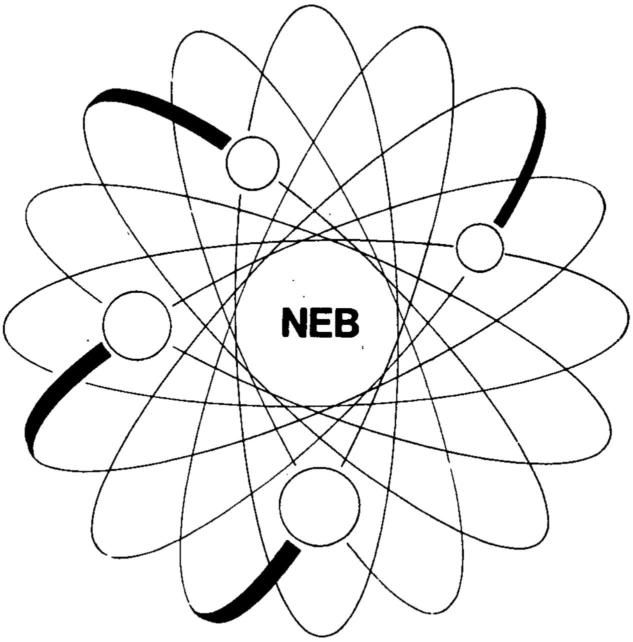
METHODOLOGY FOR PREDICTING CONTAINMENT TEMPERATURES FOLLOWING A MAIN STEAM LINE BREAK



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Methodology for Predicting Containment Temperatures Following a Main Steam Line Break

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ABSTRACT

A revised method for calculating containment conditions for intermediate and large MSLBs was developed. The revised method and the NRC-recommended method (of NUREG-0588) were evaluated by comparing results of the Carolina-Virginia Tube Reactor test with the predictions of each method. The revised method was developed to obtain more realistic temperature profiles than those predicted with the NRC's method. The severe conditions predicted by the NRC's method make equipment qualification extremely and unnecessarily difficult. The condensing heat transfer model in the revised method uses a scaled version of the heat transfer coefficients measured in the CVTR Experiment, with the bulk-to-wall temperature difference, and a revaporization rate of 10 percent. The revised method is shown to be more realistic than the NRC's method, but still conservative when comparing predictions with the results of the CVTR test.

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I. INTRODUCTION

Design criteria for nuclear power plants require that safety-related equipment be qualified to environments that will be encountered during postulated accidents. Such accidents include loss of coolant accidents (LOCAs) and main steam line breaks (MSLBs). NUREG-0588 (Ref. 2) provides NRC Staff positions concerning the methods for such equipment qualifications. Part of the equipment qualification concerns the determination of the pressures and temperatures to which equipment will be exposed during an accidnet. Acceptable methods for determining these conditions are set forth in NUREG-0588.

The harshest temperature conditions are generally the result of MSLBs. To determine these temperatures in pressurized water reactor (PWR) containments, the NRC Staff accepts a method which includes the use of an analysis code called CONTEMPT/LT (Ref. 1) with the Uchida (Ref. 6) condensing heat transfer correlation and a revaporization rate of 8-percent (used in determination of mass condensation rate). The Babcock and Wilcox, Company (B&W), used the NUREG-0588 method (without revaporization) to calculate conditions inside containment for a spectrum of MSLBs at the Bellefonte Nuclear Plant (BLN). The results indicated severely high temperatures (up to 431° F, Ref. 19) which have made equipment qualification extremely difficult or impossible.

The extreme temperatures predicted for MSLB's by the NUREG-0588 method are the result of the conservatism of the method and the sensitivity of the temperature of a superheated atmosphere to changes in specific internal energy. The NUREG-0588 condensing heat transfer correlation (Uchida) is based on data from tests in a saturated atmosphere, the coefficients are applied with the saturation-to-wall temperature difference, and the condensate mass calculation is based on experimental comparisons which used a different heat transfer coefficient. The containment atmosphere during a MSLB will be very turbulent and superheated indicating that higher heat transfer coefficients are appropriate. The presence of non-condensibles indicates that the bulk-to-wall temperature difference is appropriate. And the benchmarking of the condensate mass calculation should use the heat transfer model that will be used in the final calculations. The temperature of the superheated atmospheres of MSLB's is more sensitive to changes in internal energy than the saturated atmospheres of LOCA's, so that the conservatisms of the NUREG-0588 method produce much higher temperatures for MSLB's than for LOCA's.

To obtain relief from the conditions predicted by the B&W analysis, TVA will use a more realistic but conservative method for predicting MSLB containment atmosphere conditions. This method uses the MONSTER (Ref. 17) code (which is similar to CONTEMPT 4), a heat transfer coefficient based on data from the Carolina Virginia Tube Reactor (CVTR) tests (Ref. 7), the bulk-to-wall temperature difference, and a revaporization rate of 10 percent. This method is compared here to the 0588 method and is shown to be more realistic, yet still conservative when compared to actual test data from the CVTR tests.

The proposed methodology was developed specifically for the large dry containment of BLN. This report does not investigate the interaction of containment engineered safeguards since their actuation normally occurs well after the harshest containment conditions. Additionally, no conclusions as to the applicability of the method to other types of containments are drawn.

This report includes a discussion of the important calculational techniques used in the containment codes, MONSTER and CONTEMPT. The proposed TVA method is shown to be more appropriate to MSLB analysis than the NUREG-0588 mehtod, due to both the applicability of the data on which the methods are based and the ability of the methods to predict the results of actual experiments.

A method for applying the proposed method to MSLB analyses for BLN is presented with an example of the expected results.

II. Discussion of Code Calculations

Calculation of containment conditions during LOCAs and MSLBs is performed by computer codes such as CONTEMPT and MONSTER. These codes model important physical phenomena involved and important systems and structures. The object of such calculations is to determine the conditions of the containment atmosphere, which is treated as a homogeneous mixture of air, steam, and possibly, liquid water.

The temperature and pressure during the transient is calculated by a subroutine which determines the state using the volume, mass composition, and internal energy of the atmosphere. The volume of the containment is an input variable, but the mass of the components and the total energy are the results of mass and energy balances performed at each time step. The mass and energy transfers can be user specified, such as blowdowns, or calculated by models in the code, such as heat transfer to heat sinks, possibly with condensation mass transfer. The codes include models of other systems, such as fan coolers and Reactor Building Sprays. The following more detailed discussions include only those models that are proposed to be changed or those that are needed to explain the effects that the changes will have.

II.A Analytical Methods

II.A.1 Mass and Energy Balance

Considering the containment atmosphere as a single control volume, one may write equations that describe the mass and energy balance.

The mass balance is:

$$\Sigma \dot{M}_{in} - \Sigma \dot{M}_{out} = \frac{dM}{dt} \qquad \text{II.A.1.1}$$

where:

M - total mass in control volume (containment)

$\Sigma \dot{M}_{in}$ - sum of all mass flow rates in (from blowdown, sprays, etc.)

$\Sigma \dot{M}_{out}$ - sum of all mass flow rates out

t - time

The energy balance may be written as:

$$\Sigma \dot{M}_{in} h_{in} - \Sigma \dot{M}_{out} h_{out} + \Sigma \dot{Q} = \frac{dE}{dt} \qquad \text{II.A.1.2}$$

where:

E - total energy in the

Σ M_{in} h_{in} - sum of the enthalpy of entering fluid (from blowdown, sprays, etc.)

Σ M_{out} h_{out} - sum of the enthalpy of fluid exiting (from condensation, drains, etc.)

Σ $\dot{Q}$ - sum of energy addition rates to the control volume (primarily through non-condensing heat transfer to or from heat sinks)

During the initial phase of a pipe break transient, energy (Q) is removed from the atmosphere by passive heat sinks through convection and condensation while mass (M_{out}) is removed by condensate forming on the heat sink surfaces.

II.A.2 Thermodynamic State Determination

The mass and energy balance equations are integrated to obtain the mass of each component and the total energy in the containment atmosphere at each time step. The state of the atmosphere is determined by a procedure which finds the temperature that satisfies the mass and energy totals. The total energy in the atmosphere is:

$$E = e_a M_a + e_s M_s \qquad \text{II. A.2.1}$$

The specific volume of each component of the atmosphere is:

$$v_a = V / M_a$$
$$v_s = V / M_s \qquad \text{II.A.2.2}$$

where:

M - total mass of a component in the atmosphere

E - total energy in the atmosphere

e - specific internal energy of a component

V - volume of the containment atmosphere

v - specific volume of a component

subscripts, a and s, refer to the air and steam respectively.

(The equations, as shown, assume that no liquid water is present, but are equally valid if a mixture of liquid and vapor is substituted for the steam.)

The above equations are sufficient to specify the state of the atmosphere if the temperatures of all components are required to be equal. The temperature is found by an iterative procedure which uses the state equation of each component to determine its specific internal energy for a given temperature. Once the temperature that satisfies the above conditions is determined, the partial pressures of the components may be added to obtain the total pressure in containment.

The temperature is much more sensitive to changes in specific internal energy for superheated atmospheres than for saturated atmospheres. It can be seen from steam tables (Reference 4) that, for a given specific volume, temperature is a rapidly varying function of specific internal energy for superheated conditions. In a two-phase mixture, however, a change in specific internal energy simply causes part of the mixture to change phase. This will cause a change in pressure and the temperature of the atmosphere will follow the saturation curve but this change in temperature is not nearly as great as that which occurs in superheated atmospheres.

The above discussion indicates that the calculated temperature of the superheated atmospheres resulting from MSLBs is very sensitive to slight changes in the calculated steam mass or total energy. Hence, the calculations of the heat transfer to heat sinks and of the associated condensate mass has a much greater effect on temperature in a superheated atmosphere than in a saturated atmosphere.

II.A.3 Heat Transfer

Heat transfer plays an important role in the calculation of MSLB containment conditions. The heat sinks absorb energy from the containment atmosphere, lowering the specific internal energy, and thus the atmospheric temperature. The codes use a conventional heat transfer equation to calculate the heat transfer:

$$Q = H\,A\,(\Delta T) \qquad \text{II.A.3.1}$$

where, H = an appropriate heat transfer coefficient
A = the exposed area of the heat sink, and
Δ T = the appropriate reference temperature difference.

The heat transfer coefficient is determined by the mode of heat transfer, which depends on the heat sink surface temperature, T(wall). If T(wall), is above the containment atmospheric temperature, T(bulk), a turbulent natural convection correlation is used, and energy is transferred from the heat sink into the atmosphere. If T(wall) is below T(bulk) but above the atmospheric saturation temperature, T(sat), a turbulent natural convection correlation is still used, but energy is absorbed by the heat sink. If T(wall) is less that T(sat), then a condensing heat transfer coefficient is used. Energy is transferred from the atmosphere to the heat sink, and a condensate mass is calculated and transferred from the atmosphere to a pool region. The total enthalpy of the condensate mass is also calculated and transferred from the atmosphere to the pool.

The area to be used in the equation is specified by the user and must be estimated from the actual plant data.

The reference temperature difference used must be the difference for which the heat transfer correlation was developed. For the turbulent natural convection correlation this is the bulk-to-wall difference, which is the temperature difference across the turbulent boundary layer. For a condensing heat transfer correlation the proper temperature difference is not as obvious. The codes have built-in condensing heat transfer coefficients, the Tagami (Ref. 9) and the Uchida (Ref. 6) correlations. The codes apply these coefficients using the saturation-to-wall temperature difference.

Traditionally, the saturation-to-wall temperature difference has been used with condensing heat transfer correlations. This apparently is a carryover from correlations for condensation from a pure steam atmosphere where the condensate layer experienced the principal temperature drop which was the saturation-to-wall difference (Ref. 5). If non-condensibles are present in a significant amount, the temperature drop across the condensate layer may be negligible. The principal temperature drop is across an air rich boundary layer and is, essentially, the bulk-to-wall difference. This is the difference that should be used for a heat transfer correlation for condensation in the presence of non-condensibles (Ref. 5).

The issue is confused by the fact that the Tagami and Uchida correlations were developed from experiments with a saturated atmosphere. In such a case, the saturation and bulk temperatures are equal. It seems natural to use the saturation-to-wall temperature difference for these correlations, but it is not clear that it is the most appropriate. In fact, it has been suggested that the correct temperature difference for both of these correlations is the bulk-to-wall difference (Ref. 3). It is clear that for superheated atmospheres with non-condensibles, the bulk-to-wall temperature difference is most appropriate for calculating heat transfer, but should only be used with a heat transfer correlation that was developed for use with the bulk-to-wall difference.

II.A.4 Condensation Mass Transfer

When conditions indicate that a condensing mode of heat transfer is appropriate, the condensate mass associated with the heat transfer must also be calculated and removed from the atmosphere region. Direct measurements on which to base this calculation have not been made, but a theoretical approach should be based on an analysis of the sources of energy absorbed by the heat structures, that is, which components of the atmosphere release the energy.

The thermal energy absorbed by the heat structure can be divided into two components: the sensible heat released by mass which stays in the atmosphere ($Q_{atmosphere}$); and the heat released by the condensate mass ($Q_{condensate}$). (The second component of the absorbed heat can be divided into three subcomponents: the sensible heat released by cooling the steam from its superheated condition to saturation, the latent heat of condensation, and the sensible heat released in cooling the condensate below the saturation temperature.) The heat absorbed by the heat structure is then:

$$Q = Q_{atmosphere} + Q_{condensate}$$

If the heat lost by the condensate can be determined, the condensate mass can be calculated by:

$$M_{condensate} = \frac{Q_{condensate}}{h_{bulk} - h_{film}}$$

where: $M_{condensate}$ = the condensate mass removal

h_{bulk} = specific enthalpy of steam at bulk conditions

h_{film} = average specific enthalpy in the condensate layer

The MONSTER and CONTEMPT calculation of the condensate mass is based on the assumption that a constant fraction of the heat transferred in the condensing mode comes from the condensate. This fraction is specified in the input.

The fraction of the total heat transferred that is released by the condensate is called the condensate fraction, that is:

$$f = \frac{Q_{condensate}}{Q}$$

The revaporization rate, used by some authors, is essentially the fraction of the total heat transferred, that is released by the mass that remains in the atmosphere. That is:

$$R = \frac{Q_{condensate}}{Q}$$

So that:

$$f + R = 1$$

The value of these variables that should be used with a condensing heat transfer correlation must be a conservative value developed from comparison with experimental data. For use in MSLB calculations, that is the value that produces at least the maximum actual temperatures and pressure when used to predict experimental results such as the CTR experiments (reference 7).

II.A.5 Applicability of the Current Methodology

The method recommended by NUREG-0588 for calculating MSLB containment conditions is a modified version of a method that was originally developed for LOCA analysis. The LOCA analysis uses a heat transfer coefficient based on the saturation-to-wall temperature difference and no revaporization. The only significant change for MSLB analysis is the incorporation of revaporization. The resulting method still retains features of the LOCA analysis technique which are overly conservative when applied to large MSLBs because the nature of the MSLB blowdown is different. A LOCA blowdown is liquid which flashes to a mixture of liquid and saturated steam. The resulting containment condition is a mixture of saturated steam, liquid water, and air at the saturation temperature. The MSLB blowdown is superheated steam or saturated steam which expands to superheated conditions. The resulting containment condition is a mixture of superheated steam and air, and a high degree of turbulence will be present while the blowdown continues.

Because of this difference, the conservatisms of the NUREG-0588 method are increased when applied to MSLBs. Higher atmospheric velocities caused by the higher specific enthalpy of the blowdown indicate higher heat transfer coefficients for large MSLBs than for LOCAs. The use of the saturation-to-wall temperature difference to calculate the heat transfer, as in LOCAs, underestimates the heat transfer for MSLBs, for which the bulk-to-wall difference would more appropriate. The higher heat transfer rates that result are enough to drive the heat sink surface temperatures close to or above the saturation temperature. As the heat sink surface temperature approaches the saturation temperature, the condensation rate must drop to zero. Since the surface temperatures remain nearer the saturation temperature, the average condensate fraction will be lower (revaporization rate will be higher) for turbulent and superheated atmospheres than for saturated atmospheres.

The NUREG-0588 method for calculating MSLB containment conditions predicts lower than actual heat transfer rates and higher than actual condensation rate (relative to the heat transfer rates). The qualitative effect of the model on the calculated containment atmospheric temperature can be determined by considering the discussion of section II.A.2. With less energy and more mass being removed, the model predicts higher than actual average specific internal energies for the containment atmosphere. Due to the sensitivity of the temperature of a superheated atmosphere to changes in the specific internal energy, the predicted containment atmospheric temperature is much higher than is expected.

The above discussion indicates that the NUREG-0588 method for MSLB containment analysis is overly conservative. TVA investigated this further by performing a number of calculations with the 0588 method attempting to reproduce the results of the CVTR experiments (reference 7). These calculations and the results are described in section II.C.1.

TVA has developed a method which uses the MONSTER containment code and a condensing heat transfer model based on the coefficients measured in the CVTR experiments. These coefficients are based on the bulk temperature. The revaporization rate of 10 percent is the result of benchmarking with the CVTR experiment. The predictions of this method are compared with the results of the CVTR experiment in section II.C.3.

Another effect of the NUREG-0588 method should be mentioned here. The use of the saturation-to-wall temperature difference in the heat transfer calculation causes the heat transfer rate to go to zero as the wall temperature approaches the saturation temperature. This makes the saturation temperature an artificial upper bound on the wall temperature. Heat transfer is thus limited to the rate that can be absorbed by the heat structure when its surface temperature is slightly below the saturation temperature. Both CONTEMPT and MONSTER attempt to get around this effect by switching to a calculation which uses the minimum Uchida coefficient (2 Btu/hr-ft°F) and the bulk-to-wall temperature difference if the resulting heat transfer rate is greater than that indicated by the user-specified model. No theoretical basis is apparent for the switch and so is only an artificial fix.

II.B Experimental Heat Transfer Data

Very little experimental data exists on which to base the heat transfer calculations for LOCAs and MSLBs. This is not surprising if the scale and conditions which must be matched are considered. Three sets of experiments are often cited in connection with such calculations: those of N. Sagawa on which the Uchida correlation is based (Ref. 6), those of Tagami (Ref. 9), and the design basis accident simulations at the Carolina Virginia Tube Reactor facility (Ref. 7). All provided measurements of heat transfer in the presence of non-condensibles, but had different scales and conditions. Licensing calculations of MSLB and LOCA containment conditions have been made using the Tagami (Ref. 9) and Uchida (Ref. 6) correlations. These correlations are based on the small scale experiments conducted by the Japanese. Besides the problem of scale, these experiments, also, simulated conditions unlike those encountered in MSLBs.

The Uchida correlation is recommended by NUREG-0588 for use in MSLB analysis and for the post-blowdown period in LOCA analysis. This correlation is based on experiments of N. Sagawa at Hitachi LTD of Japan. The conditions of the experiments were intended to simulate natural convection in a mixture of air and steam, though slight effects due to forced convection caused by the blowdown were probably present (Ref. 3). The correlation that was derived from the data is based on the mass ratio of air and steam. The form of the correlation is a table of heat transfer coefficients versus air/steam mass ratios. The correlation is built into CONTEMPT and MONSTER and is easily invoked.

The Tagami correlation is approved for the blowdown period of LOCA Analysis. It is based on experiments conducted at Tokyo University. The experiments provided heat transfer measurements during a liquid blowdown into a containment of less than 2000 ft^3. The Correlation that was derived from the experiments relates the heat transfer coefficient to the blowdown rate, as can be seen from the expression for the maximum heat transfer coefficient:

$$H_{max} = C\,(Q/Vt_p)^{.62} \qquad \text{II.B.1}$$

where the following definitions apply:

H_{max} — the maximum heat transfer coefficient during blowdown (BTU/hr-ft^2-deg F)

C — a constant, 72.5 BTU/hr-ft^2 - deg. F/(BTU/ft^3 - sec)$^{.62}$

Q — integrated energy release up to the initial peak pressure (BTU)

V — volume of the containment (ft^3)

t_p — time of the initial peak pressure (sec).

The heat transfer coefficient of the Tagami correlation increases linearly from zero at the start of blowdown to H(max) at the time of initial peak pressure, according to:

$$H(t) = H_{max}\,(t/t_p) \qquad \text{II.B.2}$$

The peak pressure is usually assumed to occur at the end of the blowdown. The correlation is valid only during the blowdown, after which the Uchida correlation is used. That the correlation depends on the blowdown rate is shown by the term in parentheses in Equation II.B.1, which is equal to the average volumetric energy release rate during the time period involved. The blowdown rates for the experiments on which the Tagami correlation is based, were nearly constant. The correlation, thus, produces a heat transfer coefficient that is almost linearly proportional to the integrated volumetric energy release.

The Tagami correlation has a peculiarity in that it predicts different heat transfer coefficients under situations that should have equal coefficients. For a constant blowdown rate, the heat transfer coefficient can only depend on current and/or prior conditions. For example, the heat transfer coefficient should not be different if the blowdown were to last another 10 seconds or another 1000 seconds. For a constant blowdown, Equation II.B.1 predicts the same maximum coefficient regardless of the length of the blowdown. Equation II.B.2 shows that for an instant in time the heat transfer would be halved if the time to end of blowdown is doubled while the blowdown rate remains constant. This effect does not occur for the coefficients which TVA proposes to use.

Methods of LOCA/MSLB analysis are often evaluated on their ability to predict results of the design basis accident (DBA) simulations at the Carolina Virginia Tube Reactor (Ref. 7). These tests were conducted in the containment of a decommissioned nuclear reactor facility with a containment of about 1/15 of the volume of Bellefonte and thus are closer to full scale than any other tests available. The facility itself is typical of nuclear reactor facilities, having a steel-lined concrete containment housing all of the usual components (reactor, steam generator, pressurizer, etc.) and structures (concrete walls and floors, steel supports, etc.). Five tests were conducted: two preliminary tests to check out the facility, a natural decay cool down, and two tests using containment sprays for cool down. The natural decay cool down, CVTR Test 3, was used in an NRC study to develop the NUREG-0588 approved methods. It will also be used here.

During the simulations, steam was introduced through a specially-constructed device, called a diffuser in the report, but which actually was described as a sparger. The device was a 10-foot-long vertical pipe attached to a steam line at one end and capped at the other end. Steam was emitted through 126 one-inch-diameter holes spaced evenly along the pipe. The flow rate and superheat of the steam were maintained nearly constant for the duration of Test 3.

A wide variety of data were collected in the CVTR tests. Temperatures were measured at numerous locations throughout the facility. Pressures were measured at different elevations. Condensate catch cans were used to estimate the condensation rates. An ultrasonic anemometer was used to measure the velocities of convection currents. Heat transfer coefficients were measured with heat plugs, and calculated from temperature profiles measured in the walls.

The degree of turbulence created in the CVTR test was not as great as that expected in a large Bellefonte MSLB. The lower blowdown rate (about 1/10 of the maximum MSLB blowdown rate) and the diffused nature of the release lead to this conclusion. The experimental data indicate that substantial stratification of the atmosphere occurred with temperature differences as great as 100 degrees F between the upper and lower regions. Vertical variations in the measured heat transfer rates were also noted. Though the stratification indicates as quiescent atmosphere, the presence of some turbulence was indicated by measurements of convective velocities as high as 30 ft/sec in the upper region.

It should be noted that the calculations of heat transfer coefficients in these tests did not use an energy balance on the atmosphere to determine the heat transfer rate. Instead, temperature gradients in "heat plugs" and heat sinks were used in a program called TAEH to calculate the coefficients. Therefore, using the CVTR heat transfer coefficients to predict pressures and temperatures in the CVTR experiments is a valid test of the coefficients.

The CVTR test data is the last source of measured heat transfer coefficients considered here. The average CVTR heat transfer coefficients, (those calculated by the TAEH computer program with data from the two heat plugs) are shown in Figure 4. Though not ideal, these coefficients are believed to be the most appropriate available on which to base methods for performing MSLB calculations. The conditions of the experiments indicate that the heat tranfer coefficients measured are conservative for large MSLBs. The coefficients are based on the bulk-to-wall temperature difference and should be used with a revaporization rate that will produce conservative predictions of the pressure and temperature profiles of the CVTR Experiment 3. The use of the method to predict approximately the highest measured CVTR temperatures is a conservative comparison. A problem involved with applying the data is finding a conservative method for scaling the coefficient for a MSLB. A method for doing this is presented in Section II.D.2.

II.C Comparison of Revised Method to NUREG-0588 Method

II.C.1 NUREG-0588 Recommended Analysis of the CVTR Test

NUREG-0588 is the NRC Interim Staff Position on environmental qualification of safety-related electrical equipment. Its section entitled "Establishment of the Qualification Parameters for Design Basis Events," approves the use of CONTEMPT/LT for calculating containment conditions during MSLBs. For a condensing heat transfer coefficient, NUREG-0588 recommends the Uchida correlation with the saturation-to-wall reference temperature difference and an 8-percent revaporization. These recommendations were the result of a study conducted by the NRC and summarized in an internal memorandum from R. Tedesco to R. Mattson, V. Stello, and R. Boyd (reference 8). R. Tedesco's memorandum concluded that large main steam line break (MSLB) best estimate analysis should use the Tagami heat transfer correlation during blowdown (a recommendation not included in NUREG-0588) and the Uchida after blowdown. It also found that a 9.6-percent revaporization produced results which best fit the maximum temperature curve of CVTR and 7.6-percent produced results that bound the CVTR data. Figure 1 shows a comparison of their results with CVTR data for the two revaporization rates. (The heat transfer correlation used in these calculations was not specified in the memorandum.)

A later report, by Lamkin et al. (reference 3) concerned a study that was performed for the NRC. Without citing specific calculations, the authors point out that the Tagami/Uchida correlations are in poor agreement with the CVTR results. The report, however, recommends the use of the Tagami/Uchida correlation because (1) "no other well founded emperical correlation (is) available"; and (2) the correlations are conservative. Pointing out the lack of test documentation, the authors say that the proper temperature difference to use with the correlations is the bulk-to-wall value. For the mass transfer associated with condensation they suggested a more mechanistic model than simple specification of a revaporization fraction. The recommended model, however, requires the specification of the mass ratio of steam entering the air/steam boundary layer of a heat structure, to condensate deposited on the surface, an unknown datum for which no rigorous calculation was suggested.

In an effort to assess various methods for calculating MSLB containment conditions, TVA performed a series of calculations designed to predict the results of the CVTR experiment 3. The input models for these calculations were developed from data in the CVTR report (reference 7). Using CONTEMPT, the Uchida correlation, the saturation-to-wall temperature difference, and revaporization rates of 8 percent (NUREG-0588 recommendation) and 0 percent (for comparison), the calculations predict peak temperatures of 318°F and 360°F, respectively. These predictions are substantially higher than the CVTR measured peak of 236°F. The predicted temperature profiles are compared with measured profiles in Figure 2. Two conclusions can be drawn from the comparison: (1) the NUREG-0588 method overpredicts the rise above ambient temperature (T_{amb} =80°F) by over 50 percent, and (2) the specified revaporization rate can have a decided effect on the predicted results.

The results are also surprising since the 8-percent revaporization rate should have produced results that are bounded by the two predicted profiles in Figure I. To investigate this discrepancy TVA requested documentation of the NRC study. Charles Tinkler of the NRC authorized the transmittal of the information. R. G. Gido provided three input decks obtained from D. E. Lamkin, who had performed the calculations. The decks had features that were inconsistent with the NUREG-0588 methodology. The heat transfer coefficient specified was a tabular version of the average CVTR measured coefficients. Each of the decks included a heat sink that was not documented in the CVTR report (reference 7), and which increased the modeled steel by as much as 117 percent in area and 82 percent in volume. This is much more than the uncertainty listed for the heat structures in the CVTR report. The decks had specified revaporization rates of 0 percent, 7.6 percent, and 9.6 percent, and the last two were believed to have produced the curves in Firgure 1.

In an attempt to match the results of Figure 1 with the NUREG-0588 methodology, TVA made another run using the extra steel of the NRC model in addition to the best estimate heat sinks. The resulting temperature profile, shown in Figure 3, had a peak of 271 °F, still substantially above the highest measured CVTR temperature of 236°F. The conclusion drawn from this is that the calculations used to determine the revaporization rate for use in the NUREG-0588 approved method did not use the other features of the approved method (i.e., the Uchida correlation with the saturation-to-wall temperature difference), or used a heat sink model that was about twice as large as the actual heat sinks.

Apparently, to ensure the conservatism of the results, the NRC determination of the recommended revaporization rate used a condensing heat transfer model that produced higher heat removal rates than those calculated with the recommended model. Since the predicted temperature of the containment atmosphere is lowered if either the heat removal rate is increased or the mass removal rate is decreased, the excess heat removal caused a higher mass removal rate to produce the temperature profile that best matched the experimental data. The recommended revaporization rate is to be used with a heat transfer model that will produce lower heat removal rates than in the NRC's calculations. The individual conservatisms of the NUREG-0588 recommended condensing heat transfer correlation, reference temperature difference and revaporization rate, combine to produce a condensing heat transfer model that is excessively conservative.

TVA believes that an adequately conservative model should include heat transfer coefficients which are conservative in magnitude and based on the proper reference temperature (i.e., the bulk-to-wall value) and a revaporization rate that is determined through comparison with experimental data. The comparison calculations should be made with the complete heat transfer model to be used in the MSLB analysis calculations, and should be made with a reasonably conservative estimate of the heat sinks involved. Adequate conservatism will be ensured if both the predicted temperature and pressure profiles match or are higher than the highest measured profiles for the experimental data.

II.C.2 MONSTER vs CONTEMPT

TVA used MONSTER instead of the NUREG-0588 approved code. CONTEMPT, because the public version of CONTEMPT available to TVA (CONTEMPT/LT-26, version 1.02, as maintained at CDC's Eastern Cybernet Center) did not run as expected under certain conditions and did not allow certain options to be employed. Specifically, when a tabular heat transfer coefficient, such as the CVTR data is used, CONTEMPT does not calculate a condensation mass. (Using a non-condensing heat transfer coefficient is equivalent to using 100 percent revaporization, since both cause no mass to be transferred while heat transfer is unaffected.) This was determined from the results of several runs which had specified revaporization rates from zero to 100 percent, but which used an otherwise identical model with a tabular heat transfer coefficient. Plots of the temperature or pressure results of such cases are identical. One such case is included in Figure 3. The curve labeled "CONTEMPT with CVTR HTC & 117-percent HS" can be generated with any revaporization rate from zero to 100 percent. CONTEMPT also did not allow the use of the bulk temperature with either the Uchida correlation or a tabular heat transfer coefficient. TVA's investigation of containment analysis included various cases in which the Uchida correlation or a tabular heat transfer coefficient was used with the bulk temperature. These cases required the use of MONSTER. The method for containment analysis which TVA believes is most appropriate also requires these options which are unavailable in CONTEMPT.

To justify the use of MONSTER, a number on comparison calculations were made which show that the results of MONSTER and the NRC approved code, CONTEMPT, are equivalent if equivalent models are used. Calculations with CONTEMPT and MONSTER using the Uchida correlation with revaporization rates from zero to 100 percent and using a tabular heat transfer coefficient with 100 percent revaporization were performed. In all cases the results of equivalent runs in the two codes were essentially the same. The temperature results of two sets of these runs (Best Estimate CVTR model using Uchida with zero and 100 percent revaporization) are shown in Figure 5. There is no discernable difference in the plotted results for the equivalent cases. The actual differences in temperature and pressure results were of the order of .2 deg. F and .01 PSI at the time of peak containment conditions. The differences in the results of the equivalent MONSTER and CONTEMPT runs are insignificant.

II.C.3 TVA Comparitive Calculations

TVA's investigation included CONTEMPT and MONSTER calculations demonstrating the effects of various options in the heat transfer model. Since the temperature is of primary interest in MSLB analysis it is the only variable for which plots were prepared. The behavior of other variables was also investigated by comparison of the output. The investigation included preliminary calculations to determine the heat structure noding and time step size for the calculations and to determine the effect of varying the initial conditions and the size of the heat structures. These were performed to account for the effect of uncertainties in experimental data.

Figure 3 shows the results of several calculations that were attempts to duplicate the curves of the NRC's study of revaporization, Figure 1. The fifth curve, shown for comparison, is the highest measured CVTR temperature profile. The first curve has already been described in Section II.C.1. That calculation used a heat sink model equivalent to the best estimate plus the extra steel heat sink of the NRC's input decks (Ref. 14). With this model the NUREG-0588 methodology predicts a peak average containment temperature 35 deg. F above the highest peak temperature measured in the CVTR experiment. This is extremely conservative considering that the steel heat sink capacity was approximately twice the best estimate.

The second curve in Figure 3 has aslo been discussed previously. This curve was the result of an attempt to duplicate the NRC results with CONTEMPT and the CVTR heat transfer coefficient and the same heat sink model described above. As discussed in Section II.C.2, the results were the same regardless of the specified revaporization rate. The calculations were equivalent to using a revaporization rate of 100 percent and used the saturation-to-wall temperature difference in the heat transfer model. The predicted peak temperature was less than the CVTR measured peak because the extra water mass that remained in the atmosphere lowered the specific internal energy.

The third curve was the result of a MONSTER calculation that was similar to the CONTEMPT calculation that produced the second curve except that a revaporization rate of 8 percent was specified and properly implemented. The curve showed a higher early rise in temperature than the CONTEMPT calculation, and which was due to a smaller water mass in the atmosphere. This temperature reached a temporary plateau, however, because the excess steel heat sink removed much more heat than in the actual experiment. Eventually, the heat sink surface temperatures approached the saturation temperature so that the heat transfer driving temperature difference was reduced. The resulting drop in the heat transfer rate allowed the containment temperature to rise again. The peak temperature still did not reach the experimentally measured maximum because of the excess steel.

The fourth curve was the result of a CONTEMPT calculation which showed the result of using the public version of CONTEMPT with a best estimate model and the average measured CVTR heat transfer coefficients. The calculation was equivalent to using 100 percent revaporization and used the saturation-to-wall temperature difference, but the results would have been similar if the bulk-to-wall difference had been used, since the atmosphere was saturated during most of the transient. As in the other CONTEMPT calculation with the CVTR heat transfer coefficient the temperature of the containment atmosphere did not rise above the saturation temperature except briefly at the start of the blowdown. The heat transfer was limited as the heat structure surface temperatures approached the atmosphere temperature. The smaller heat sink model in this calculation reduced the amount of heat removed from the atmosphere. The higher resulting specific internal energy drove up the pressure and the saturation temperature. The peak temperature still did not reach the highest peaks measured in the CVTR experiment, because of the 100 percent revaporization.

The sixth and last curve in Figure 3 was the result of a CONTEMPT calculation which was presented in the CVTR report (Ref. 7). A best estimate heat sink model and the average CVTR heat transfer coefficients were used similar to one of the CONTEMPT calculations discussed above. The calculation predicted lower than measured temperatures indicating that the same problems with the public version of CONTEMPT were experience, even though they were not discussed in the report. Figure 3 demonstrates the problems that were encountered when the public version of CONTEMPT was used in attempts to duplicate the results of the NRC's revaporization study.

TVA evaluated the use of both the Uchida correlation and the CVTR heat transfer coefficients with the saturation-to-wall temperature difference. Figure 2 showed that with 8-percent revaporization the Uchida correlation predicted overly conservative temperatures for the CVTR experiment. In fact, to obtain the approximate maximum temperature profile, a revaporization rate of at least 25 percent was required. With the CVTR heat transfer coefficients, a revaporization rate of only 12 percent was required to produce similar results. Both of these methods were judged to be inappropriate for MSLB analysis. The heat transfer rates of the Uchida method are so low that an unrealistically high revaporization rate is required to obtain results that match experimental data. The use of the saturation-to-wall temperature difference with the CVTR coefficients is obviously inappropriate since the coefficient is based on the bulk-to-wall difference.

TVA believed that the most appropriate method should use either the Uchida correlation or the CVTR heat transfer coefficients with the bulk-to-wall temperature difference. The use of the bulk-to-wall temperature difference for condensing in the presence of non-condensibles has been recommended by numerous authors (Ref. 2, 10, 11, 12, 16, and 17), and it has been specifically recommended for the Uchida correlation (Ref. 3). The proper revaporization rate for each method should be determined from comparison calculations for the CVTR experiment. The use of the CVTR experiments for evaluating analysis procedures of this type is common practice (Ref. 4, 8, 10, 11, 12, 16, and 17).

Figure 6 shows the temperature profiles of the comparison calculations for the Uchida/bulk temperature method. With this method a revaporization rate of about 20 percent is required to approximately match the maximum peak temperature of the CVTR experiment. It is also noted that the best match of the temperature profile was obtained with a revaporization rate of 50 percent. There is, however, a sharp change in the slope of the 50-percent curve at about 57 seconds into the transient. The output showed that the relative humidity had reached 100 percent and that afterwards an increasing mass of liquid water was retained in the atmosphere. The temperature continued to rise at a rate that kept the profile only slightly below (up to 10 degrees F) the CVTR maximum measured temperature profile. The peak temperature of the profile was 237 degrees F which compares well with the maximum measured peak of about 236 degrees F. The use of 100-percent revaporization produced results that were almost identical to the 50-percent curve except for the initial rise in temperature.

The temperature profiles predicted with the CVTR heat transfer coefficients and the bulk temperature are shown in Figure 7. The method produces results which best match the CVTR data with a revaporization rate of 10 percent. The output showed that this profile bound the CVTR data except for the period from about 80 to 140 seconds, during which the predicted temperature was a maximum of 6 degrees F below the maximum measured temperature profile. The predicted peak temperature of 245 degrees F was 9 degrees above the maximum measured peak of 236 degrees F. Figure 8 shows that the predicted pressure was conservative throughout the transient when compared to the experimental data.

Figures 6 and 7 also show that higher revap rates have little effect on the predicted peak temperature. Above 20 percent for the Uchida correlation or 15 percent for the CVTR heat transfer coefficients, increases in the specified revaporization rate produce no significant reduction in the peak temperature. This is because the higher amounts of water retained in the atmosphere bring it to saturation conditions, at which the temperature is a weak function of specific internal energy and the temperature follows the saturation curve for the steam partial pressure.

II.C.4 Discussion and Evaluation of Alternative Methodologies

A number of studies have been published on modeling of the heat transfer processes during loss of coolant accidents (LOCA) and main steam line breaks (MSLB) which are characterized by the presence of noncondensibles and high turbulence. Many of these (references 3, 8, 10, 11, 12, 16, and 17) use the CVTR report (reference 7) for evaluation of their proposed methodologies. These studies compared the effects of using different correlations for heat transfer, and different models for the condensation mass calculations. Most of these studies (3, 10, 11, 12, 16, and 17) and other published studies (Ref. 5 and 15) indicate that the proper reference temperature difference is the bulk-to-wall difference. Even when the saturation-to-wall difference is used, the proposed model may be modified for superheated conditions (Ref. 13). Some researchers attempted to divide the heat transfer into that which comes from the bulk air/steam mixture and that which comes from the condensation process (references 3 and 11). These methods always require benchmarking to determine the value of certain variables. None of the techniques studied here takes into account the high degree of turbulence expected during a full-scale MSLB.

The heat transfer correlations that were usually used were the Tagami and/or Uchida correlations. It is unclear from the literatrue what reference temperature difference is appropriate with these correlations. CONTEMPT implements them with the saturation-to-wall difference. While noting that the conditions of the Tagami and Uchida experiments were at saturation, the authors of reference 3 suggest that the proper temperature difference should be the bulk-to-wall. Whether this is so or not, the applicability of the Tagami and Uchida correlations to large PWR dry containments is questionable due to the scale (reference 3 and 17). (The NRC's approval of the correlations is based on the fact that they have been shown to be conservative.) The CVTR heat transfer coefficients have also been used (reference 7 and 8). These coefficients were obtained for conditions which are quite applicable to MSLB analysis, and the scale was also appropriate. The only problem with applying the coefficients to MSLB analysis is that of finding a proper correlation or scaling method.

Figures 6 and 7 show that both the Uchida correlation and the CVTR coefficients can be used to predict the CVTR maximum temperature peaks if the right revaporization rate is selected. The approximate temperature profiles can similarly be predicted. The figures show that using the CVTR heat transfer coefficients does a better job of doing both simultaneously. Since the CVTR heat transfer coefficients are obviously more applicable to the CVTR experiment, the associated revaporization rate is also believed to be more realistic.

For the above reasons, it was concluded that the best heat transfer coefficient data available are those calculated from the CVTR data (reference 7). These coefficients are based on the bulk-to-wall temperature difference. The proper revaporization rate was determined to be 10 percent by the benchmarking runs shown in Figure 7. The use of all of the heat sinks documented in the CVTR study (reference 7), for the benchmarking runs is conservative, even though some of the CVTR heat sinks were inactive. The higher calculated heat removal rate, due to the inclusion of the inactive heat sinks, serves to decrease the indicated revaporization rate. This will increase the predicted temperatures in the MSLB calculations. A method for scaling the CVTR heat transfer coefficients for the BLN MSLB analyses is presented in Section II.D.2.

II.D. Application of Revised Method to Bellefonte MSLB

II.D.1 Comparison of the CVTR Experiment to a Bellefonte MSLB

To demonstrate the applicability of the CVTR experimental data to a Bellefonte MSLB, a comparison of the CVTR facility and experiment with the Bellefonte (BLN) containment and MSLB is presented. The CVTR facility was described briefly in Section 1I.B. BLN is typical of nuclear facilities, with a steel-lined containment housing a Babcock and Wilcox (B&W) 205 Fuel Assembly (FA) Nuclear Steam Supply System (NSSS) and the associated nuclear components. The comparison shows that the various features of the two are similar or of such a nature that proper application of the data to BLN is appropriate and conservative.

The facilities of the CVTR and BLN are quite similar. Though BLN has a free volume of 3,400,000 ft^3, which is about 15 times the 227,000 ft^3 of the CVTR, the length scales are not very different. The vertical height of BLN (approximately 270 ft.) is about 2.25 times that of the CVTR (approximately 120 ft.), which is reasonable when comparing heat transfer coefficients. The main heat sinks in each case are the walls and dome of the containment which are very similar. Both have a 1/4-inch steel liner backed by concrete, except that the dome of the CVTR is 1/2-inch steel on concrete. One difference is that the nuclear components of the CVTR facility were not operating during the experiment, and so, were probably significant heat sinks. Even so, taking into account these components only for CVTR, the ratios of significant parameters in the facilities are comparable: free volume to steel heat sink area, 8.84 ft. (CVTR) and 11.2 ft. (BLN); free volume to concrete heat sink area, 19.8 ft. (CVTR) and 22.9 ft. (BLN); volume of steel to free volume, .0051 (CVTR) and .0026 (BLN).

A comparison of the blowdowns also supports the use of the CVTR data for BLN MSLB analysis. The smallest BLN break for which the CVTR data will be used is a .6 ft^2 single-ended steam line break (SESLB). Significant ratios for the CVTR experiment and this break are: maximum mass release rate to free volume, .00048 lbm/sec-ft^3 (CVTR) and .00047 lbm/sec-ft^3 (BLN .6 ft^3 SESLB); maximum energy release rate to free volume, .58 BTU/sec-ft^3 (CVTR) and .59 BTU/sec-ft^3 (BLN .6 ft^3 SESLB). The nature of the blowdowns indicates that the turbulence and therefore the heat transfer coefficients will be greater in the BLN MSLB than in the CVTR experiment. The diffuser in the CVTR experiment, which was described in Section 1I.B, reduced the level of turbulence that would be expected for a single stream release of a similar magnitude. A BLN MSLB would release a more uniform stream or jet of highly superheated steam which would create a higher level of turbulence. The locations of the releases indicate that in a BLN MSLB, more of the heat sinks would be active. Approximately 45 percent of the free volume was above the elevation of the CVTR release and most of the structural heat sinks were below this elevation. The BLN MSLB release would be located within the bottom 1/5 of the containment volume and in the vicinity of many of the structural heat sinks.

The use of the average CVTR measured heat transfer coefficients is also conservative. These coefficients were measured in the upper region of the CVTR containment where the effective heat sinks were located. In the BLN MSLB nearly all of the heat sinks would be in an area where the conditions would be comparable, except that a higher level of turbulence would be present, a condition which indicates that heat transfer coefficients would be greater.

II.D.2 Scaling of the CVTR Heat Transfer Coefficients

In order to use the CVTR heat transfer correlation, a method for scaling is necessary. Because the high heat transfer coefficients are believed to be primarily due to turbulence, and the turbulence is caused by the blowdown, it was considered appropriate to scale on the blowdown rate. The method for doing this is not rigorous, but it does have a precedent in the development of the Tagami correlation (reference 9). The Tagami correlation, which was discussed in more detail in Section II.B, relates the peak coefficient to the volumetric energy release rate. Higher volumetric energy release rates produce higher levels of turbulence and thus higher heat transfer coefficients. The Tagami correlation ramps the heat transfer coefficient linearly from zero at the beginning of the blowdown to the maximum value at the end of blowdown. Since the method was devleoped from constant blowdown experiments, this, in effect, makes the heat transfer coefficient a function of the integrated energy release.

For the scaling method developed here, the assumption was made that the heat transfer coefficient is a function of the integrated volumetric energy release. That is:

$$H_{MSLB}\,(t_{MSLB}) = H_{CVTR}\,(t_{CVTR}) \qquad \text{II.D.2.1}$$

if:

$$\left(\int^{t_{MSLB}} \frac{h\,\dot{M}\,dt}{V}\right) = \left(\int^{t_{CVTR}} \frac{h\,\dot{M}\,dt}{V}\right)_{CVTR} \qquad \text{II.D.2.2}$$

Where:

H_{MSLB} = heat transfer coefficient in MSLB

H_{CVTR} = heat transfer coefficient in CVTR

t_{MSLB} = elapsed time in MSLB

t_{CVTR} = elapsed time in CVTR

h = specific enthalpy of release

$\dot{M}$ = mass release rate

V = volume of respective containments

The heat transfer coefficient, scaled in this manner, is applied only until the MSLB release rate drops to less than the average release rate of the CVTR experiments. The heat transfer coefficient is then ramped to a value of 4 BTU/hr $ft^2\,°F$ at the end of the blowdown. This value is similar to the Uchida correlation for air/steam mass ratios of about 50. It is quite conservative for all transients so far examined, but must be checked each time.

In order to simplify the scaling process, several assumptions, which are conservative, are made. First, the specific enthalpies, h, of the MSLB and the CVTR releases are assumed to be constant and equal. The specific enthalpy of the MSLB releases is actually slightly higher. The mass release rate of the CVTR experiment is assumed to be constant and equal to the calculated average release rate. The release rate was actually controlled at a relatively constant rate. With these assumptions, equation II.D.2.2 may be written:

$$\int^{t_{MSLB}} \frac{\dot{M}_{MSLB}\,dt}{V_{MSLB}} = \frac{\bar{\dot{M}}_{CVTR}\,t_{CVTR}}{V_{CVTR}} \qquad \text{II.D.2.3}$$

$\dot{M}_{MSLB}$ = the mass release rate for a BLN MSLB

$\bar{\dot{M}}_{CVTR}$ = the average mass release rate for the cvtr experiment

The mass release rate for the MSLB was assumed to be constant for scaling purposes, over the period for which the scaled coefficient is applicable. The release rate is actually much higher early in the release. If the actual integrated release had been used, the heat transfer coefficient would have increased more rapidly in the early part of the blowdown. This assumption delays the calculated rise in the heat transfer coefficient, but the maximum value reached is the same.

With this assumption, equation II.D.2.3 becomes:

$$\frac{\bar{\dot{M}}_{MSLB}\,t_{MSLB}}{V_{MSLB}} = \frac{\bar{\dot{M}}_{CVTR}\,t_{CVTR}}{V_{CVTR}} \qquad \text{II.D.2.4}$$

where:

$$\bar{\dot{M}}_{MSLB} = \frac{\int^{t'_{MSLB}} \dot{M}_{MSLB}\,dt}{t'_{MSLB}} \qquad \text{II.D.2.5}$$

and:

t'_{MSLB} = elapsed time when $\dot{M}_{MSLB}$ is less than $\bar{\dot{M}}_{CVTR}$

Substituting II.D.2.4 and II.D.2.5 into II.D.2.3 and solving for t_{CVTR} gives:

$$t_{CVTR} = t_{MSLB} \quad \frac{\int^{t'_{MSLB}} \dot{M}_{MSLB}\,dt}{V_{MSLB}} \Bigg/ \frac{\bar{\dot{M}}_{CVTR}\,t'_{MSLB}}{V_{CVTR}} \qquad \text{II.D.2.6}$$

These assumptions lead to the relation between the MSLB and CVTR heat transfer coefficients which is described by:

$$H_{MSLB}(t_{MSLB}) = H_{CVTR}(S \cdot t_{MSLB}) \qquad \text{II.D.2.7}$$

where: S is a time scaling factor which can be calculated by:

$$S = \frac{\int^{t'_{MSLB}} \dot{M}_{MSLB}\,dt}{V_{MSLB}} \Bigg/ \frac{\bar{\dot{M}}_{CVTR}\,t'_{MSLB}}{V_{CVTR}}$$

Because the volumetric mass release rate for the BLN MSLB is greater than the average CVTR volumetric mass release rate throughout the integral, the value of S is always greater than one. Equation II.D.2.3 shows that for such a case, the scaled CVTR heat transfer coefficient will be equal to the CVTR coefficient at the CVTR time equal to the problem time multiplied by the scaling factor, S. The effect is shown in Figure 10. The shape of the CVTR heat transfer coefficient curve is the same, but the curve is compressed in time.

Besides the conservatism in the scaling process, the use of the CVTR data for large MSLB calculations is inherently conservative. The introduction of steam to the CVTR facility was through a sparger (also called a diffuser) a 10-foot-long section of pipe capped on one end and welded to the steam line at the other and with 126 1-inch-diameter holes. This system would be expected to produce mush less turbulence than a large steam line break which would be expected to discharge most of its mass in one or two streams. The much higher release rates early in the transient would also be expected to produce higher coefficients than in the CVTR experiment. The CVTR heat transfer coefficients are never exceeded, but only manipulated in time by matching them with levels of turbulence.

II.D.3 Revised Predictions for Bellefonte MSLBs

The revised methodology was developed to determine if a more realistic but still conservative approach to MSLB analysis could be used to predict less extreme containment conditions. The predicted temperature and pressure profiles of three new calculations are shown in Figures 11 & 12. The first two curves in each figure were predicted with the new methodology using scale factors of 4.07 and 1.08 respectively for the scaling of the CVTR heat transfer coefficients. The third curve of each figure is for a .15 ft^2 break, for which the volumetric blowdown rates were less than those of the CVTR experiment. Therefore, the revised heat transfer coefficients could not be applied and the NUREG-0588 method was used. The peak temperatures of the three curves, 353 degrees F, 304 degrees F, and 305 degrees F respectively, compare to 383 degrees F, 408 degrees F and 378 degrees F, predicted in the previous calculations (Ref. 19). The peak pressures, 24.1 psig, 17.0 psig, and 18.8 psig compare with 26.9 psig, 23.3 psig, and 10.9 psig respectively, for the previous analysis.

The temperatures predicted with the new method are significantly lower, as expected. The new predicted pressures, however, are only slightly lower than those previously predicted. A look at the printed output from the calculations reveals that some of the heat structures maintained surface temperatures very near the saturation temperature of the containment, and that the heat transfer mode switched between the condensing mode and the natural convection mode as the surface temperature alternately rose above or fell below the saturation temperature. This condition indicates that with the higher heat transfer coefficients durign MSLBs, the thermal properties of the heat structures play a more important role in controlling the heat transfer rates. For these heat structures the increased heat transfer coefficients used did not provide the increased heat transfer rates that might have been expected. (The heat transfer was limited to that which could be absorbed by the heat structure with its surface temperature at the saturation temperature.) The higher revaporization rate resulted in larger amounts of water in the atmosphere, which reduced the degree of superheat of the atmosphere but did little to reduce the pressure.

The switching of the heat transfer mode was also observed in the benchmark calculations but much later in the transient and to a lesser degree. This fact supports the use of the higher revaporization rate. The heat transfer coefficients in the MSLBs would be larger even than those used in these calculations, especially for surface temperature above the saturation temperature. These calculations used a natural convection correlation for a situation that would obviously be very turbulent and for which a forced convection correlation would be more appropriate. Since the surface temperatures would be at or even above the saturation temperature, a greater fraction of the energy removed from the atmosphere would be released by the bulk air and steam mixture, and a lesser fraction would come from condensation. (The condensation must reduce to zero as the surface temperature rises to the saturation temperature.)

The temperatures and pressures for the .15 sq.ft. break which were predicted by the NUREG-0588 method, are lower than the results of the B&W calculations. The lower results are due to the use of 8 percent revaporization by TVA, and an updated heat sink model. Eight percent revaporization was not used by B&W. TVA was able to duplicate the results of the B&W calculations when an equivalent model was used. For the worst case predicted by B&W (32" DESLB ' 80 percent power, and EOL w/MSIV failure) the use of 8 percent revaporization reduces the peak temperature only by about 8 F.

Figure 14 shows the temperature rofile for the worst case predicted by the NUREG-0588 method in the previous analysis (Ref. 19). Comparison of the figure with Figure 11 indicates that a reduction of approximately 60 degrees F in the peak tmeperature of the composite post accident temperature profile may be expected. Such a reduction would significantly improve TVA's ability to obtain equipment with proven operating histories for use in safety-related applications.

III. Conclusions

To obtain relief from overly conservative temperature profiles predicted with the NUREG-0588-approved method for MSLB containment analysis, TVA should use the revised method presented here. The over-conservatism of the NUREG-0588 method as applied to MSLBs has been indicated in the literature and by comparisons of calculations with experiment results. The revised method uses all of the approved calculational techniques of the NUREG-0588 method with the exception of the condensing heat transfer model and has been shown to be conservative.

The condensation heat transfer model is appropriate and conservative for MSLB analysis. It is based on data obtained in the CVTR experiments, (Ref. 7) which were intended to simulate MSLBs. The coefficients are based on the bulk-to-wall temperature difference as recommended by the literature. The revaporization rate was determined by conservatively benchmarking against the maximum measured temperature profile of the CVTR experiment. Comparison of the CVTR experiment with a Bellefonte MSLB indicates that the data are conservative for MSLB analysis. The method of applying the coefficients to a Bellefonte MSLB, (i.e., the scaling process) is conservative and has a precedent in the Tagami correlation which is approved for LOCA analysis by NUREG-0588. Results of the MSLB analyses with the revised method indicate that indeed the method is conservative.

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NRC'S COMPARISON OF VARIOUS REVAPORIZATION RATES
USED IN MODELING THE CVTR TEST DATA (REF. 8)

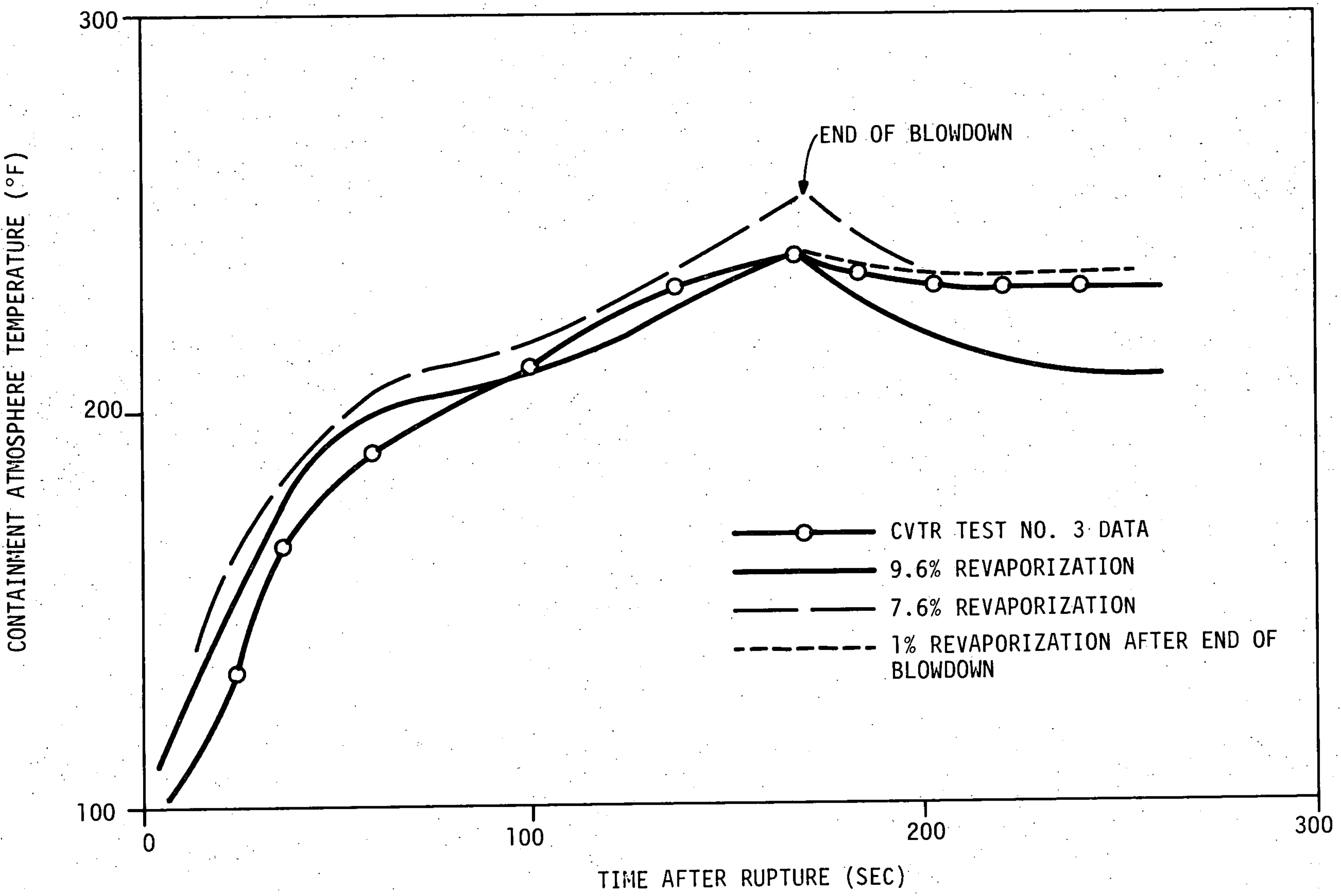


FIG 1

CVTR CONTAINMENT TEMPERATURE PROFILES
PREDICTED WITH UCHIDA CORRELATION AND SATURATION TEMPERATURE
COMPARED TO MAXIMUM MEASURE TEMPERATURE PROFILE

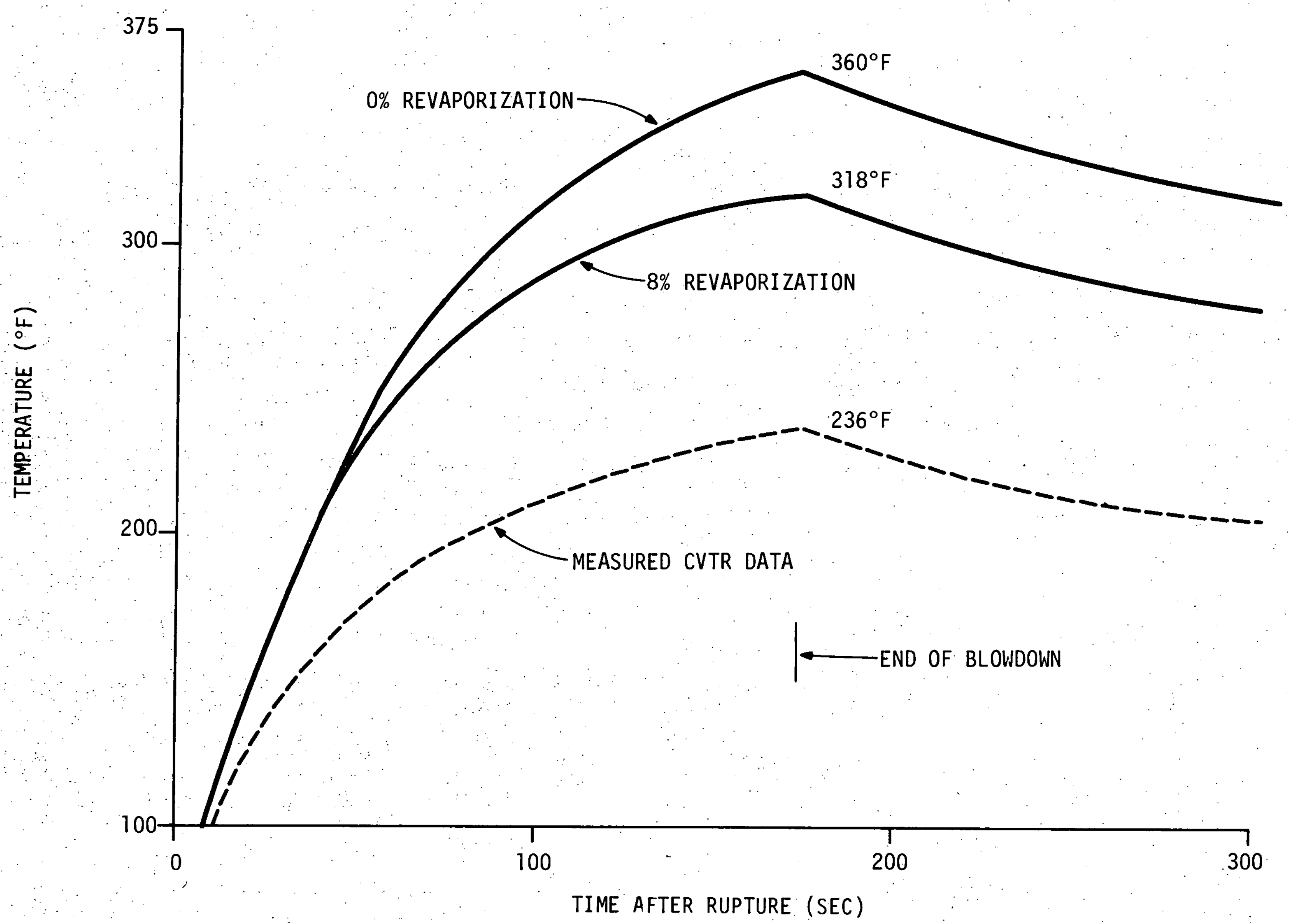
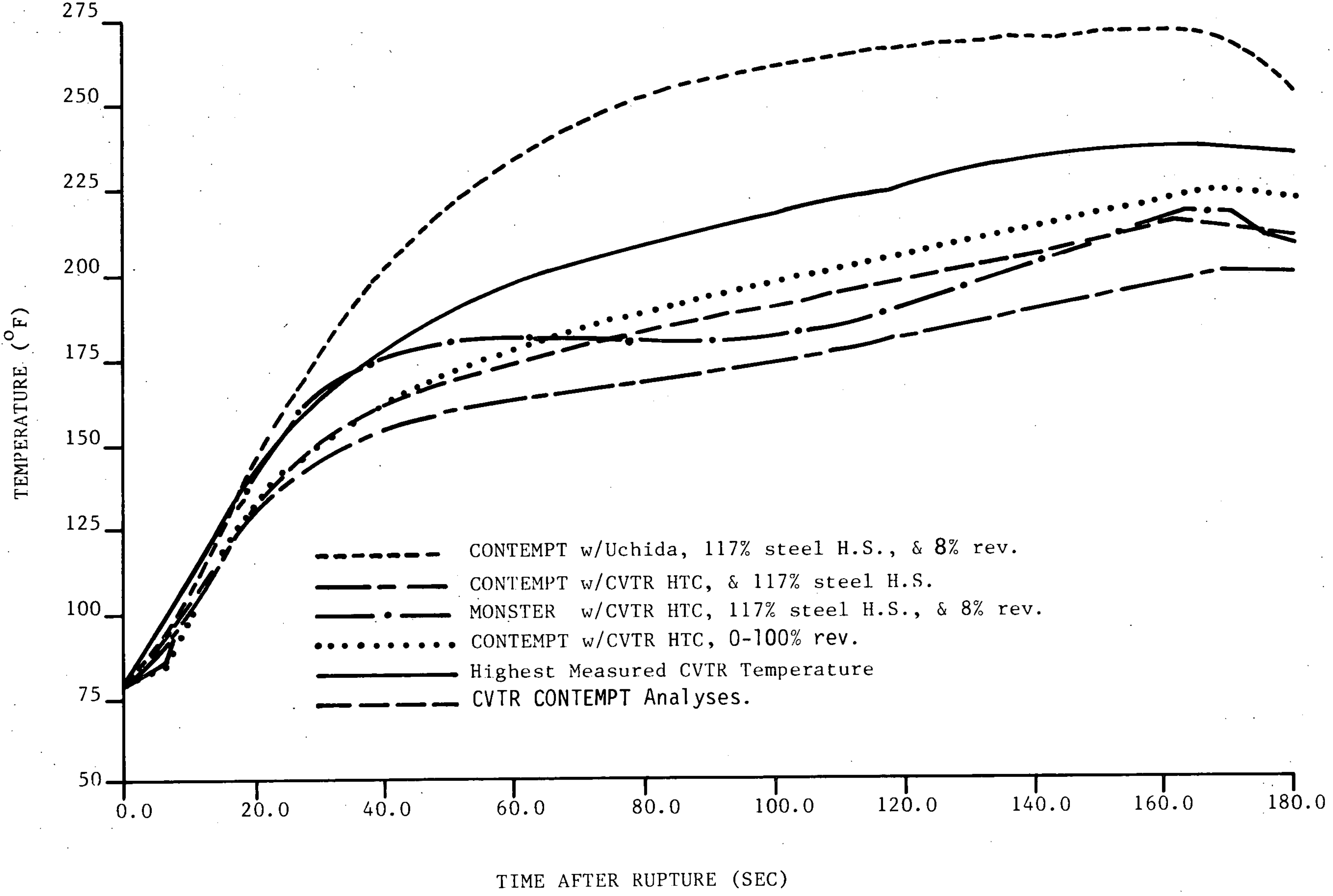


FIG 2



CVTR CONTAINMENT TEMPERATURE PROFILES
PREDICTED WITH VARIOUS ANALYSES
COMPARED TO MAXIMUM MEASURED PROFILE

FIG. 3

AVERAGE MEASURED CVTR HEAT TRANSFER COEFFICIENTS
CALCULATED BY TAEH PROGRAM

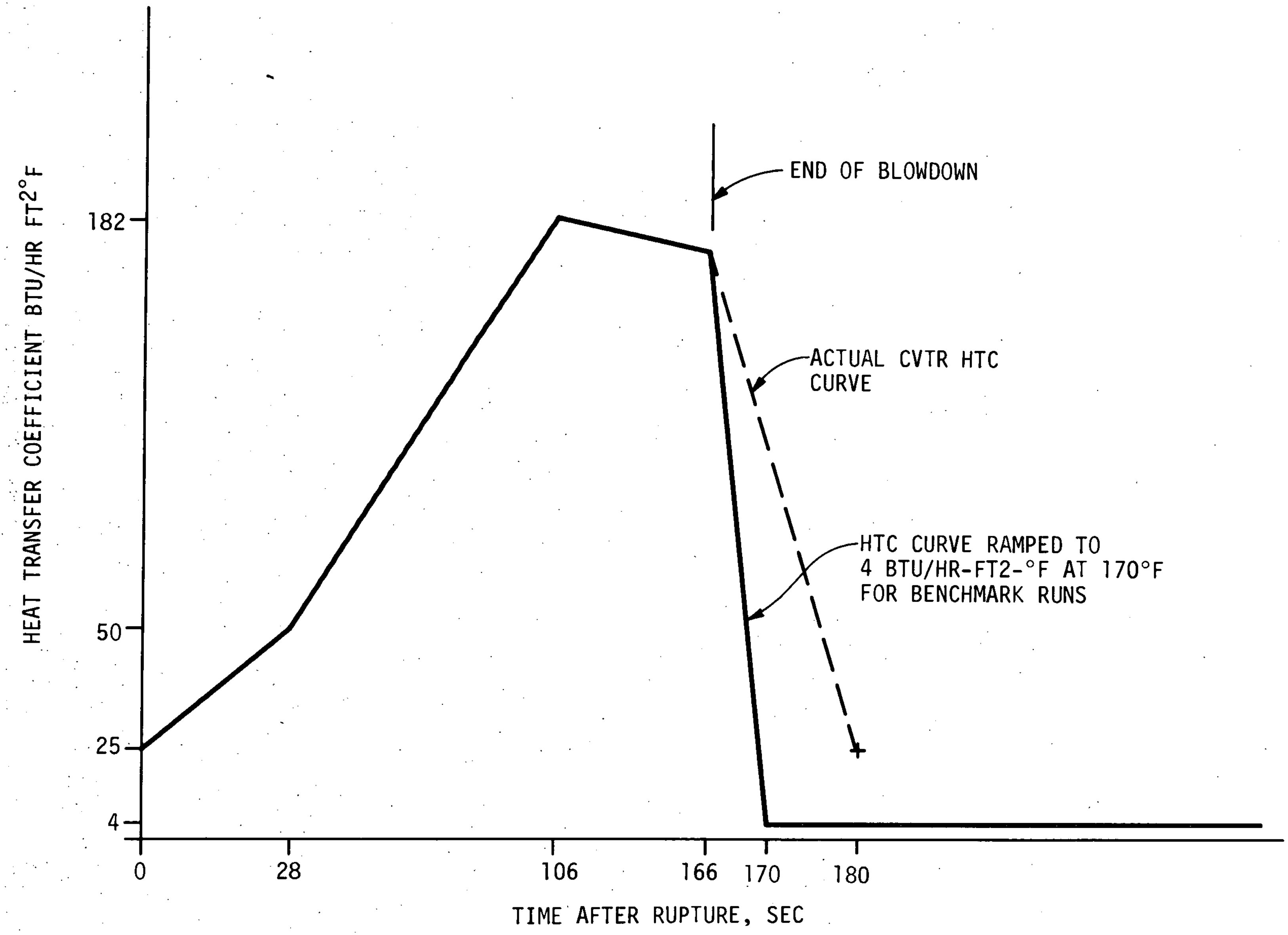


FIG 4

COMPARISON OF MONSTER & CONTEMPT CVTR CONTAINMENT TEMPERATURE PROFILES PREDICTED USING UCHIDA CORRELATION & SATURATION TEMPERATURE

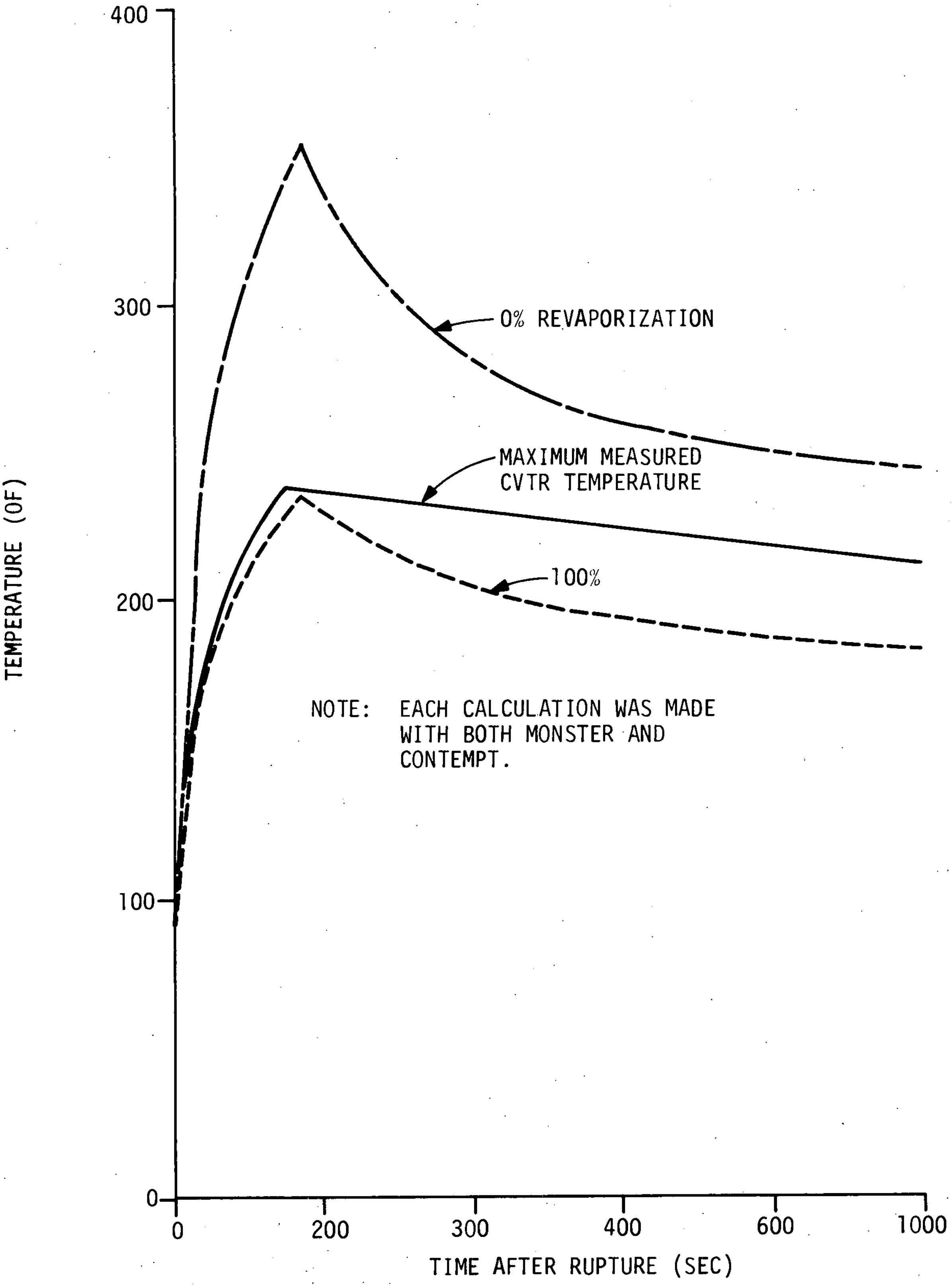


FIG 5

CVTR CONTAINMENT TEMPERATURE PROFILES PREDICTED WITH UCHIDA CORRELATION WITH BULK TEMPERATURE COMPARED TO MAXIMUM MEASURED TEMPERATURE PROFILE

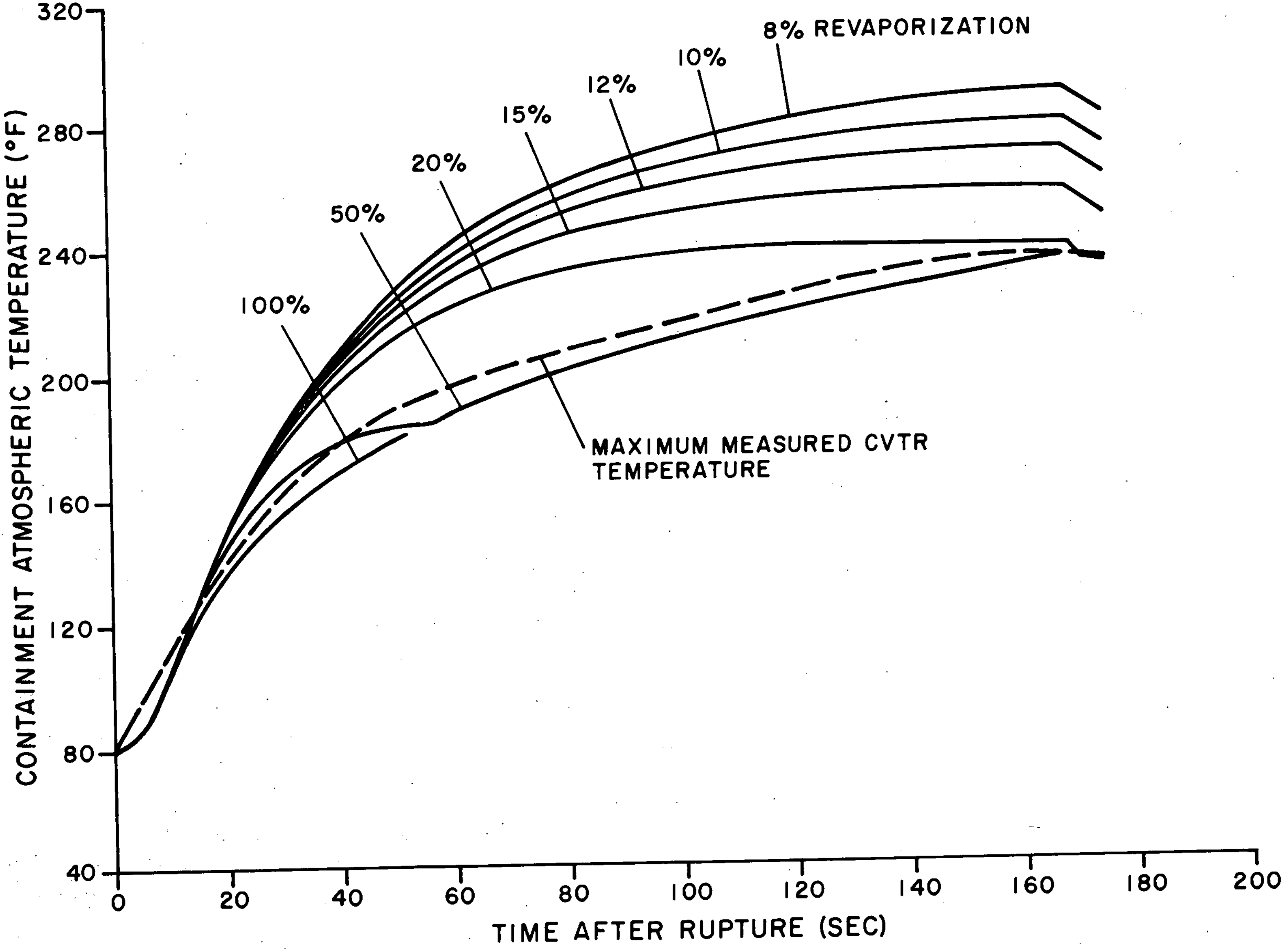


FIG 6

CVTR CONTAINMENT TEMPERATURE PROFILES PREDICTED WITH AVERAGE CVTR HEAT TRANSFER COEFFICIENTS AND BULK TEMPERATURE WITH VARIOUS REVAPORIZATION RATES COMPARED TO MAXIMUM MEASURED TEMPERATURE PROFILE

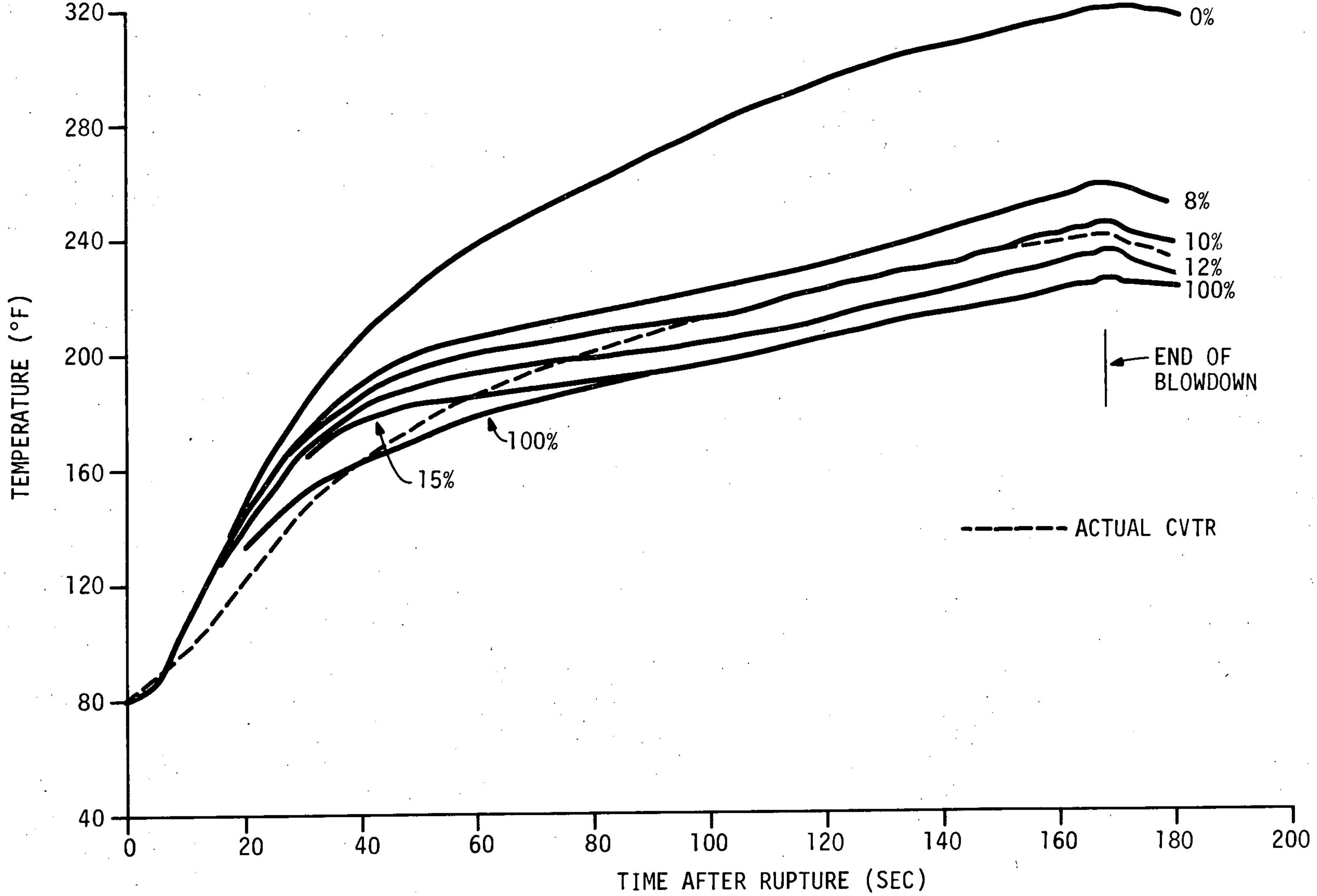


FIG 7

CVTR CONTAINMENT PRESSURE PROFILE PREDICTED WITH AVERAGE CVTR HEAT TRANSFER COEFFICIENTS BULK TEMPERATURE AND 10% REVAPORIZATION COMPARED TO MEASURED PRESSURE PROFILE

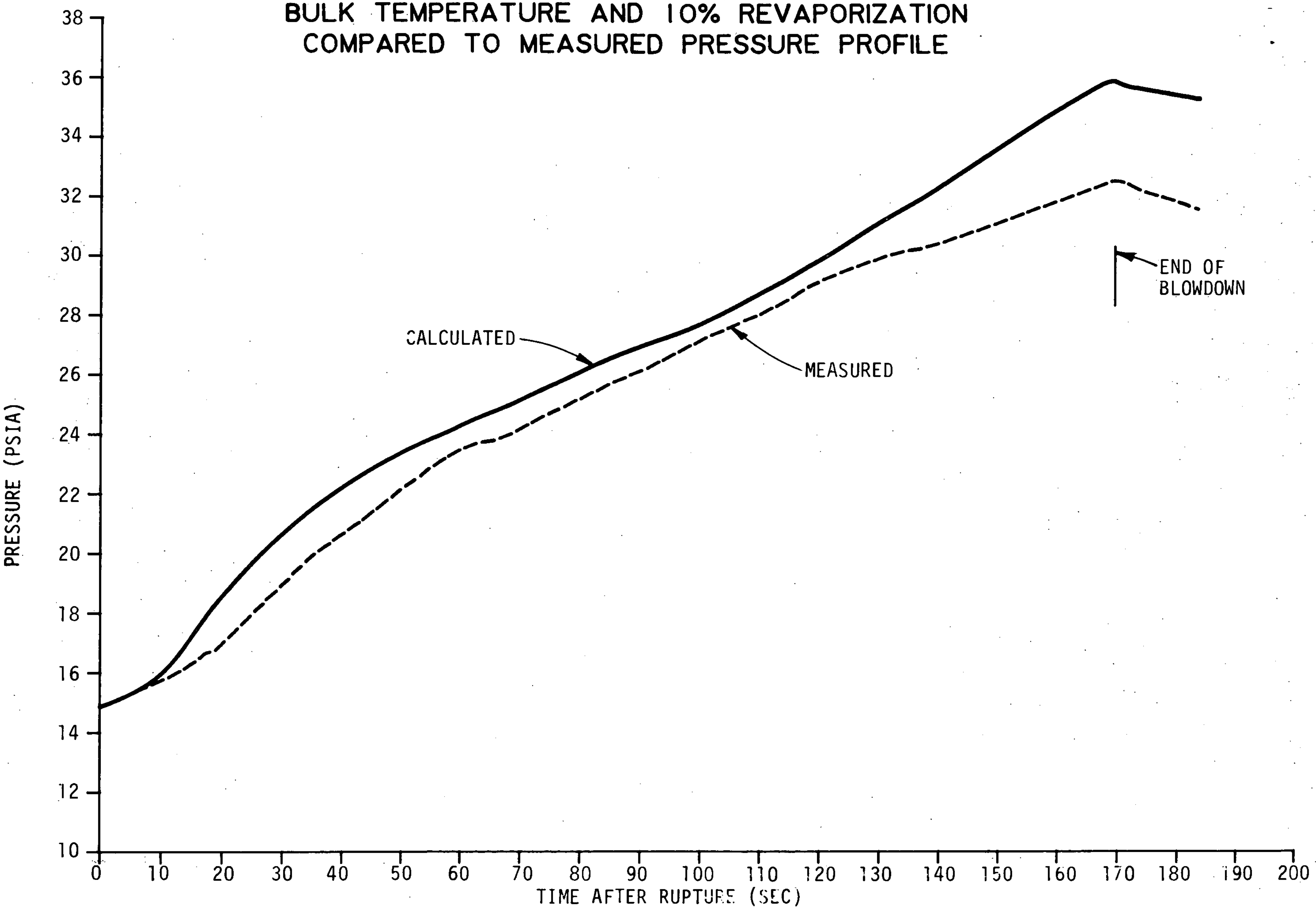
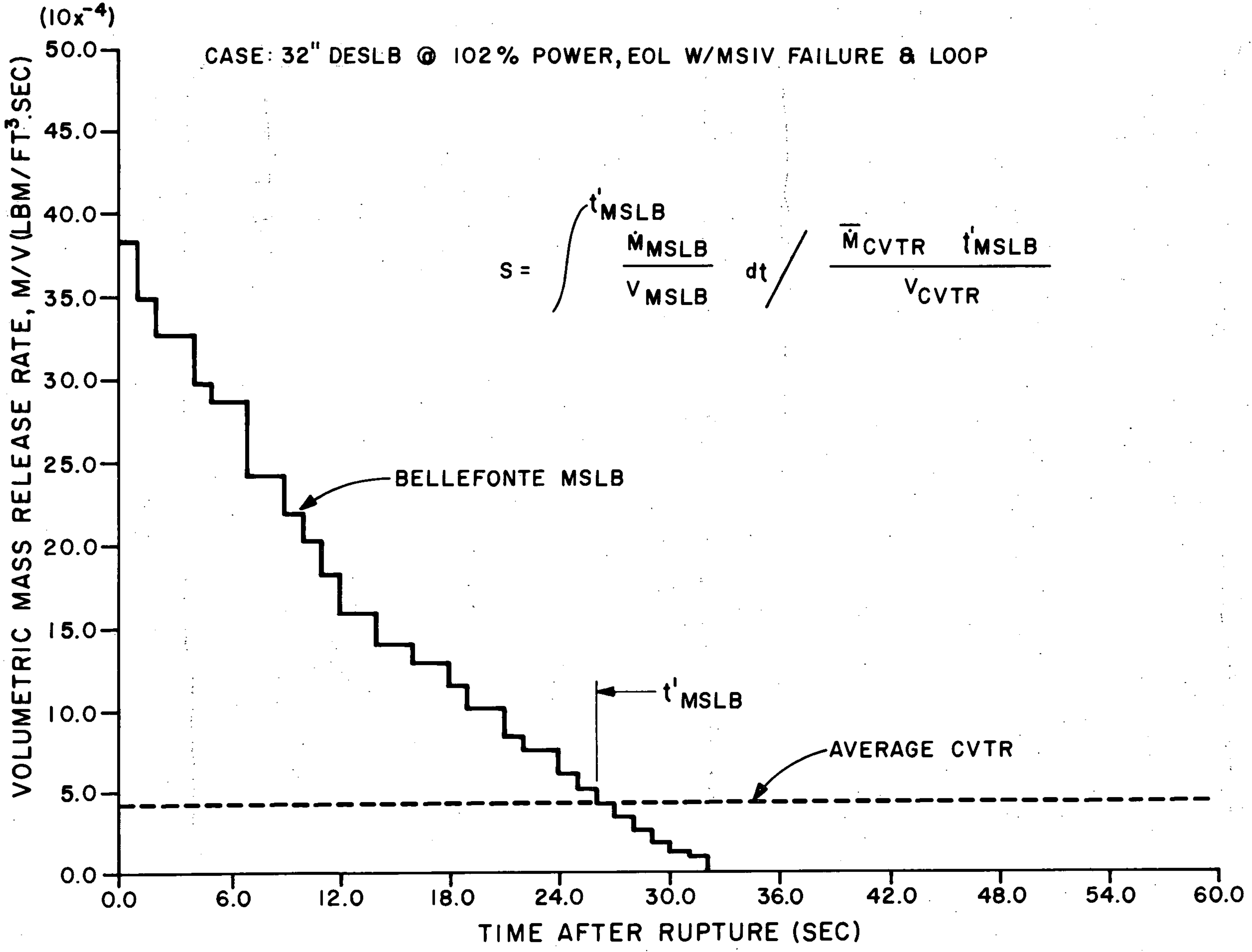


FIG 8

VOLUMETRIC MASS RELEASE RATES BELLEFONTE MSLB AND AVERAGE CVTR FOR CALCULATION OF SCALE FACTOR, S



$$S = \int^{t'_{MSLB}} \frac{\dot{M}_{MSLB}}{V_{MSLB}}\, dt \bigg/ \frac{\bar{M}_{CVTR} \quad t'_{MSLB}}{V_{CVTR}}$$

FIG 9

CVTR AVERAGE HEAT TRANSFER COEFFICIENTS MEASURED & SCALED FOR BELLEFONTE MSLB

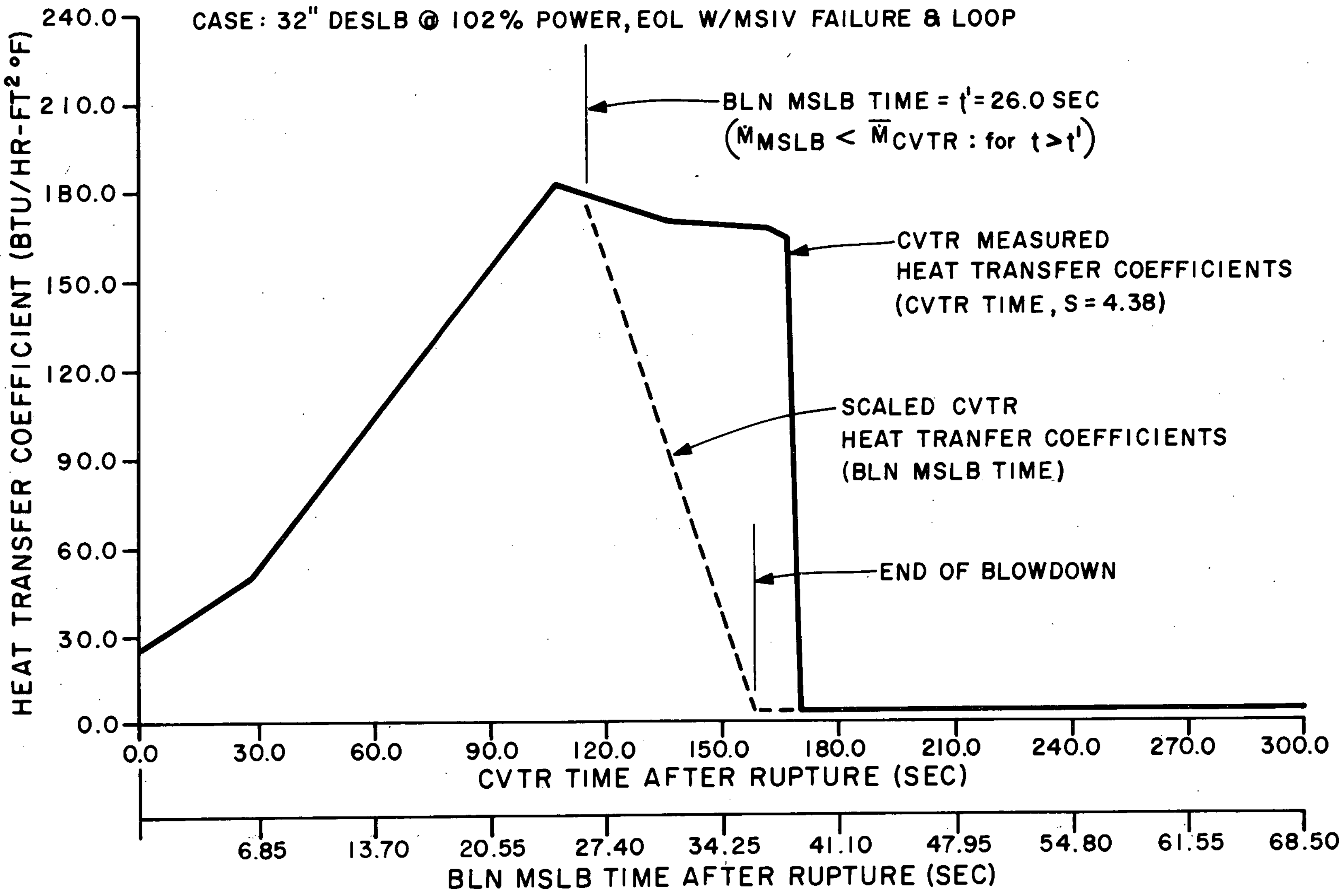


FIG 10

PREDICTED CONTAINMENT TEMPERATURE PROFILES DURING BELLEFONTE MSLBs

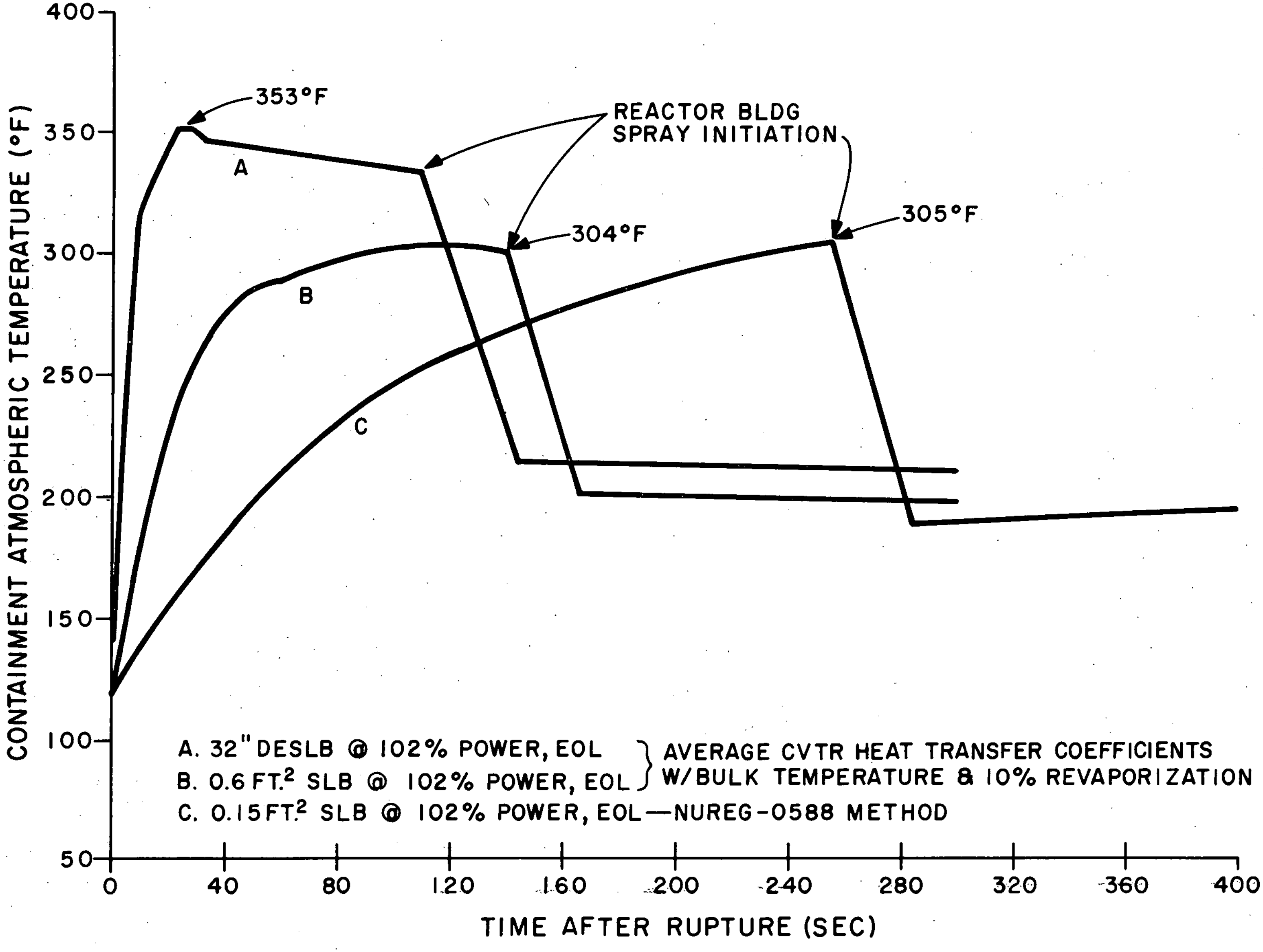


FIG 11

PREDICTED CONTAINMENT PRESSURE PROFILES
DURING BELLEFONTE MSLBs

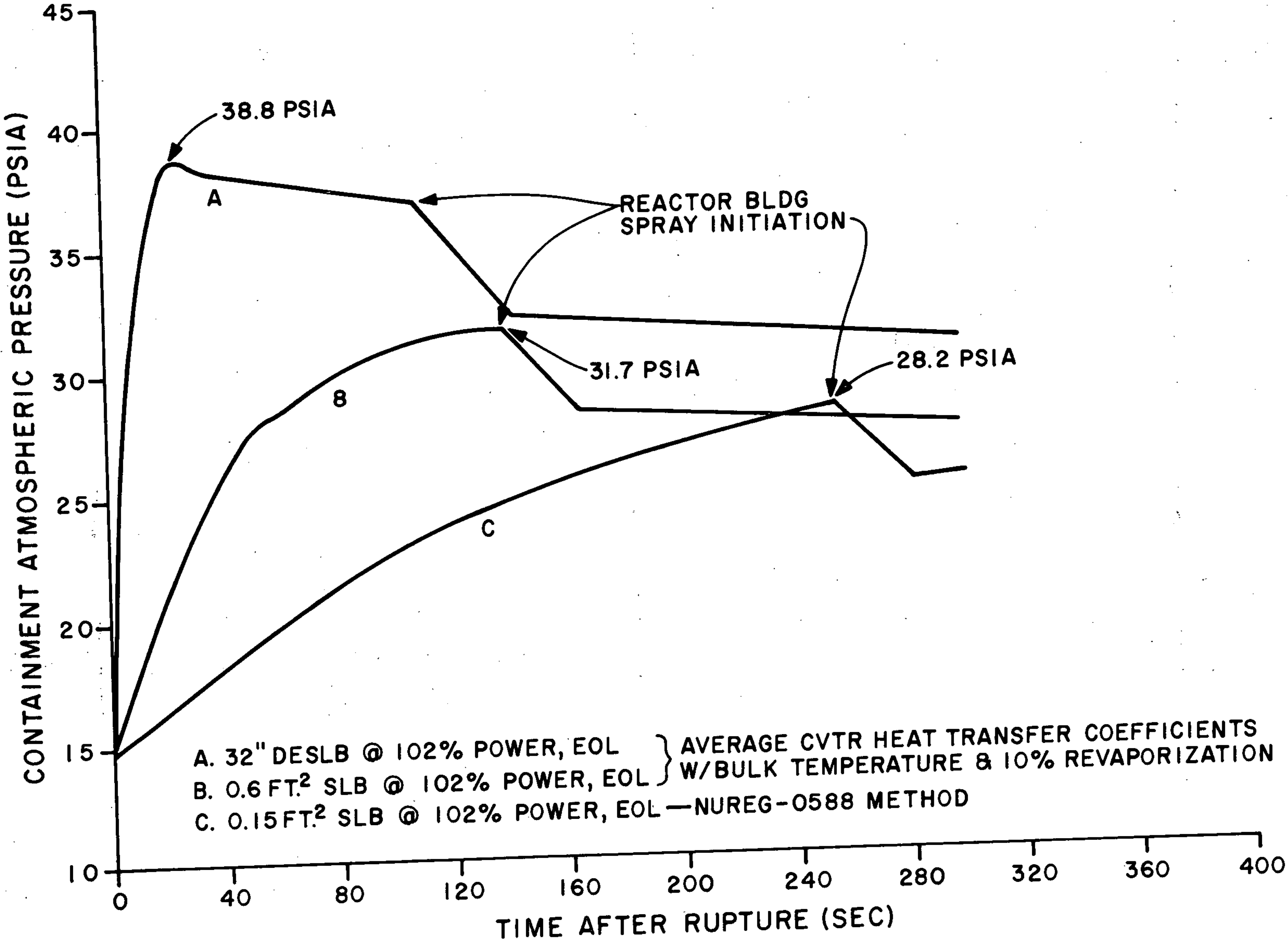


FIG 12

PREDICTED BELLEFONTE CONTAINMENT TEMPERATURE PROFILE 32" DESLB @ 80% POWER, & EOL, W/MSIV FAILURE USING UCHIDA, SATURATION TEMPERATURE & 0% REVAPORIZATION

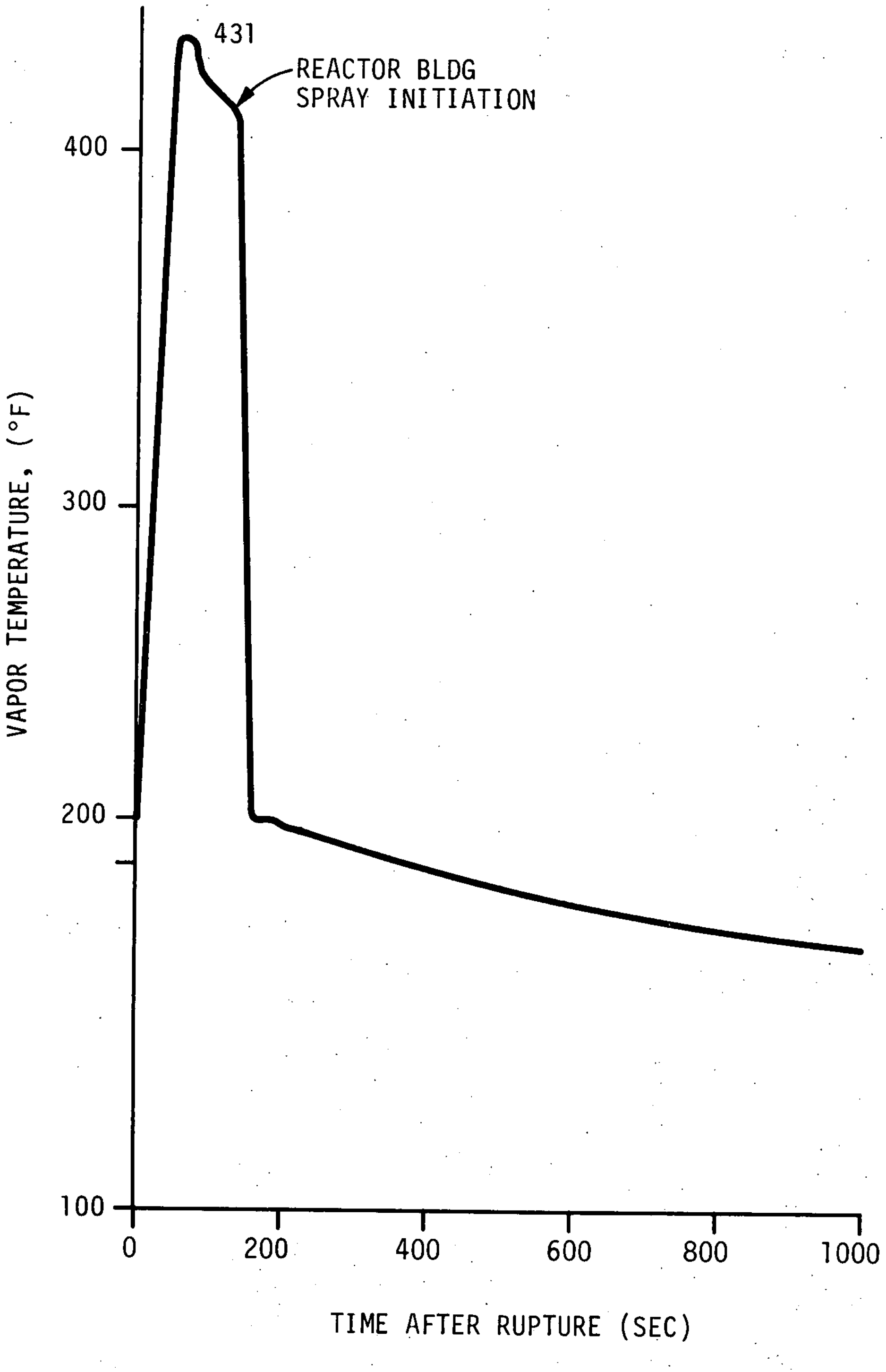


FIG 13