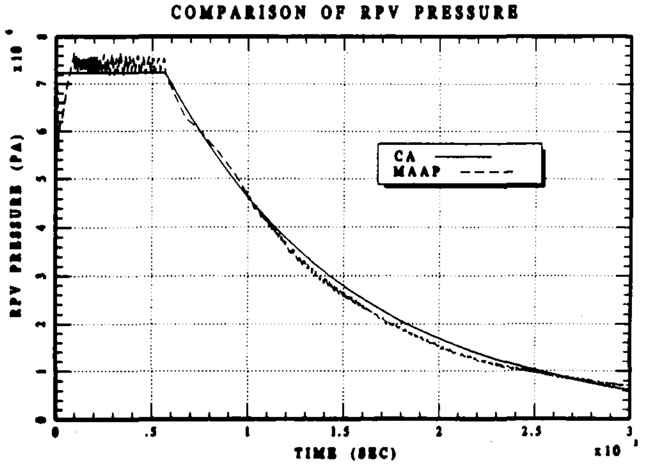


Figure 2 - Comparison of Primary System Pressure Predicted by the Computational Aid and by MAAP 3.0B.

tion of the initial reactor power level, and the time elapsed after shutdown (see Figure 1). This decay power expression can be analytically or numerically integrated to compute the average steam generation rate from the core before the vessel starts to depressurize. A time-dependent steam generation rate after core uncovery can be easily obtained by dividing the decay power correlation by the latent heat of vaporization.

C. Void Fraction in the Core

Once the steam generation rate from the core is determined, the void fraction and the two-phase water level can be estimated so that the core uncovery time and water decreasing rate in the core can be calculated. The drift flux model described by Wallis[7] is adopted to calculate the average void fraction for a water pool with a volumetric steam source from the core. The drift velocity is assumed to be the churn-turbulent flow for the bubbly flow regime with the experimental coefficients proposed by Zuber.

D. Key Timings and Reactor Water Level

After the break flow rate and the steam generation rate are determined, the decreasing rates of the collapsed water level can be obtained by dividing the total water losing rate (summation of the break flow rate and the steaming rate) by the water density and the vessel cross-sectional area, which changes with water level (above or below the top of the active fuel and above the top of the jet pump). When the reactor water level drops below the top of the jet pump, the water flow rate through the break is used to determine the collapsed water level in the lower downcomer. The two-phase mixture density, which is calculated from the void fraction, is used to calculate the two-phase water level inside the core. The rates at which the water level decreases in the core and the upper and lower downcomer, are used to determine the times at which the core and the break start to uncover. The uncovered core will heat up and the uncovered break will accelerate depressurization of the primary system, which in turn could produce more steam due to flashing and promote steam/zirconium oxidation, ultimately leading to core damage.

E. RPV Depressurization

The primary system pressure starts to depressurize when the break is uncovered. The rate-of-change in the RPV pressure is determined by the gas flow rate through the break and the steam generation rate due to decay heat; the change in the gas volume is neglected. Since the decay heat expression is a function of time, the derived RPV pressure is also a time-dependent expression. Because the gas flow through the break is driven by the system pressure, the expression for the gas flow rate through the break is also a function of time. The flashing rate when the RPV is depressurizing can be deduced from an energy balance on the water by assuming that the water is at saturation temperature. The Clapeyron equation is used to relate the saturation temperature to the RPV pressure.

F. Water Level in the Core

Before the break is uncovered, the decay heat is the sole source to boil down water in the core. After the break is uncovered, steaming due to system depressurization also contributes to boil off in the core. Once the expressions for the RPV pressure and the steam generation rate due to flashing are obtained, the water level in the core can be easily derived from an energy balance in the core by assuming that the contribution of the decay heat for steaming is proportional to the covered fraction of the core. A Mathcad built-in root function can be used to evaluate the expression of the core water level and determine the time at which the core is fully uncovered.

G. Core Heatup & Onset of Zirconium Oxidation

After the core is uncovered, the uncovered portion of the fuel heats up by the decay power and transfers heat to the adjacent steam flow, which is produced by the decay power on the covered core region. The steam outlet temperature is assumed to be equal to the fuel temperature. The total fuel-to-steam heat transfer coefficient can be obtained by combining the conduction heat transfer coefficient through the fuel and the convective heat transfer coefficient where the Dittus-Boelter correlation[8] is selected for turbulent flow in the core. Based on a simple energy balance of the fuel, the average cladding temperature can be derived as an expression which is a function of the time-dependent decay power and steam generation rate from the core.

The fuel temperature distribution in the core is highly dependent on the peaking factors distribution in the core. Local peaking factors can be 50% above the core average behavior. To simplify the calculation for this application, the peak cladding temperature is assumed to be higher than the average cladding temperature by the uncovered fraction of the core times 50% to account for the impact of the peaking factor. The onset of zirconium oxidation occurs when the peak cladding temperature exceeds 1250 K.

H. Hydrogen Generation

As the cladding temperature escalates, the high temperature Zircaloy cladding would oxidize in a steam environment forming hydrogen. Since at this stage the core is completely uncovered, the steam comes from flashing of the lower plenum water when the vessel depressurizes.

The hydrogen generation rate calculated here is based on the parabolic rate equation proposed by Cathcart, et. al.,[9] for cladding temperature up to 1850 K and the Baker-Just equation[10] for higher temperatures. With the peak cladding temperature derived above, the oxidation rate, the hydrogen generation rate, and the accompanied reaction rate can be obtained and are limited by the steam generation rate due to flashing in the lower plenum. The accumulated hydrogen mass can be easily calculated by integrating the hydrogen generation rate over the time interest.

I. Fuel Heatup to Onset of Fuel Relocation

Hydrogen generation occurs when the Zircaloy clad is overheated, and it is accompanied by a high-energy release rate. The energy release rate increases the local temperature, and can therefore amplify itself until the reaction is limited by the steam starvation condition. The acceleration of damage due to the exothermic oxidation of zirconium can impede recovery from an accident. The oxidation reaction rate calculated above can be feed back, in addition to the decay energy, to the expression of the peak cladding temperature. The onset of fuel relocation occurs when the peak cladding temperature exceeds 2500 K.

RESULTS

According to MAAP 3.0B results, it takes 15 seconds after the reactor scrammed until the main steam isolation valves are completely closed and the feedwater pumps are tripped. During this short time period, the water inventory in the reactor vessel changes rapidly due to temporary imbalance between steam going out of the main steam line and feedwater coming in before they shut off completely. To simplify calculation, this time period is not included in the analysis; the initial water level predicted by MAAP 3B after complete MSIV closure and feedwater pump trip is used.

Table 1 shows that this computational aid (CA) predicts the break flow rate, the steaming rate, and several key timings in good agreement with MAAP results. The CA estimates that the onset of Zr oxidation occurs at 1116 seconds when the peak cladding temperature exceed 1250 K, as compared to 1240 seconds for MAAP results. The MAAP code computes the steam/ zirconium reaction as soon as the core is uncovered, although at a very slow rate, and predicts that at about 1050 seconds the total hydrogen generated exceeds 1 kg.

Table 1 - Key Quantities and Timings Comparison

	Computational Aid	MAAP 3.0B Results
Water flow rate through a break	229 kg/sec	235 kg/sec
Steaming rate before core uncovered	55 kg/sec	60 kg/sec
Timings:		
Core uncovered	387 sec	376 sec
Break uncovered	567 sec	557 sec
Core fully uncovered	989 sec	1000 sec
Onset of Zr oxidation	1116 sec	1240 sec
Onset of Fuel Relocation:		
Case 1: 20% of area used	1630 sec	1600 sec
Case 2: 40% of area used	1770 sec	1600 sec

The CA predicts that the primary system pressure, as exhibited in figure 2, is in very good agreement with the MAAP results. The gas flow rate through the break calculated by the CA, as shown in figure 3, is higher than the MAAP results when the vessel depressurizes. This is because the gas temperature used to evaluate the gas flow rate is the initial gas temperature at the reactor full power level for the whole depressurization time period. Figure 4 shows that the boiled-up water level in the core agrees well with MAAP results.

Because the CA treats the core as a single lumped mass with uniform temperature, a sensitivity study is performed on the fraction of the total fuel surface area participating in the oxidation reaction. In MAAP, the core is divided into five radial and ten axial nodes. Case 1 assumes that one radial segment of the core (or 20 % of the total fuel surface area) participates in the oxidation reaction. Case 2 assumes participation of two radial nodes. During the early phase of oxidation, the hydrogen generation rate obtained from case 1 agrees well with the MAAP results, as shown in figure 5. Case 2 shows a better agreement when intensive oxidation reaction takes off after 1500 seconds. A steam starvation condition occurs at about 1900 seconds. Figure 6 exhibits that the

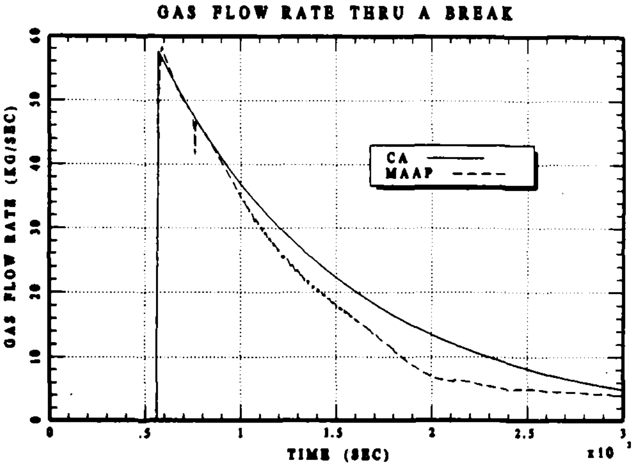


Figure 3 - Comparison of Gas Flow Rate Through the LOCA Break.

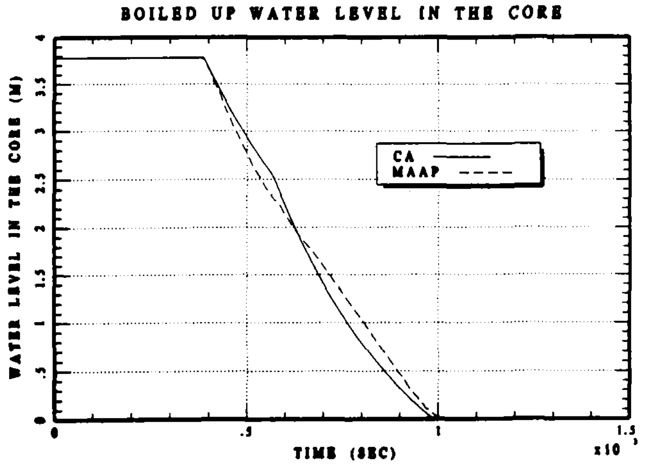


Figure 4 - Comparison of Boiled Up Water Level in the Core.

MAAP-calculated hydrogen mass generated in the core is in between the two sensitivity cases up to 2600 seconds.

Figure 7 shows that before 1500 seconds the CA predicts a higher peak cladding temperature than MAAP does. However, the temperature escalates slower once oxidation starts. In CA, the peak cladding temperature is assumed to be 50 % higher than the average fuel temperature and the energy released from oxidation reaction is uniformly distributed in the core.

SUMMARY

A PC-based computational aid is currently being developed to assist operators and technical support personnel in performing "back of envelope" calculations related to severe accident phenomena. This self-powered, self-contained system consists of a set of useful engineering expressions built on the Mathcad software running on a notebook or desktop PC.

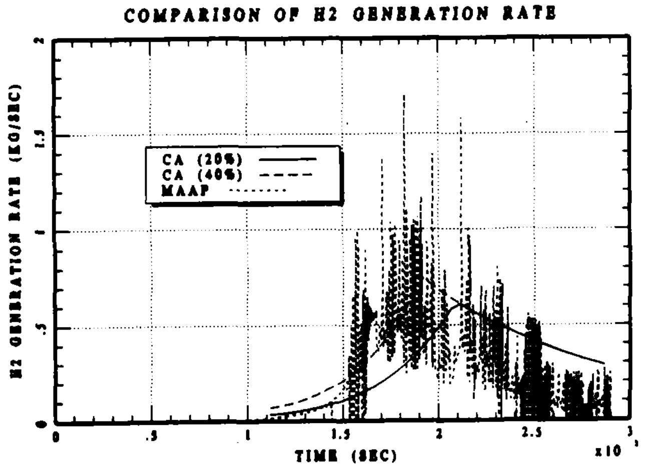


Figure 5 - Comparison of Hydrogen Generation Rate in the Core.

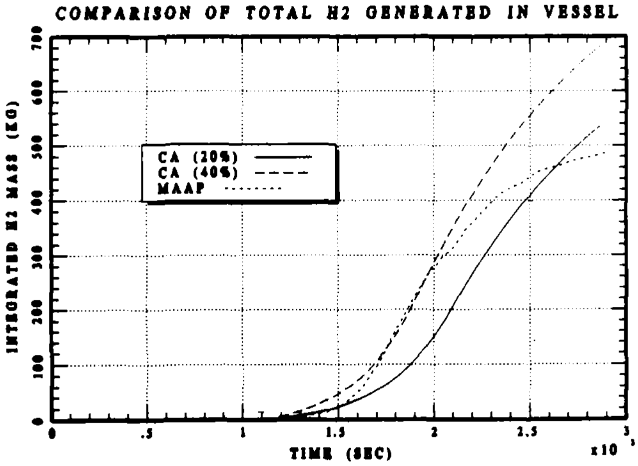


Figure 6 - Comparison of Cumulative Hydrogen Gas Generated in the Core.

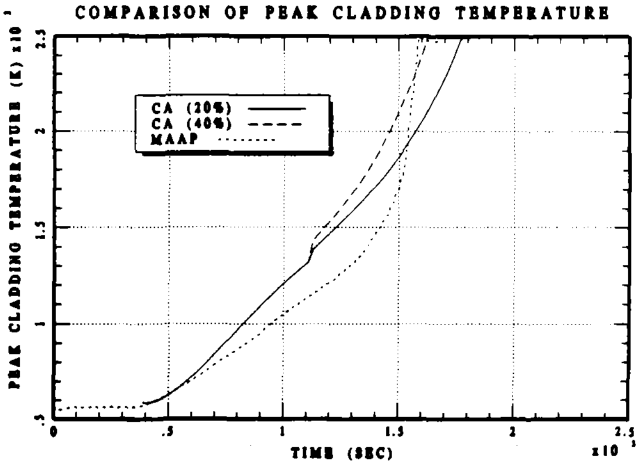


Figure 7 - Comparison of Peak Fuel Clad Temperature in the Core.

Literal evaluation of symbolic expressions displayed on the screen enables the user to quickly grasp the models used and assumptions made in the engineering expressions. By altering the values assigned to the symbols, or even altering the expressions themselves, a sensitivity study can be easily carried out. This system can also be used to store important plant information as well as graphs and tables characterizing important phenomena.

It has been shown how such a computational aid can be used to estimate key timings and quantities leading to the onset of fuel damage during a small LOCA in a BWR. A reasonable agreement was obtained with the results of the fully integrated simulation code, MAAP 3.0B.

In the future, bounding calculations and best estimate calculations related to core melt relocation, molten pool formation in the core, lower plenum debris bed formation, vessel failure, ex-vessel phenomena such as corium-concrete interaction and containment pressurization, and operator actions with injections to the vessel and containment will be added to the computational aids. Also, under development is the break area estimation based on plant instrumentation readings.

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The Architect Engineer's Concerns about Hydrogen Releases and Behavior Inside the Containment, the Belgian Approach

B. Centner (BELGATOM)

Session 25
Severe Accident Management-II