ENCLOSURE 2

METHODOLOGY FOR PREDICTING CONTAINMENT TEMPERATURE FOLLOWING A MAIN STEAM LINE BREAK

NEB

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ABSTRACT

This study evaluates the current methodology utilized to calculate the environmental conditions following a main steam line break (MSLB) inside a large, dry nuclear containment building. A new technique is presented which provides a more realistic, yet still conservative evaluation of the containment temperature for use in equipment qualification programs.

A discussion of the basis for the current methodology is presented along with an analytical comparison of this methodology to actual test data. An analysis of the Carolinas Virginia Tube Reactor (CVTR) test series using this methodology significantly overpredicted the peak containment temperature and is therefore believed to be too conservative for use in conjunction with some portions of environmental qualification programs.

The new technique is based on the use of the bulk atmospheric temperature along with the heat transfer coefficients calculated from the CVTR test data and 10-percent revaporization of condensate. The analytical basis of the new technique is presented and evaluated through comparison to the CVTR data. The new technique provides excellent agreement with the test data in predicting atmospheric temperature and pressure.

The new methodology has been extended for use in calculating the environmental response following a large MSLB in a large, dry containment. Analytical predictions using the new methodology demonstrate a 60°F reduction in peak temperature compared to that predicted by the current methodology. This substantial reduction will greatly enhance TVA's ability to provide electrical equipment environmentally qualified to withstand the effects of an MSLB.

CONTENTS

I. Introduction

Safety evaluations for power reactor operations require an estimate of the containment environmental pressure and temperature response due to postulated loss-of-coolant accidents (LOCAs) and main steam line breaks (MSLBs). Mass and energy release rates determined from independently performed pipe break analyses are inputted to computer codes such as CONTEMPT/LT 26 (ref. 1) to compute the containment response. These computer codes perform a mass and energy balance on the contents of the atmosphere (air and water), sump (pool), and condensate layer taking into account the effects of containment heat sinks (walls, structural steel, etc.) and engineered safety systems (containment sprays, reactor building coolers, etc.).

One type of safety evaluation which utilizes the predicted containment environmental profiles is the environmental qualification of safety-related class 1E electrical equipment (ref. 2). This effort focuses on simulated operation (testing or analysis) at the harshest environmental conditions for which a piece of equipment is required to function. The equipment's operational success rate during such evaluations is dependent upon the harshness of the environmental conditions being simulated. Due to the extremely high peak atmospheric temperatures calculated for an MSLB, environmental qualification of equipment is difficult and many times impossible for equipment currently available. Therefore, although the analytically predicted environmental conditions should be *conservative* to allow for any analytical or experimental uncertainties in order to assure public safety, they should also be as *realistic* as possible to increase the equipment's chances of demonstrating satisfactory performance without excessively conservative overdesign. This study was initiated with the primary objective of providing relief from the currently predicted temperatures for large MSLBs which were believed to be overly conservative.

This report establishes, through direct comparison with actual test data, a methodology for predicting the containment environmental response following an MSLB which utilizes more realistic assumptions than are typically used in such analyses but which are still conservative. In particular, the report examines changes to presently accepted methods of selecting heat transfer coefficients and source temperatures for heat sinks modeled in the presence of superheated atmospheres. The thermal processes of the heat sink condensate layer exposed to such atmospheres will also be examined. The report presents and evaluates an analytical technique based on the use of the bulk atmospheric temperature for heat transfer calculations, heat transfer coefficients derived from experimental data, and 10-percent revaporization of condensate.

Since the proposed methodology was developed specifically for large dry containments, this report does not investigate the interaction of containment engineered safeguards since their actuation normally occurs well after the harshest transient environmental conditions are experienced by the containment. Additionally, no conclusion as to the applicability of this methodology to other type containments is forwarded by this report.

II.A.2 Thermodynamic State Point

The mass and energy balance equation may be integrated with respect to time to obtain the total mass and energy in the containment. The steam specific volume (v_s) and specific internal energy (e_s) can then be determined and the thermodynamic state point fixed from:

$$v_s = \frac{V}{M-M_a} \tag{3}$$

$$e_s = \frac{E-M_a e_a}{M - M_a} \tag{4}$$

where:

M - mass

E - energy

e - specific energy

V - volume

v - specific volume

a, s - subscripts referring to the atmospheric air and steam respectively.
(nonsubscripted quantities refer to total conditions)

This procedure for fixing the atmospheric state point and hence temperature is extremely sensitive to the value of e_s during a superheated atmospheric condition. Examination of the steam tables (ref. 4) shows that for a given pressure the temperature of superheated steam is a very rapidly varying function of specific internal energy whereas the temperature in the saturated/two-phase region does not vary given changes in the specific internal energy. Therefore, relatively small variations in the computation of the steam mass or total energy in the superheated region can produce extremely large changes in the predicted temperature, but will have no effect on temperature in the saturated/two-phase region. Hence, the mass and heat removal associated with condensation upon the passive heat sinks has a much greater effect upon the temperature in a superheated atmosphere than in a saturated atmosphere.

II. Discussion

Computer codes, such as CONTEMPT/LT 26, used to predict the in-containment environmental conditions following a LOCA or MSLB assume the containment atmosphere to be a single homogeneous mixture of air and water (both liquid and vapor). The analytical technique conserves mass and energy inside containment in order to determine the thermodynamic state point of the containment atmosphere. The mass and energy balances are performed for the air and water in the atmosphere while also considering any water which condenses on the heat sinks inside containment. The codes contain a conductive heat transfer subprogram which determines the temperature response for each heat sink. The extent of the interaction of the heat sinks with the containment atmosphere is controlled by user selected convective and/or condensing heat transfer coefficients.

The following discussion (fashioned after that found in ref. 3) describes the mass and energy balance technique, thermodynamic state point determination, the selection of the wall to atmosphere heat transfer coefficient, the selection of the heat transfer source temperature, and the determination of the fraction of condensation.

II.A Analytical Methods

II.A.1 Mass and Energy Balance

Considering the containment atmosphere as a single control volume with a mass addition from the pipe break blowdown and mass removal to the sump due to condensation, one may write equations that describe the mass and energy balance.

The mass balance is:

$$\dot{M}_{in} - \dot{M}_{out} = \frac{dM}{dt} \qquad (1)$$

where:

M - total mass in control volume

$\dot{M}_{in}$ - mass flow rate in (from blowdown)

$\dot{M}_{out}$ - mass flow rate out

t - time

The energy balance may be written as:

$$\dot{M}_{in}\, h_{in} - \dot{M}_{out}\, h_{out} + \dot{Q} = \frac{dE}{dt} \qquad (2)$$

where:

E - total energy

h_{in} - specific enthalpy of entering fluid (from blowdown)

h_{out} - specific enthalpy of fluid exiting (from condensation)

$\dot{Q}$ - rate of energy addition in control volume

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 condensation forming upon the heat sinks.

II.A.3 HEAT TRANSFER

Heat sinks play an important role in the calculations of MSLB containment conditions because they absorb heat from the atmosphere reducing its temperature. The heat transfer is calculated with an equation of the form:

Q = HA T

where: H = an appropriate heat transfer coefficient
A = the exposed surface area of the heat sink
T = the appropriate reference temperature difference

The applicable heat transfer coefficients are determined by the mode of heat transfer, which depends on the surface temperature of the heat structure and containment conditions. Heat transfer coefficients are usually for condensing heat transfer or turbulent natural convection, if condensation does not take place. If condensation does not take place, energy only is simply removed from the atmosphere. The appropriate temperature difference is the drop across the convective boundary layer, which is the bulk-to-wall value. If condensation takes place, a condensation mass must be calculated and removed. Energy will be transferred to the heat structure and an additional amount will leave with the removed mass. The appropriate temperature difference here is not quite as apparent. There are temperature drops across the air/steam boundary layer and across the condensate layer. Traditionally, the saturation-to-wall difference has been used for condensing coefficients, but these have been for pure steam condensation where the condensate layer showed the principal temperature drop which was the saturation-to-wall value (reference 5). If noncondensables are present in a significant amount, the temperature drop across the condensate layer may be negligible and the appropriate reference temperature difference should be that across the boundary layer, which may be asusemd to be the bulk-to-wall value (reference 5).

Confusing the issue is the fact that the two most often used correlations, Tagami and Uchida, were developed from experiments with saturated atmospheres. In such cases, the bulk and saturation temperatures are equal. These correlations have been used for superheated atmospheres using the saturation-to-wall temperature difference (referenc 1). It has been suggested that the bulk-to-wall differences would be appropriate for the Tagami and Uchida correlations (reference 3).

II.A.4 CONDENSATION MASS TRANSFER

The condensate mass associated with the heat transfer must also be calculated and removed from the atmosphere region. Direct measurements of this type have not been made, but a theoretical approach should be based on an analysis of the sources of energy absorbed by the heat transfer.

The thermal energy absorbed by the heat structure can be divided into two components: first, the sensible heat absorbed from mass which stays in the atmosphere ($Q_{atmosphere}$); second is 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 conditon 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 could be determined, the condensate mass could be calculated by:

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

where: $M_{condensate}$ = the condensate mass removal
h_{bulk} = enthalpy of steam at bulk conditions
h_{film} = average enthalpy in the condensate layer

The heat lost by the condensate is modeled as a specified fraction of the total heat transfer. The literature calls this fraction the condensation fraction, and it is related to the revaporization rate of reference 2 by:

$$f = (1 - R)$$

where: f = the condensation fraction
R = revaporization rate

The fraction would be determined by comparison calculations with experimental data such as the temperature and pressure profiles found in the CVTR experiments (reference 7).

II.A.5 Applicability of the Current Methodology

The method recommended by NUREG-0588 was originally developed from methods for loss of coolant accident (LOCA) analysis. The LOCA analysis uses a heat transfer coefficient based on the saturation-to-wall temperature differences and no revaporization. The only significant change for MSLB analysis was the incorporation of revaporization. The resulting method still retains features of the LOCA analysis technique which are overly conservative when applied to large main steam line breaks (MSLBs) because the nature of this blowdown is different. A LOCA blowdown is saturated liquid which flashes to a mixture of liquid and steam. The resulting containment conditions is a mixture of saturated steam, liquid water, and air. The MSLB blowdown is superheated steam or saturated steam which would expand to superheated conditions, and the resulting containment condition is a mixture of superheated steam and air.

Because of this difference, the conservatisms of the NUREG-0588 method are increased when applied to MSLBs. Because the specific enthalpy of the blowdown is much greater, higher atmospheric velocities, and therefore, higher heat transfer coefficients would be expected 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 be more appropriate. This is especially significant since the heat transfer is great enough to drive the heat structure surface temperature close to the saturation temperature, causing the heat transfer rate to decrease to near zero. The saturation temperature is thus caused to be an artificial upper bound on the heat structure surface temperature.

As was discussed in part II.A.2, the atmospheric temperature, which is determined after the mass and heat transfer calculations, is very sensitive to the specific internal energy in the superheated region. It is therefore important that the proper relationship between the heat transfer and condensation mass be established. This is specified in the program by the value of the condensation fraction. This variable should ideally be a function of the existing conditions. In the CONTEMPT and MONSTER codes, the value is a constant which is input by the user. The proper conservative value is determined through benchmarking with available experimental data. The benchmarking must be done with the heat transfer model that will be used in the final analysis. Therefore, the value proposed in NUREG-0588 is not necessarily the proper value to be used with a revised heat transfer model.

The preceding discusison indicates that the NUREG-0588 method is overly conservative when applied to MSLB analysis. This is further established by comparison of test data with predictions as discussed in section II.C.1. A revised method is proposed which uses heat transfer coefficients experienced in a test which is similar to a superheated blowdown, and which are based on the bulk-to-wall temperature difference. The revaporization rate is determined by benchmarking with this same test data. Comparison of test data with predictions of this revised method is discussed in section II.C.4. The extension of the method to the Bellefonte MSLB releases is developed in section II.D.

II.B Experimental Heat Transfer Data

In order to formulate the appropriate heat transfer assumptions for use in containment analyses, a series of tests was performed in the Carolinas Virginia Tube Reactor (CVTR) containment system (reference 7). The CVTR containment is a steel-lined concrete containment which houses a decommissioned nuclear reactor. During each test, superheated steam from a nearby steam plant was injected into the containment through a 10-inch diameter pipe connected to a 42-inch diffuser. All of the mechanical equipment associated with the reactor operation (steam generator, pressurizer, coolers, cranes, etc.) was still in place and served as a heat sink in addition to the concrete walls, floor, and steel liner. Since a primary objective of the CVTR test was to provide experimental containment heat transfer data, the test instrumentation included measurements of pressure, temperature, steam condensation rates, wall internal temperatures, and convective wind velocity.

The CVTR containment has a free volume of 227,000 ft^3. Its ratio of free volume to heat sink surface area is 6.115 ft^3/ft^2. The volume of steel in the heat sink per free volume is 5.1 E-3 ft^3 of steel per ft^3 of free volume. The ratio of the mass and energy addition rates per free volume are 4.8 E-4 $lbm/sec/ft^3$ and .58 $Btu/sec/ft^3$, respectively.

During the CVTR tests, the pressure measurements indicated a nearly uniform pressure throughout the containment; however, the temperature measurements indicated a superheated environment with a large vertical temperature gradient. In the upper region of the containment, which was where the steam was introduced into the containment atmosphere, the temperature was approximately 100°F higher than in the lower regions of the containment. This variation was due in part to poor mixing of the steam and air caused by the diffuser and the buoyancy of the hotter steam. Variations in other measurements such as condensation rates and wall internal temperature profiles corresponded approximately to the measured atmospheric vertical temperature gradient.

The temperature gradient in the concrete wall was measured with thermocouple instrumented heat plugs at both the approximate elevation of the steam injection point and at a second point about twenty feet lower. The data was analyzed by an inverse heat conduction code, TAEH (reference 7), specially developed for this test series. The code solves the inverse problem of heat conduction or the calculation of unknown surface conditions from known internal and bulk atmospheric temperature behavior; which, in this case were both experimentally determined. The code calculates surface heat fluxes, temperatures, and effective heat transfer coefficients. Differences were noted in the TAEH-generated heat transfer coefficients for the two locations; which was possibly due to the geometric surroundings of the second point. The second measurement point was located approximately 4 feet above a floor which extended across a portion of the containment diameter. Due to the presence of the floor, the second measurement point could have been partially shielded from the bulk atmosphere by eddy currents existing in the corner between the floor and wall, and thus, experienced an extremely conservative (i.e., low) rate of heat transfer as compared to the major portion of the containment heat sinks. In order to ensure overall conservatism, an average of the heat transfer coefficients calculated for the two locations was presented.

During the test, an ultrasonic anemometer measured maximum convective wind currents of 30 ft/sec in the vicinity of the upper heat plugs which experienced the high heat transfer rate. This velocity is felt to be very important considering that the diffused steam injection did not contribute substantially to the creation of air currents beyond that induced by natural convection buoyancy. In an actual MSLB, the steam exiting from the broken pipe would be expected to form a jet. Momentum transfer from the jet would create even higher levels of turbulence than that experienced in the CVTR tests, would virtually eliminate any boundary layers and increase the fraction of condensate revaporization compared to that of CVTR.

II.C.1 COMPARISON OF CVTR TEST DATA TO THE NRC-RECOMMENDED METHODOLOGY

NUREG-0588 is the NRC Interim Staff Position on environmental qualification of safety-related electrical equipment. In its section entitled "Establishment of the Qualification Parameters for Design Basis Events," CONTEMPT-LT is stated to be acceptable 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. It is believed that these recommendations were the result of a study conducted by the NRC and summarized in reference 8. The summary document (reference 8) concluded that large main steam line break (MSLB) best estimate analysis should use the Tagami heat transfer correlation during blowdown and the Uchida after blowdown. It also found that a 9.6-percent revaporization produced best estimate results and 7.6-percent produced results that were adequately conservative. Figure 1 shows their results for the two revaporization runs. (The heat transfer correlation used was not specified but the Tagami/Uchida was implied.)

A later study, by Lamkin et al. (reference 3) was performed for the NRC. In this study the use of the Tagami/Uchida correlation was recommended because (1) no other well founded empirical correlation (is) available" and (2) the correlations are conservative. The authors point out, however, that the Tagami/ Uchida correlations are in poor agreement with the CVTR results.

Pointing out the lack of test documentation, they surmise 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 realistic model than simple specification of a revaporization fraction. It required the specification of the mass ratio of steam entering the boundary of a heat structure to condensate deposited on the surface. No rigorous method for determining this value was suggested.

In an effort to assess various methods for calculating post-MSLB containment conditions, TVA used the NRC recommendations and a best estimate model developed from the data in reference 7. For comparison a similar run was made with 0-percent revaporization. The resulting peak temperatures were 318°F (8-percent) and 360°F (0-percent). The results are compared with actual CVTR data in Figure 2, which shows two things: (1) that the NRC methodology over predicts the temperature rise above ambient (80°F) by over 50-percent, and (2) that the specification of the revaporization can have a decided effect on peak temperature. In a final effort to duplicate the results reported in reference 8, the model taken from reference 14 was used with the NRC-recommended methodolgy. (This model was obtained for this purpose, and assurance was provided from C. G. Tinkler that this model was used in reference 8.) The peak temperature of this run (see Figure 3) was 271°F, still substantially above the 236°F reported in reference 7. (It should be noted that the model from reference 14 included an additional steel heat structure not listed in reference 7. This heat structure increased the modeled steel surface area by 117-percent, which is more than the 50-percent uncertainty given in reference 7 for the value of the steel heat sink.)

II.C.2 DISCUSSION OF CONTEMPT/LT AND MONSTER

TVA made various runs with the public version of CONTEMPT (CONTEMPT/LT-26 version 1.02 as maintained by CDC at their Easter Cybernet Center) in which the CVTR measured heat transfer coefficients were input in tabular form. It was found that such tabular heat transfer coefficients are treat as noncondensing (i.e., no matching mass transfer is calculated which is equivalent to 100-percent revaporization. That the specificaton of revaporization in such case has no effect can be seen from in Figure 3 in the curve labelled "CONTEMPT with CVTR HTC & 177-percent H.S.," which was a plot of runs with 0-percent and 100-percent revaporization specified. It was also found that the saturation to wall temperature difference was used with tabular coefficients to calculate heat transfer event though the coefficient is treated as noncondensing.

In order to use the CVTR heat transfer coefficients as a condensing heat transfer coefficient and with the bulk-to-wall temperature difference, TVA used the MONSTER code. MONSTER is a TVA version of CONTEMPT4/MOD2 with various fixes and enhancements. The code produces essentially identical results as CONTEMPT/LT with similar input. This can be seen in Figure 5 where two runs which each code are compared. The runs used the internal Uchida correlations of each code and 0 or 100-percent revaporization. (When graphed the runs appear to be identical but the printed output did show minute differences. Only temperature is shown here but similar behavior occurred in other variables.)

II.C.3 TVA COMPARATIVE RUNS

TVA made a number of runs with CONTEMPT and MONSTER to assess the effects of various heat transfer options. A number of these are shown in Figure 3. As discussed before, even with the 117-percent extra steel surface, the NRC-recommended methodology appears to be overly conservative (that is, predicts extremely high containment temperature). If the extra steel is used in conjunction with CVTR measured heat transfer coefficients, and the saturation-to-wall temperature difference in CONTEMPT, the maximum temperature is underpredicted due to excessive heat transfer and no condensation mass transfer, MONSTER with the same input except using the CVTR coefficient in condensing with 8-percent revaporization underpredicts the maximum temperature by a smaller margin (Figure 3). Here the underprediction is due only to excessive heat transfer to the 117-percent extra steel surface. CONTEMPT with the best estimate model and the CVTR heat transfer coefficients underpredicts the peak temperature because no condensation is allowed Figure 3). This results from a lower atmospheric-specific enthalpy.

The results of four MONSTER runs which used the CVTR heat transfer coefficient in the condensing mode are shown in Figure 6. The saturation-to-wall temperature difference was used in these runs even though this is not considered appropriate. These runs were made for comparison with the runs shown in Figure 7, in which the bulk-to-wall temperature difference was used. No significant difference in the runs were noted except that as expected the former runs predicted a higher peak temperature when the same revaporization was used. The runs showed no evidence that the saturation-to-wall temperature difference could be used to predict the overall temperature profile better than the bulk-to-wall temperature difference.

The runs shown in Figure 7 were made with the methodology which TVA concluded was most appropriate. One of the purposes of the runs was to determine the correct revaporization rate by benchmarking against the CVTR data. The 10-percent revaporization rate is seen to match the CVTR profile best and is slightly conservative in predicting the maximum temperature.

One other feature shown in Figure 7 is noteworthy. It is seen that revaporization rates above about 15-percent produced no significant further reduction in peak temperature. TVA concluded that this was because once the excess water mass reduced the specific internal energy of the atmosphere to the saturation point, further temperature reduction would result only from reducing the saturation temperature (that is, by reducing the pressure). Increasing the amount of retained water mass at the saturation point has little effect on pressure.

II.C.4 EVALUATION OF ALTERNATIVE METHODOLOGY

A number of studies have been published on the heat transfer process during loss of coolant accidents (LOCA) on main steam line breaks which is characterized by the presence of noncondensable and high turbulence. Many of these (references 4, 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 heat transfer correlations, and different condensation mass calculations. Most of these studies (reference 2, 10, 11, 12, 16, and 17) and other published reports (reference 5 and 15) suggest that the proper reference temperature difference is the bulk-to-wall difference. Even when the satuation-to-wall difference is used, effects due to superheating may be considered (reference 15). 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 usually used are the Tagami and/or Uchida correlations. It is unclear from the literature 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 Tagmai 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).

For the above reasons, it was concluded that the best heat transfer correlation available is the time dependent correlation calculated from the CVTR data (reference 7). This correlation is 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. This is the range of the minimum Uchida coefficients which are for air/steam mass ratios of 50 or greater.

II.D Extension of New Methodology to Full-Scale MSLB

II.D.1 Comparison of CVTR Test to a Full Scale MSLB

In order to demonstrate the use of this new methodology, a comparison of the CVTR containment and test to an MSLB in a full-scale large dry containment will be made using TVA's Bellefonte Nuclear Plant (BLN) as representative of a full-scale plant. BLN has a steel-lined concrete containment housing a Babcock and Wilcox (B&W) 205 Fuel Assembly (FA) Nuclear Steam Supply System (NSSS) with its associated once-through steam generators (OTSG). An MSLB at BLN would release a *jet* of highly superheated steam into the containment atmosphere thereby creating a high level of atmospheric superheat and turbulence. The high turbulence from the jet enhances the heat transfer process compared to the diffuse injection in the CVTR test. Unlike CVTR, the OTSG and pressurizer cannot act as heat sinks during plant operation due to their elevated temperature; however, all other components such as cranes, walls, and structural steel are capable of absorbing heat.

The BLN containment has a free volume of 3,400,000 ft^3 as opposed to 227,000 ft^3 for CVTR. BLN has a free volume to heat sink surface area ratio of 7.53 ft^3/ft^2 while CVTR has a ratio of 6.115 ft^3/ft^2. The volume of steel in the heat sinks per free volume is 2. E-3 ft^3 of steel per ft^3 of free volume for BLN as opposed to 5.1 E-3 for CVTR. The ratio of the mass and energy addition rates per free volume for a small (.6 ft^2) MSLB for BLN are 4.8 E-4 $lbm/sec/ft^3$ and .59 $Btu/sec/ft^3$, respectively, compared to 4.8 E-4 and .58 , respectively, for CVTR.

Comparison of CVTR's characteristics with those of BLN shows that the CVTR containment represents approximately a 1/10-scale model of an average full- scale dry containment. The heat sink surface area ratios are very close; however, CVTR has twice the volume of steel in its heat sinks per free volume of containment. This is primarily due to the inclusion of CVTR's steam generator and pressurizer in the heat sinks. The CVTR steam generator and pressurizer were located in the lower portion of the containment. The temperature map of the test shows that very little steam reached the lower portion of containment and thus these components were inactive heat sinks. CVTR's mass and energy release rates per free volume are comparable to a small MSLB at BLN. A large double-ended MSLB at BLN would release steam at a much faster rate (38.3 E-4 $lbm/sec/ft^3$ and 4.68 $Btu/sec/ft^3$) thereby creating a hotter, more turbulent atmosphere. An MSLB at BLN would release the steam near the bottom of the containment as opposed to near the top in the CVTR test. Consequently, the steam's buoyancy would not tend to prevent the steam from interacting with a portion of the heat sinks at BLN. Therefore, any heat transfer assumptions (i.e., heat transfer coefficient, temperature difference, etc.) based on a comparison of CVTR to a small MSLB at BLN will be conservative when used to predict the results of a large MSLB at BLN since a higher heat transfer rate will exist during the large MSLB than that predicted based on CVTR data.

II.D.2 SCALING OF THE CVTR HEAT TRANSFER COEFFICIENTS

In order to use the CVTR heat transfer correlation, a method for scaling must be developed. Because the high heat transfer coefficients are believed to be primarily due to turbulence, it was considered appropriate to scale on turbulence. 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 relates the peak coefficient to the volumetric release rate which is used as a measure of turbulence. Higher volumetric release rates produce higher levels of turbulence and thus higher heat transfer coefficients.

For the scaling method developed here, the assumption was made that the level of turbulence is a function of the integrated volumetric energy release. Further it is assumed that te CVTR heat transfer coefficient is a function of this variable. Therefore:

$$H_{mslb}\,(t_{mslb}) = H_{cvtr}\,(t_{cvtr})$$

if:

$$\frac{\int^{t_{mslb}} hm\,dt}{V_{mslb}} \qquad \frac{\int^{t_{cvtr}} hm\,dt}{V_{cvtr}}$$

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

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 value of 4 Btu/hr ft^2 ^{o}F at the end of blowdown. This value is similar to the Uchida value 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 are made that also add to the conservatism of the scaling. First, the specific enthalpy, the release are assumd to be constant and equal. The specific enthlapy 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 average release rate. The release rate was actually controlled at a relatively constant rate. 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 so that this assumption delays the calculated rise in turbulence and thus the rise in the heat transfer coefficient.

These assumptions lead to the relation between the MSLB heat transfer coefficient which is described by:

$$H_{mslb}(t) = H_{cvtr}(S\ t)$$

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

$$\frac{\int^{t_{Mmslb}} V_{mslb}\, dt}{M_{cvtr}\ t'}$$

where: t' = elapse time when Mmslb is less than Mcvtr
M = the average mass release rate

Besides the conservatism in the scaling process, the use of the CVTR data for large MSLB calculations is considered inherently conservative. The introductin 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 capped on one end and welded to the steam line at the other. This system would be expected to produce much less turbulence than a double-ended line break which would be expected to discharge most of its mass in one or two steams. 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 Predicted Results for a Full-Scale MSLB Using the New Methodology

The resultant temperature and pressure profiles for a few of the postulated break sizes at BLN are shown in figures 12 and 13. As can be seen, the temperature and pressure rise quickly for large breaks, followed by a rapid drop due to the reduction in blowdown. The transient is essentially terminated at approximately 110 to 150 seconds by the actuation of containment sprays since the blowdown stops shortly thereafter. For very small breaks (0.15 ft^3), the temperature and pressure rise more slowly. The sprays reduce the temperature sharply; however, the temperature begins to rise again slowly due to blowdown continuation.

Figure 14 shows the temperature profile using the current methodology for the break which previously produced the highest peak temperature prediction. Comparison of figures 12 and 14 shows that the new methodology produces a 60°F reduction in peak-predicted containment atmospheric temperature.

III Conclusions

The current methodology used to calculate the environmental conditions following a main steam line break in a large, dry containment has been evaluated and shown to be overly conservative. Using an overly conservative temperature profile in environmental qualification work is costly due to the artificially-induced need for overdesigned equipment. Therefore, a new methodology has been proposed and shown to give a conservative but yet more realistic prediction of the CVTR test data. This methodology has been extended for use in the prediction of a main steam line break in a full-scale containment. The new methodology provides approximately a 60°F relief in the peak temperature at TVA's Bellefonte plant compared to the current methodology. This reduction will result in both a significant cost savings as well as permitting the acquisition of equipment for applications for which no equipment could be found which was qualified to the previous temperature.

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

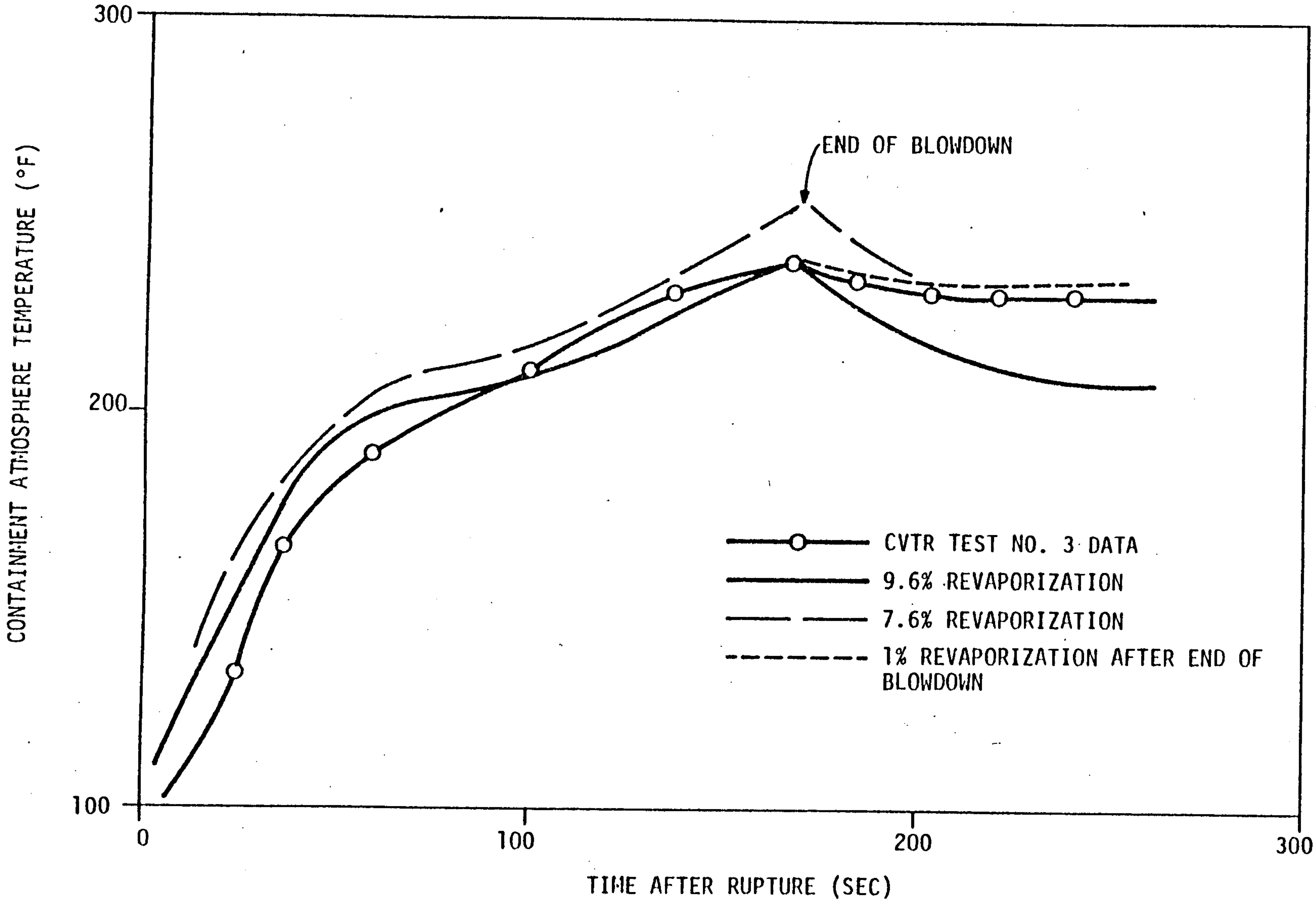


FIG 1

COMPARISON OF ACTUAL CVTR DATA TO CONTEMPT CALCULATIONS USING THE UCHIDA HEAT TRANSFER CORRELATION AND SATURATION TEMPERATURE

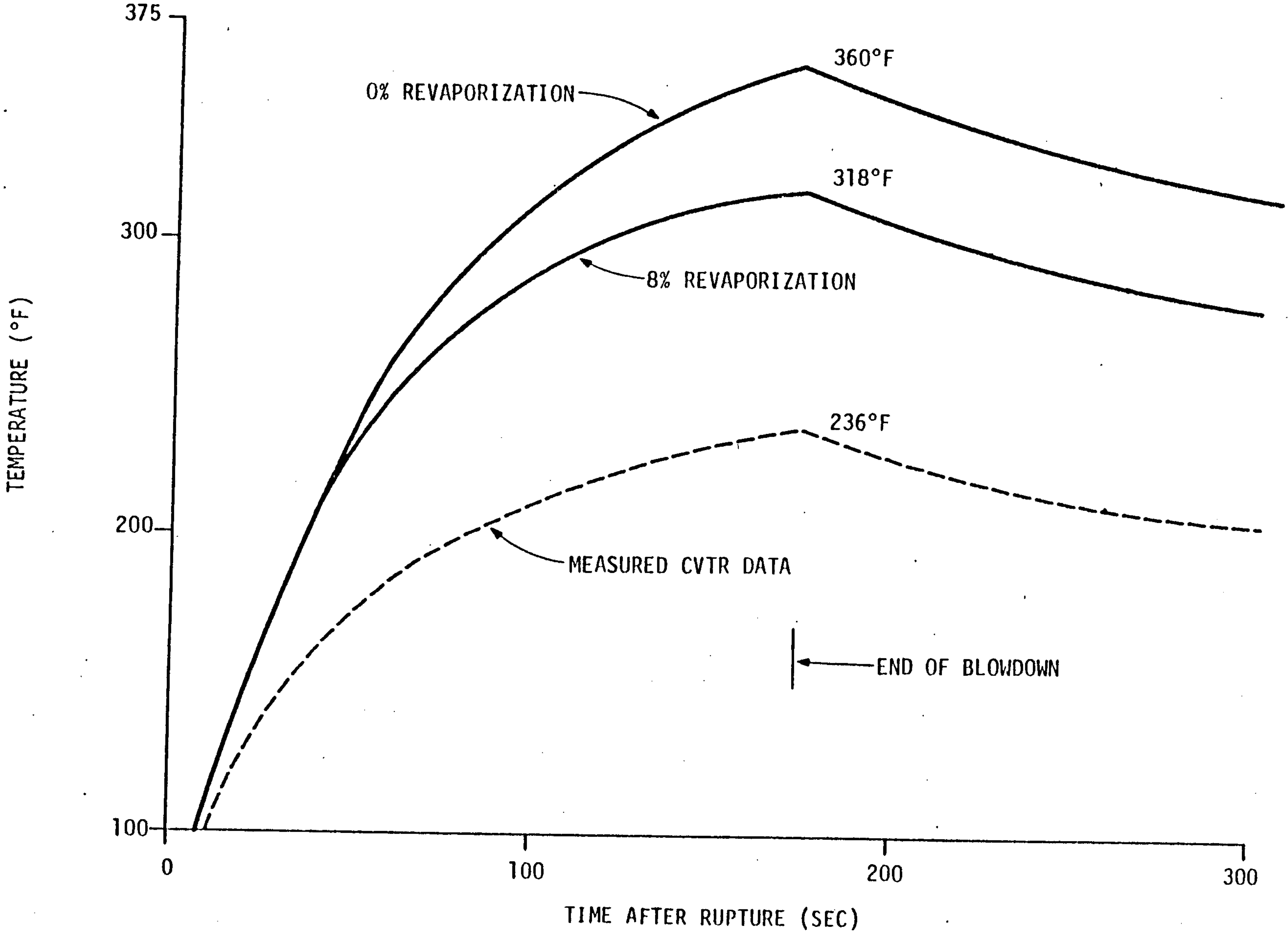


FIG 2

PREDICTED CVTR TEMPERATURE PROFILES USING VARIOUS ANALYSES

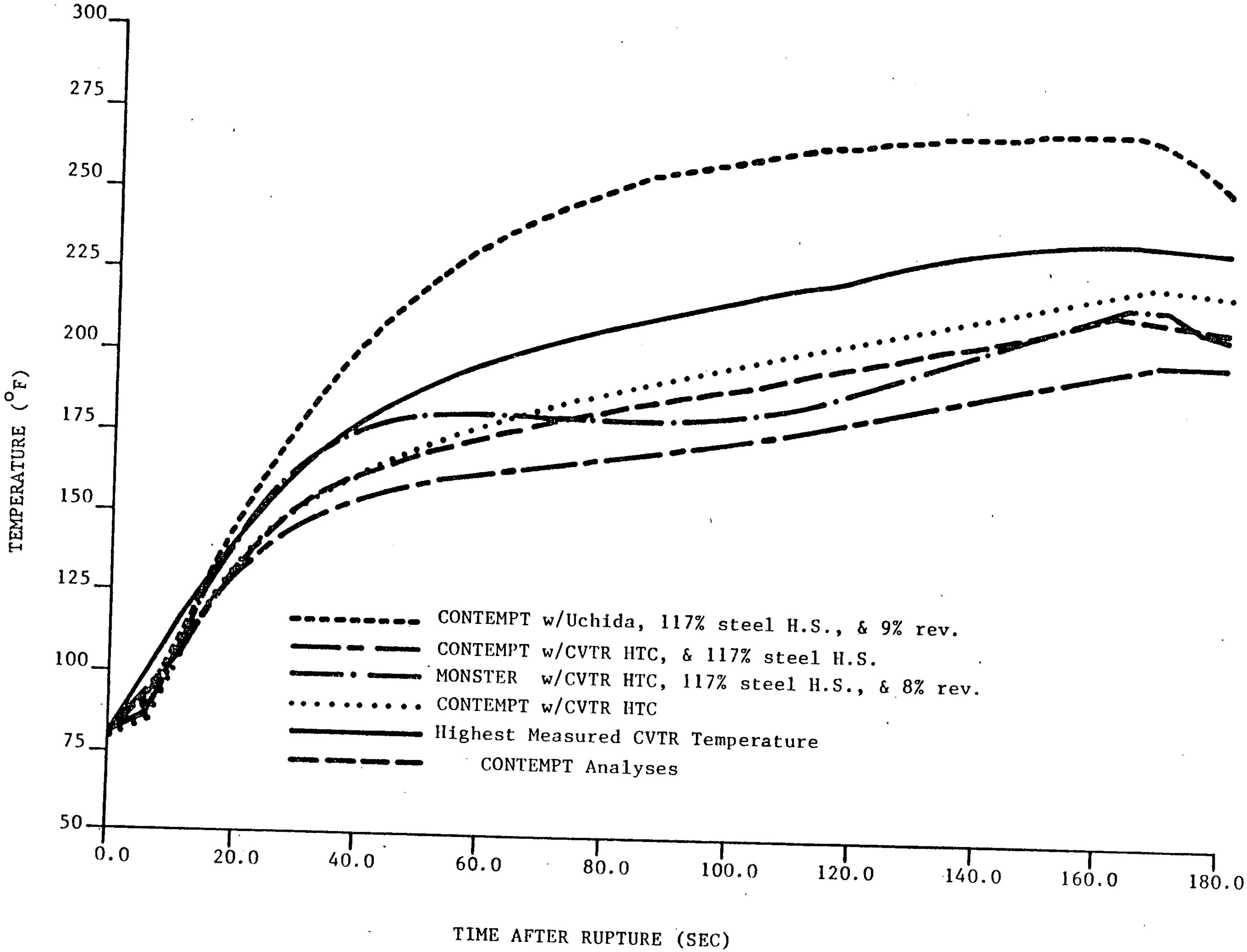


FIG. 3

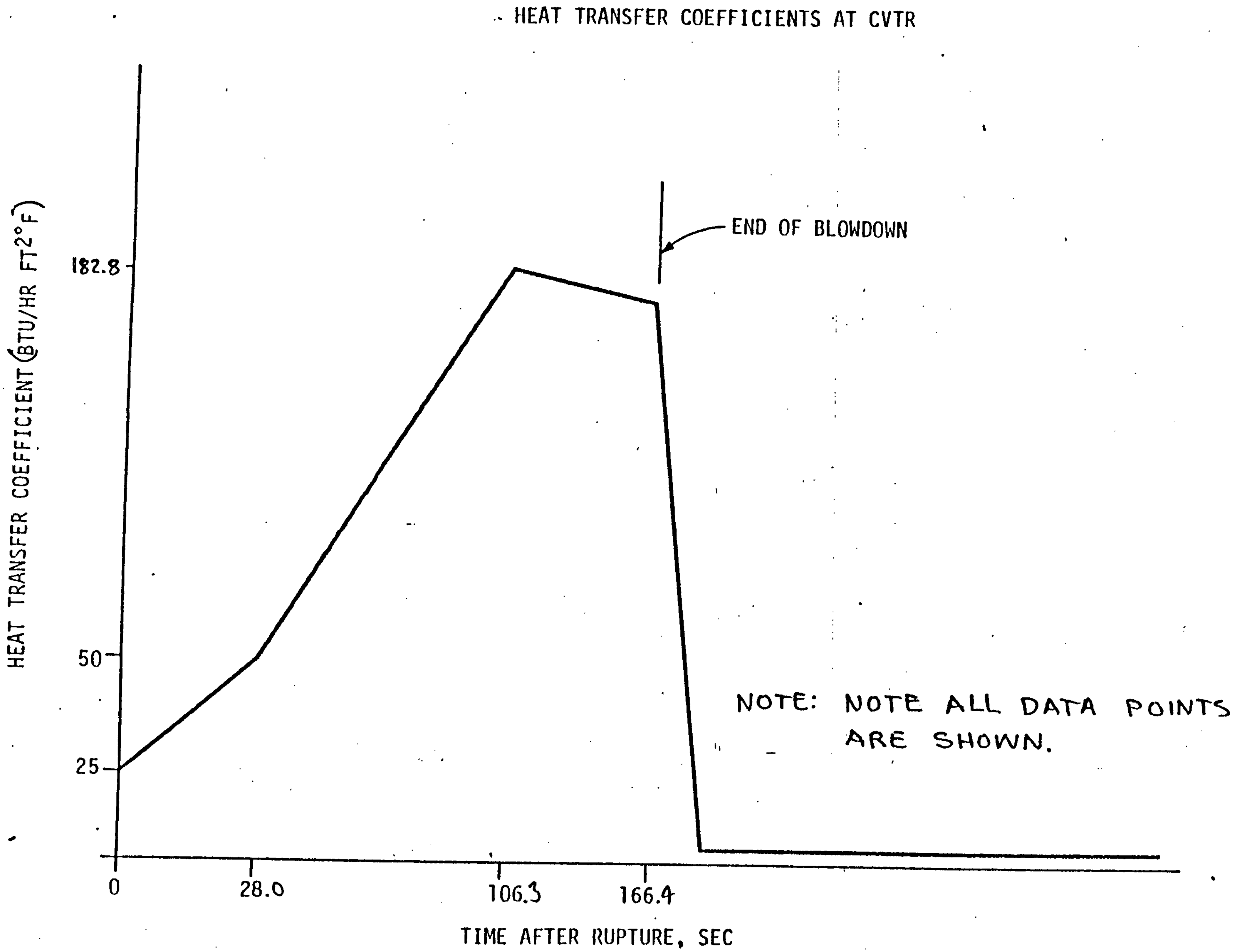

HEAT TRANSFER COEFFICIENTS AT CVTR
HEAT TRANSFER COEFFICIENT (BTU/HR FT2°F)
182.8
50
25
END OF BLOWDOWN
NOTE: NOTE ALL DATA POINTS ARE SHOWN.
0
28.0
106.3
166.4
TIME AFTER RUPTURE, SEC

FIG 4

COMPARISON OF CVTR DATA WITH
CONTEMPT AND MONSTER CALCULATIONS

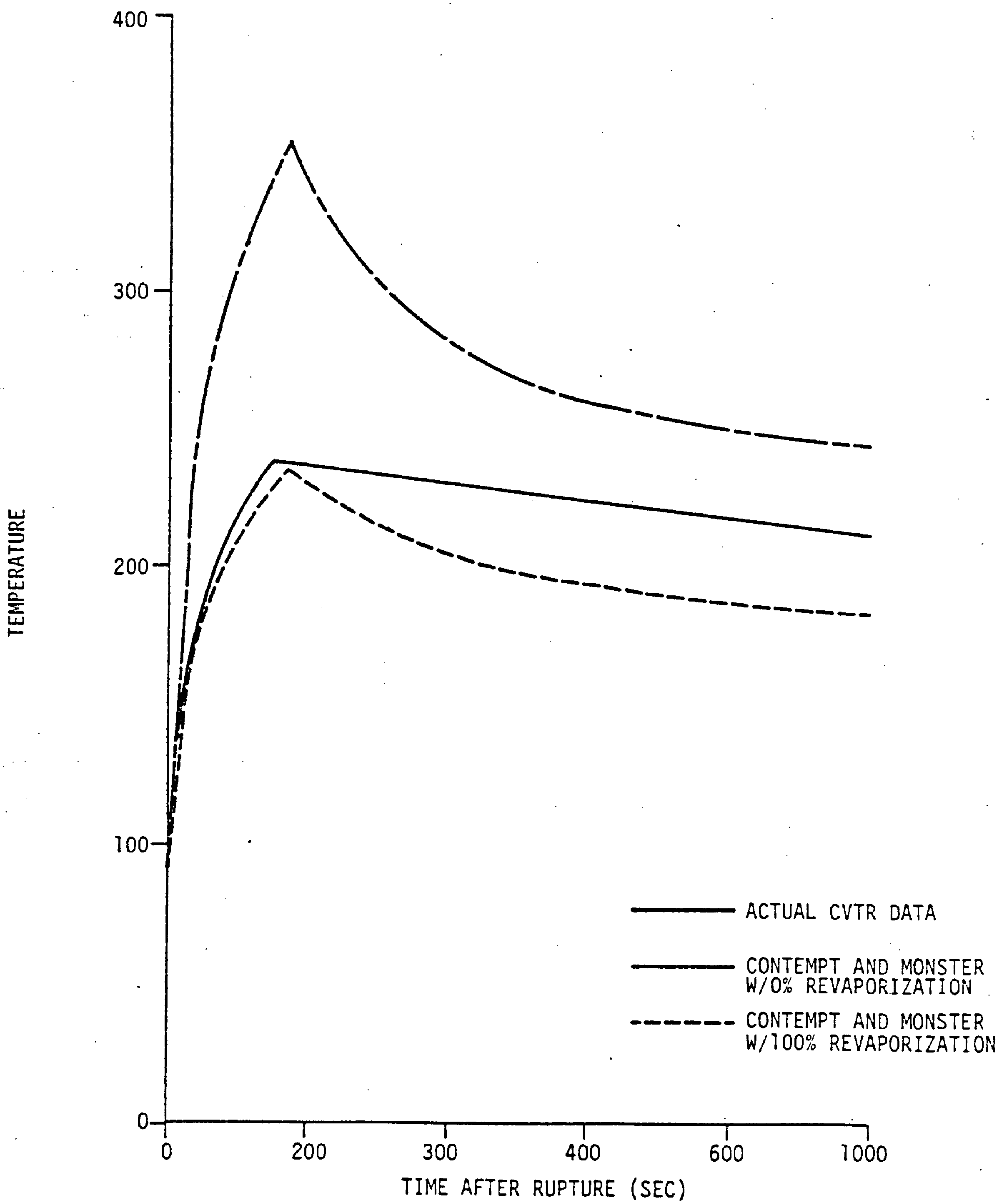


FIG 5

VARIOUS REVAPORIZATION FRACTIONS IN CONJUNCTION WITH TAEH HEAT TRANSFER COEFFICIENT AND T_{SAT}

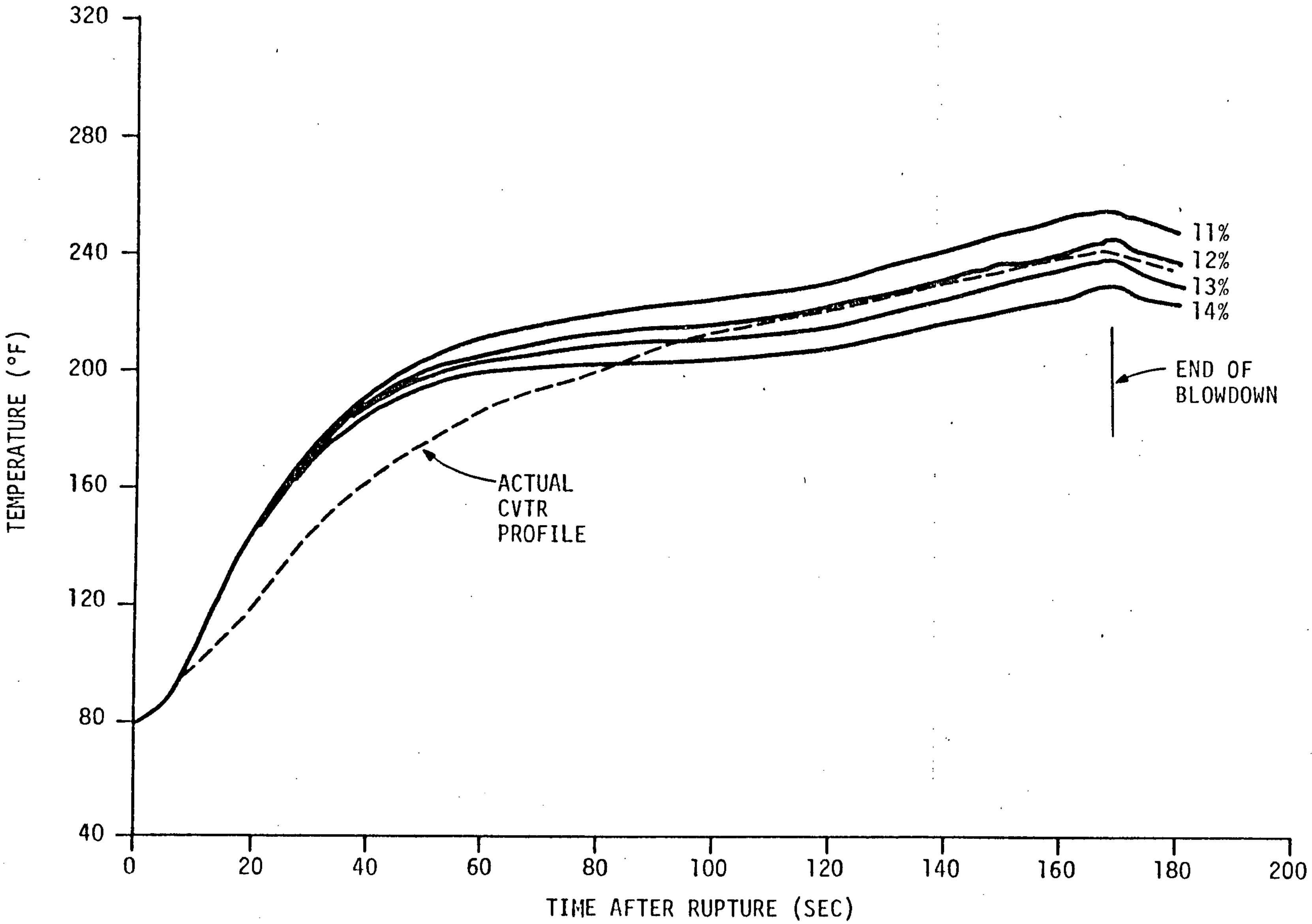
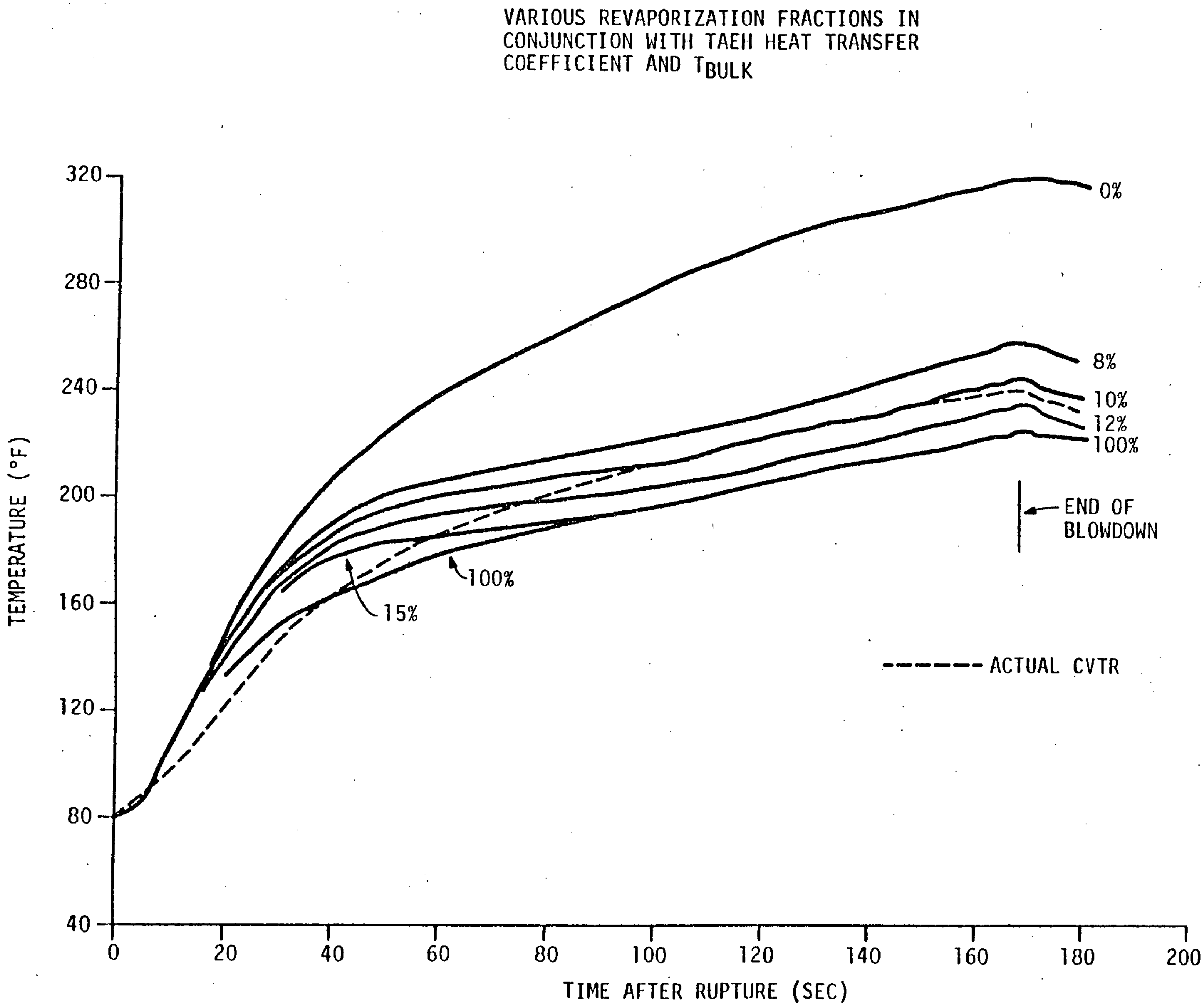


FIG 6



VARIOUS REVAPORIZATION FRACTIONS IN CONJUNCTION WITH TAEH HEAT TRANSFER COEFFICIENT AND T_{BULK}
TEMPERATURE (°F)
320
280
240
200
160
120
80
40
0
20
40
60
80
100
120
140
160
180
200
TIME AFTER RUPTURE (SEC)
0%
8%
10%
12%
100%
100%
15%
END OF BLOWDOWN
ACTUAL CVTR

FIG 7

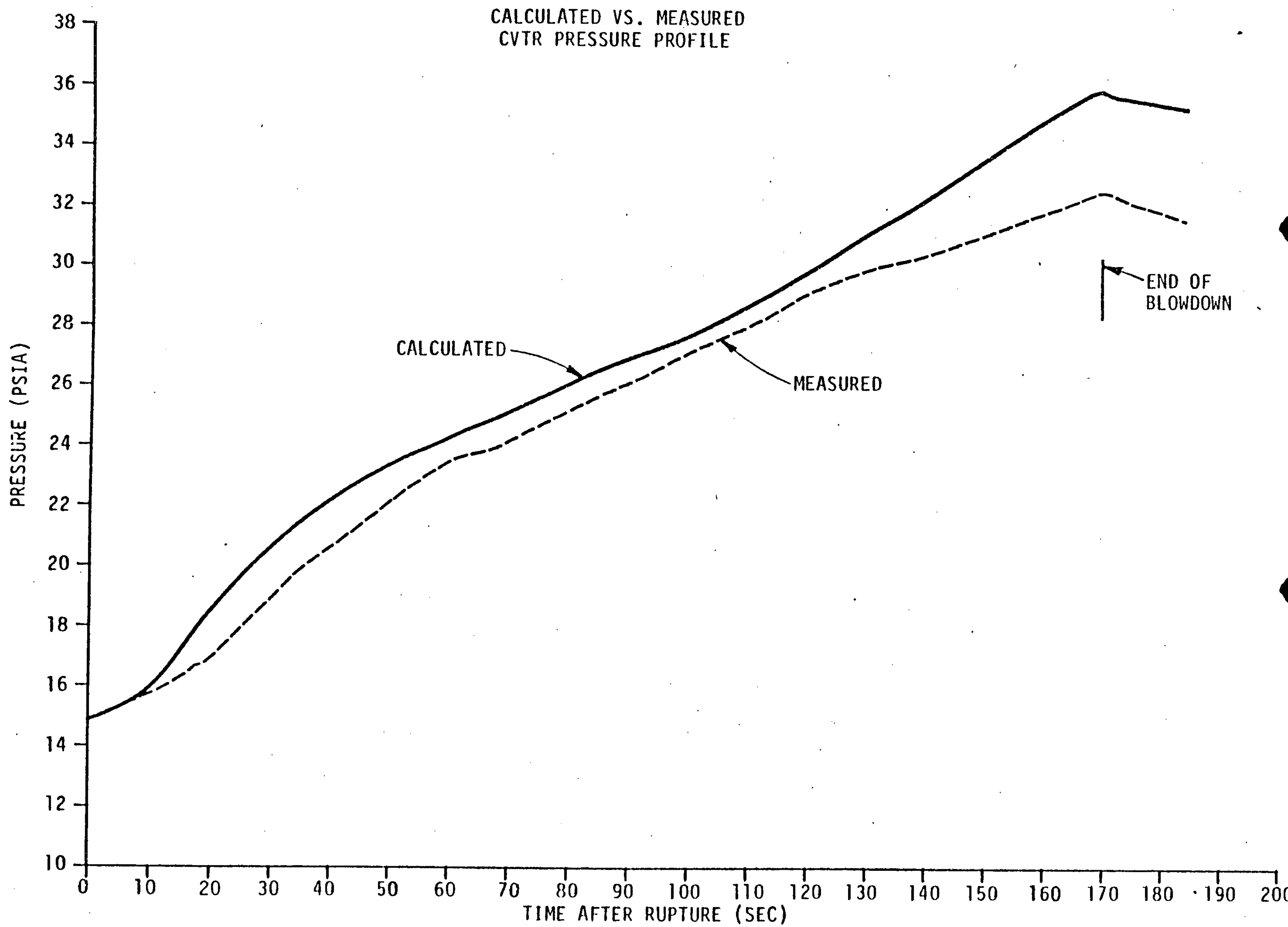

CALCULATED VS. MEASURED
CVTR PRESSURE PROFILE
PRESSURE (PSIA)
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
CALCULATED
MEASURED
END OF
BLOWDOWN
0
10
20
30
40
50
60
70
80
90
100
110
120
130
140
150
160
170
180
190
200
TIME AFTER RUPTURE (SEC)

FIG 8

CALCULATION OF TIME FACTOR (S) FOR SCALING CVTR HEAT TRANSFER COEFFICIENTS

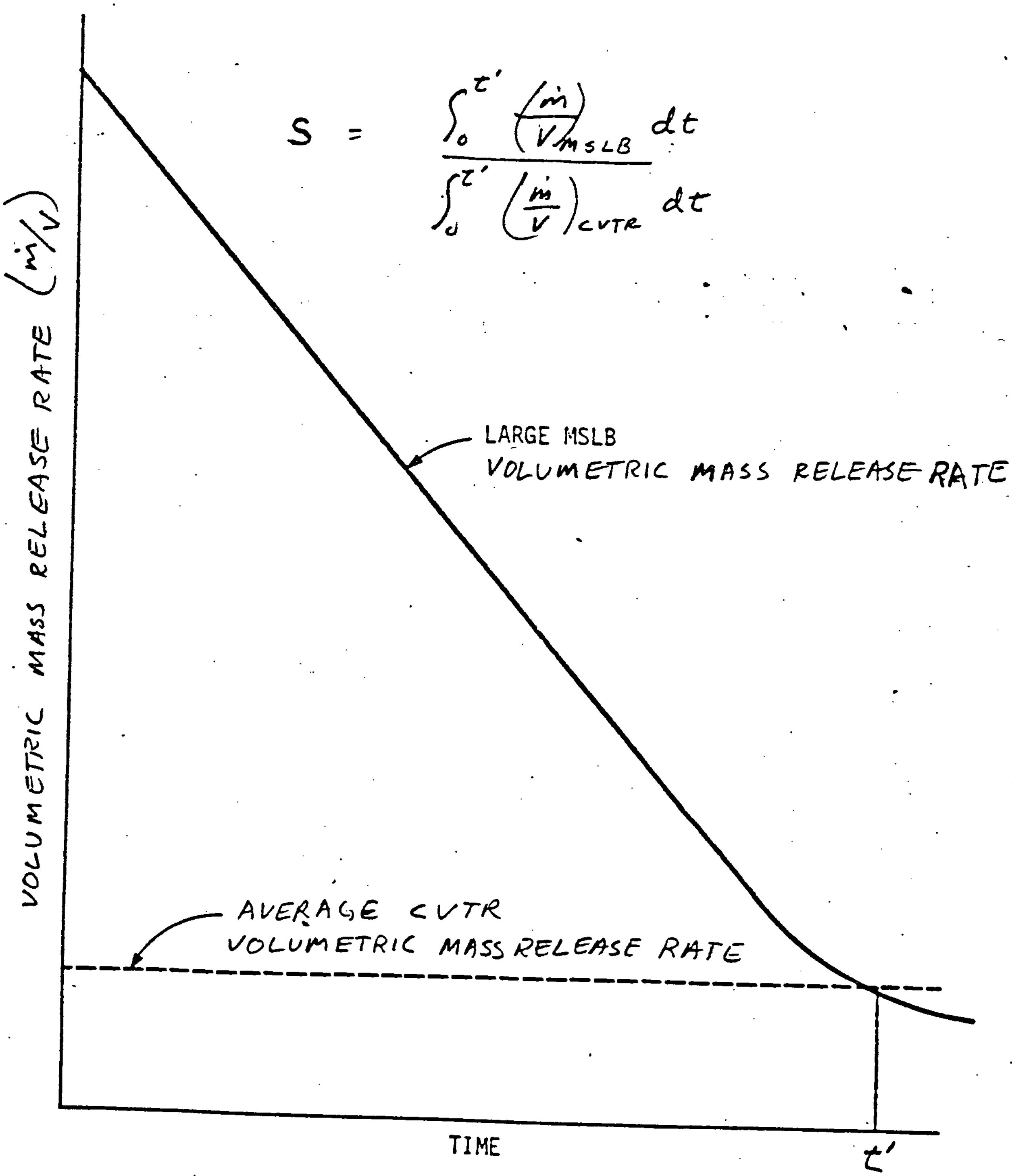


FIG 9

CVTR HEAT TRANSFER COEFFICIENTS
SCALED FOR BELLEFONTE MSLB

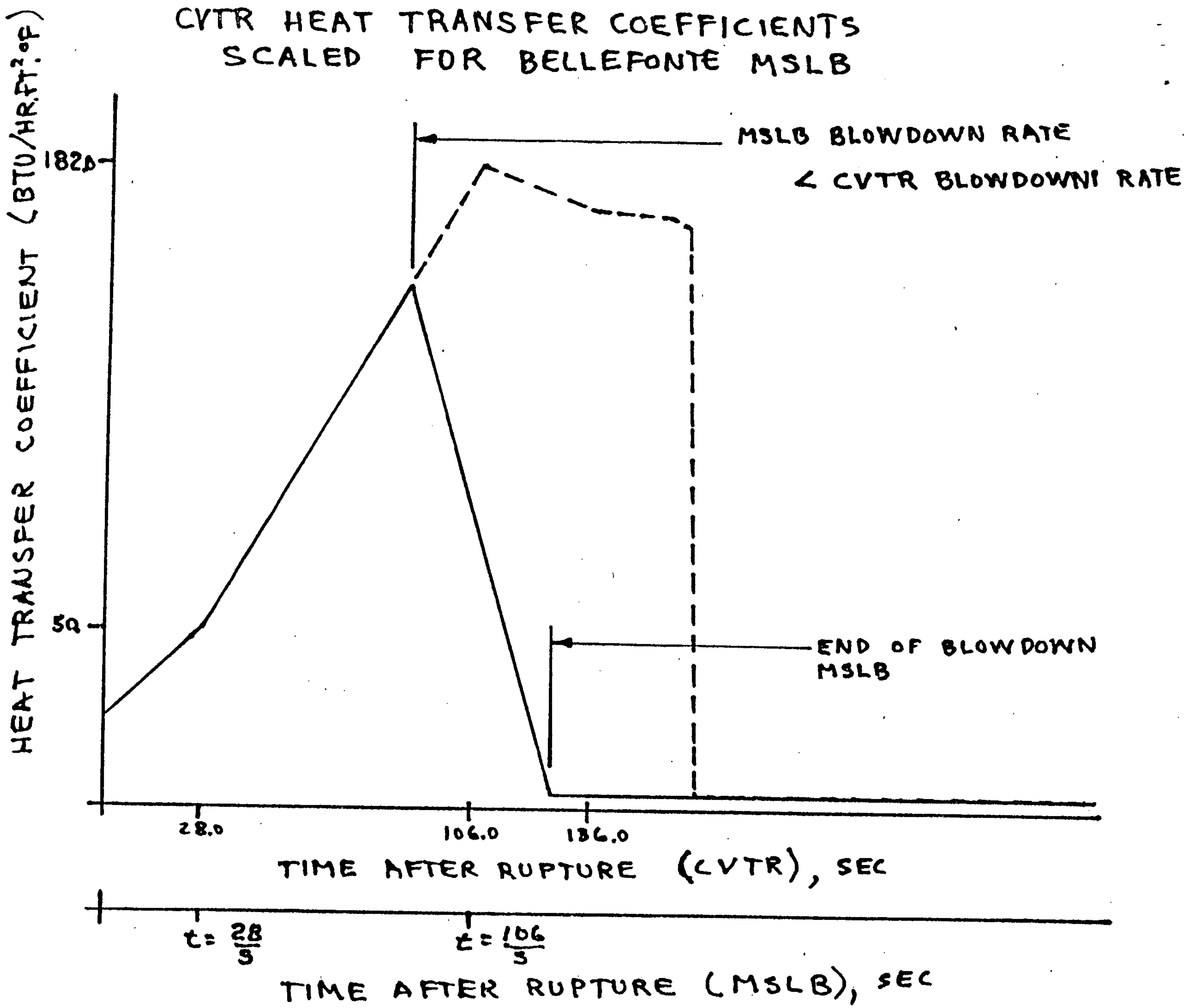


FIG 10

USE OF TAEH HEAT TRANSFER COEFFICIENTS
FOR SMALL STEAM LINE BREAKS

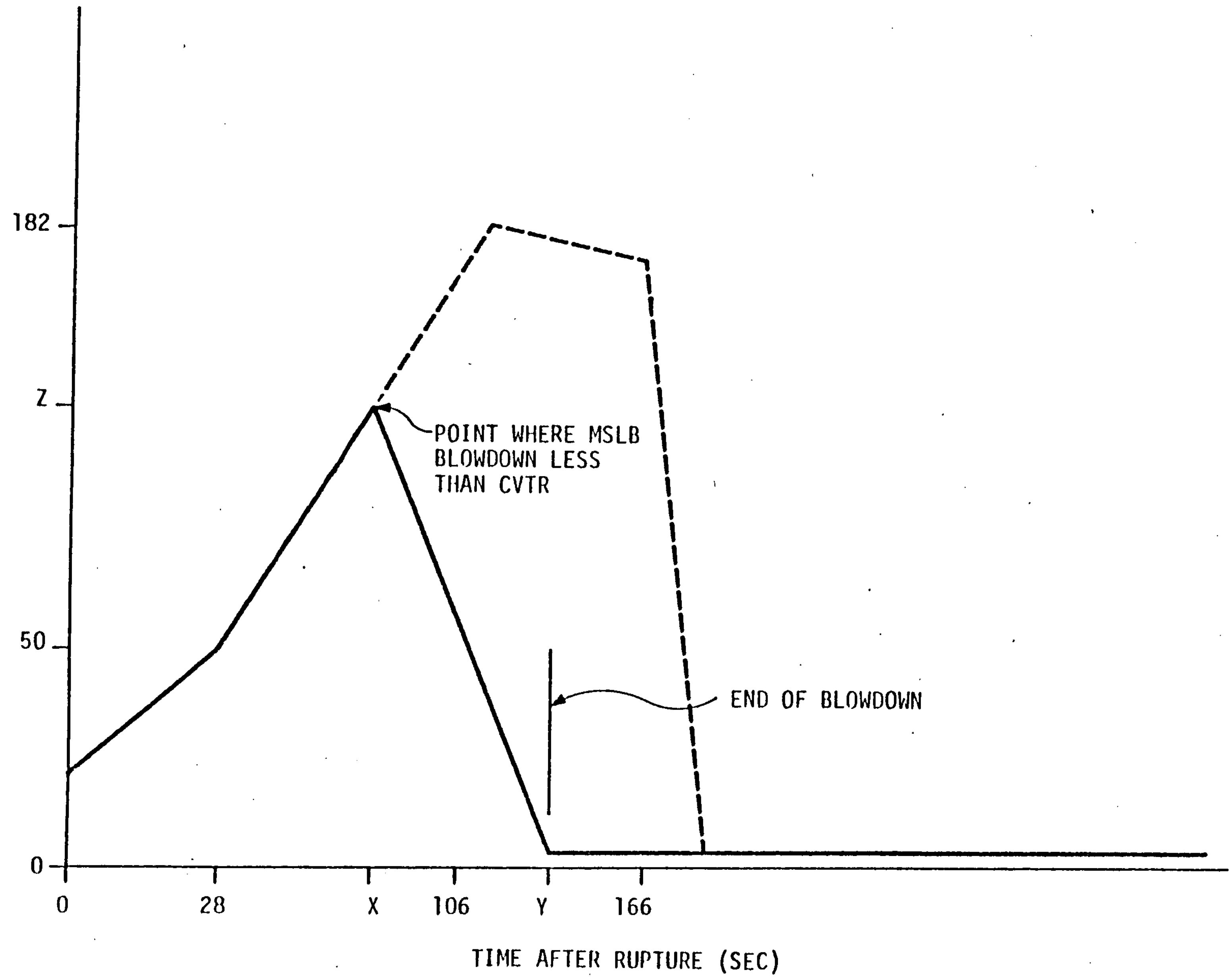


FIG 11

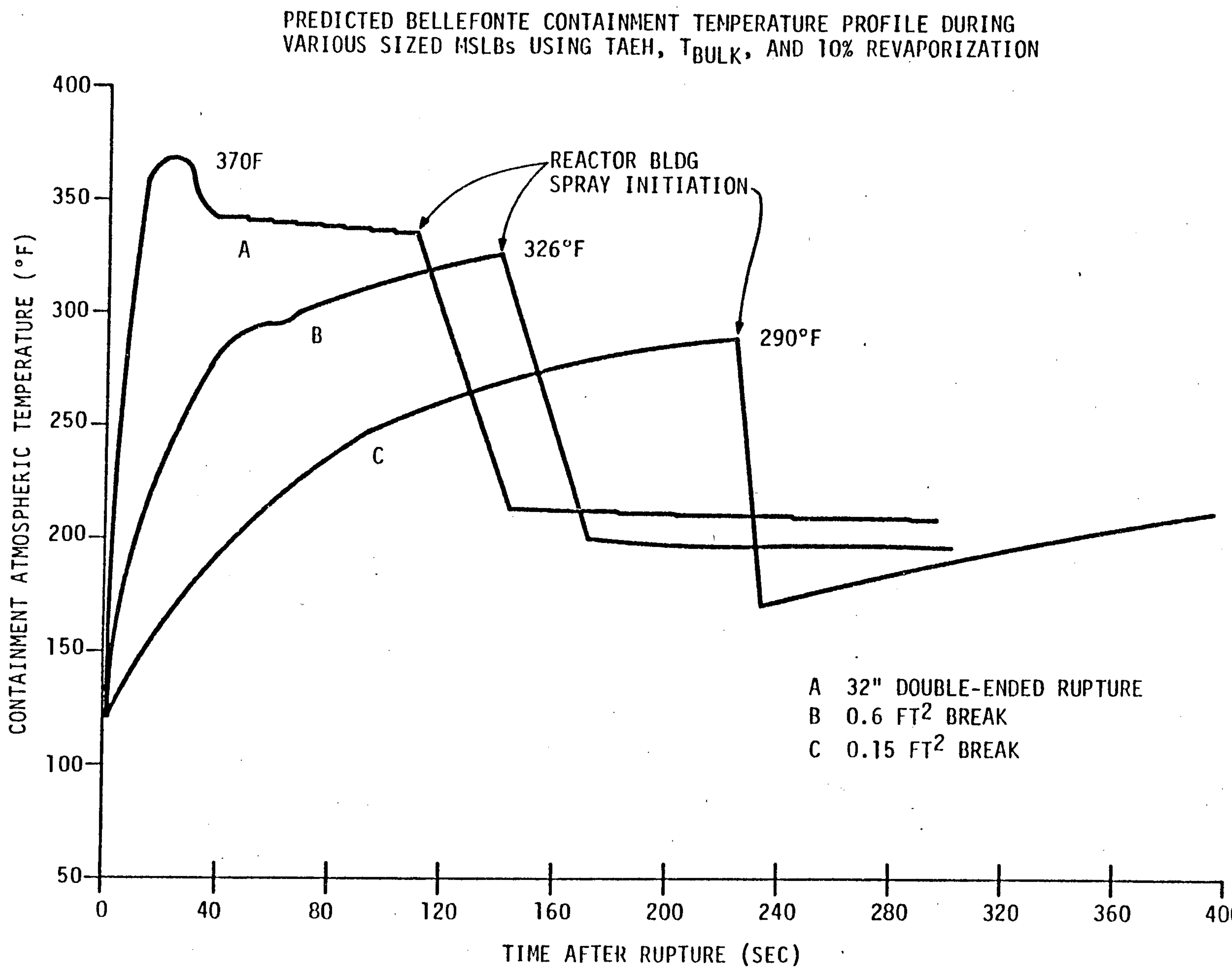

PREDICTED BELLEFONTE CONTAINMENT TEMPERATURE PROFILE DURING
VARIOUS SIZED MSLBs USING TAEH, TBULK, AND 10% REVAPORIZATION
CONTAINMENT ATMOSPHERIC TEMPERATURE (°F)
400
350
300
250
200
150
100
50
370F
REACTOR BLDG
SPRAY INITIATION
326°F
290°F
A
B
C
0
40
80
120
160
200
240
280
320
360
400
TIME AFTER RUPTURE (SEC)
A 32" DOUBLE-ENDED RUPTURE
B 0.6 FT2 BREAK
C 0.15 FT2 BREAK

FIG 12

PREDICTED BELLEFONTE CONTAINMENT PRESSURE PROFILE DURING VARIOUS SIZED MSLBS
USING TAEH, T_{BULK}, AND 10% REVAPORIZATION

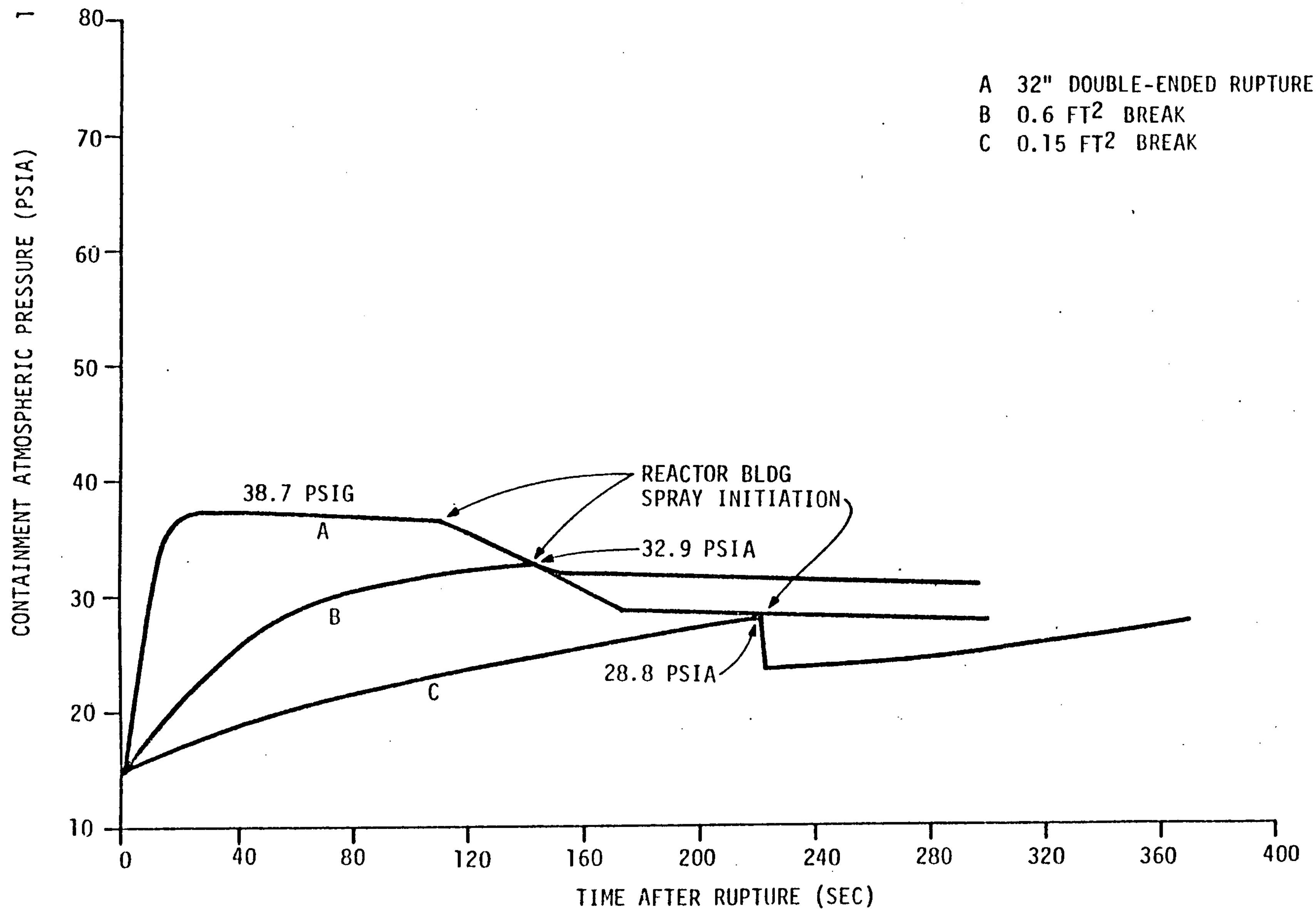


FIG 13

PREDICTED BELLEFONTE CONTAINMENT TEMPERATURE PROFILE DURING VARIOUS SIZED MSLBs USING UCHIDA, TSAT, AND 0% REVAPORIZATION

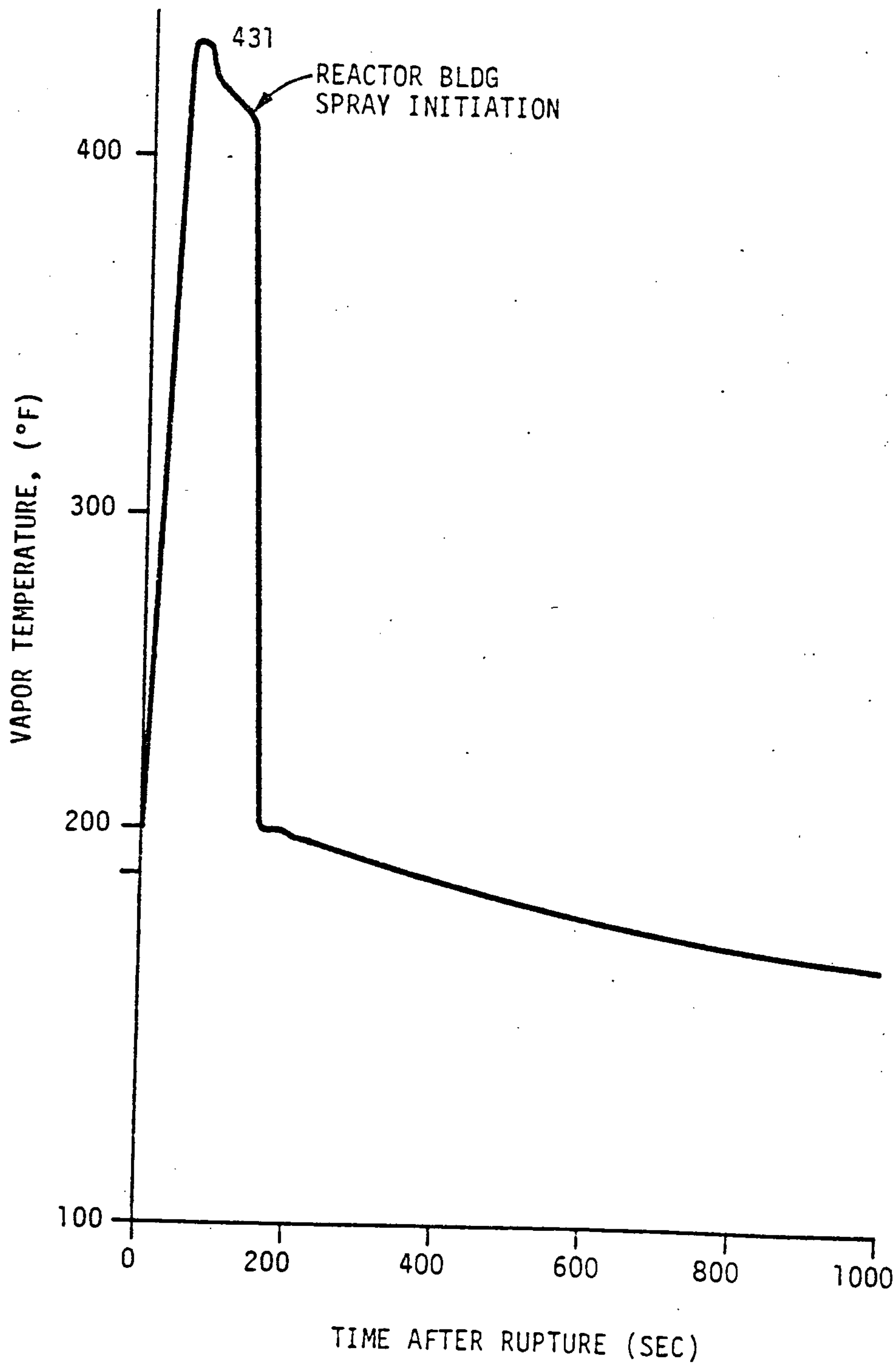


FIG 14