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CORRELATIONS TO PREDICT MAXIMUM PWR CONTAINMENT
PRESSURES FOLLOWING A LOSS-OF-COOLANT ACCIDENT

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I. INTRODUCTION

As the last barrier to the accidental release of radioactive contaminants to the public, the containment buildings of large nuclear generating stations must provide for a reliable separation between the internal volume and the outside environment. This separation is essential particularly in the event of an accidental loss of reactor coolant when extensive fission products are likely in the containment atmosphere. To assess the structural margins and to evaluate the possibilities of a breached barrier under loss-of-coolant conditions requires extensive analyses of the pressure and temperature transients.

Of major importance in the evaluation of the adequacy of the containment buildings is the maximum containment pressure reached during the accident. The prediction of the maximum pressure normally requires a detailed analysis of the depressurization of the primary coolant system and the concomitant pressurization of the containment building. Although such analyses are necessary for a thorough safety analysis, an independent means is desirable for estimating the loads for design studies, licensing reviews, and providing a means for quickly assessing the results of more detailed analyses. In addition, the analyses are necessary for determining the effect of the containment transients on the equipment design, leakage to the environment, and plant operation and recovery. The present analysis employs known selected primary system and containment parameters to produce a method for prediction of the maximum containment pressure as a result of the depressurization of the primary system.

The first work directed toward the estimation of maximum containment pressures was reported by Edwards⁽¹⁾. In his paper, Edwards described a nomograph which, through rather cumbersome iterative techniques, could be used to approximate pressure and temperature transients in dry containments. Edwards assumed complete mixing of the phases and that the thermodynamic state at any time consisted of saturated vapor, liquid, and air in thermal equilibrium. The present analysis differs in that it does not involve iterative techniques, and the assumption of thermal equilibrium between phases is not required. However, the present analysis results only in maximum containment pressures and does not address itself to the overall pressure and temperature transients.

In this paper, dry containments refer to the class of containments which do not employ passive pressure-suppression systems such as pool-suppression or ice-condenser systems. The dry containments, sometimes called volume, vapor, adiabatic, drywell, or pressure containments are often associated with pressurized water reactors; pool type pressure-suppression systems are sometimes called heat capacity containments and normally associated with boiling water reactors^(2,3).

The following section describes the particular mathematical models and assumptions used in this analyses. However, certain implicit assumptions not discussed in the following section arise from the use of the CONTEMP-PS^(4,5)

computer program as the principal analytical tool in the study^(a). These implicit assumptions are that the entire containment volume can be described by two regions: a bottom region containing liquid water, and a single top region containing a mixture of water vapor and air. The contents of each region are assumed to be well mixed and to have a uniform temperature, but the temperatures of the contents of each region may be different. Boiling of the liquid in the bottom region is allowed, but evaporation is not treated. The containment building is represented as consisting of several heat-conducting sections whose thermal behavior can be described by a one-dimensional multiregion transient heat-conduction equation. To calculate the thermodynamic state of the vapor phase, the principal consideration of this analysis, CONTEMPT-PS performs mass and energy balances for the liquid and vapor regions in the containment building as functions of time. Various mass and energy input rate functions are averaged over small time increments and are included in the mass and energy balances. Results of the mass and energy balances from one time interval are used as initial conditions for the next time interval.

The term "maximum pressure" in preceding and succeeding portions of this report is considered to be the maximum pressure as a result of decompression of the primary system. However, in the absence of containment safety systems, this pressure may be exceeded later in the transient due to other mass and energy sources such as reactor decay power or metal-water reactions⁽⁶⁾.

II. ANALYSIS OF CONTAINMENT RESPONSE

The highest predicted pressure in dry containment buildings normally occurs near the end of decompression of the primary system but before containment safety systems become operational. During this period many of the parameters considered in a detailed safety analysis of the containment atmosphere assume secondary importance. Sensitivity studies on those parameters that take a more active role in the containment pressurization lead to trends which can be normalized to form correlations for predicting the required pressure loadings. These concepts are applied in the following paragraph which summarizes the method of analysis. Subsequent paragraphs describe the assumed containment model and the parametric variations considered.

1. METHOD OF ANALYSIS

The CONTEMPT-PS computer program was used to determine the containment pressure transients of a number of hypothetical accidents in an arbitrary containment volume. The pressure results of these calculations were correlated with appropriate input parameters as described in Section III. Adequacy of the correlation is established by comparison of the predicted pressures from the correlation with the pressures obtained from the detailed analyses published in safety analysis reports for large power reactors.

Use of the correlations is not strictly an independent method of containment evaluation because both the correlations and many of the analyses published in safety analysis reports are based on CONTEMPT-PS or one of its derivatives^(b). However, the correlation can be used independently of the CONTEMPT-PS users by licensing review committees and hence possible errors in the detailed analyses can be recognized.

(a) CONTEMPT-PS is an advanced version of the integrated containment codes described in References 4 and 5.

(b) Although the code is almost universally accepted and was recently demonstrated conservative in the case of simulated loss-of-coolant accident tests in the Carolinas Virginia Tube Reactor (CVTR) containment system, a rigorous verification has not been feasible because of lack of test data.

2. DESCRIPTION OF CONTAINMENT MODEL

A simplified containment model was analyzed parametrically to provide the information used to construct the correlations. An arbitrary containment volume without containment safety systems was selected for the study, and various amounts of constant-enthalpy water were released to simulate the blowdown following a loss-of-coolant accident. The water addition rate to the containment was assumed to decrease linearly with time. The general trends of mass flow rate and coolant enthalpy for the assumed model are compared in Figures 1a and 1b with the shapes of typical curves obtained from safety analysis reports for large pressurized water reactors. The simulated blowdown causes a containment pressure and temperature response similar to that predicted for large PWR containments(6). The containment pressure increases rapidly at first and the rate of increase slows as the mass rate decreases near the end of blowdown when heat absorption in the containment structures increases. The containment pressure reaches a maximum near the end of blowdown as shown in Figure 1c; the variations in this maximum are correlated with different assumptions in the succeeding section.

Ten heat-conducting structures (from Reference 6) were included in the containment model to represent the containment building and internals which absorb energy from the air-steam mixture during blowdown. The distribution area among the ten heat-conducting structures was constant as shown in Table I; the total area was varied from 0 (adiabatic) to values representative of those for large PWR's.

Fig. 1 Containment Pressure Response and Comparison of Transient Behavior of Assumed Containment Model with Typical Large PWR Behavior

The coefficients used for condensing-steam heat transfer between the containment atmosphere and the heat-conducting regions were varied linearly from a value of 2 Btu/hr-ft²-°F at the initiation of the accident to a maximum of 105 to 710 Btu/hr-ft²-°F at the end of decompression. The maximum value was computed from the recommended Tagami correlation(8).

In all cases, the following initial conditions were assumed for the containment model:

- initial pressure, 14.7 psia
- initial temperature, 100°F
- initial humidity, 30%
- outside temperature, 100°F

These values are typical of the assumptions used by vendors for containment response calculations and slight deviations from these values would not significantly affect the maximum calculated containment pressures.

TABLE I
PROPORTIONS OF SURFACE AREAS USED IN THE ANALYSIS⁽⁶⁾

Building Surface	Material	Thickness (ft)	Percent of Building Area	Percent of Total Area ^[a]
Containment Dome	Steel Lined Concrete	3.5	27.0	18.0
Upper Walls of Containment	Steel Lined Concrete	4.5	31.1	20.7
Lower Walls of Containment	Steel Lined Concrete	4.5	28.3	18.6
Floor of Containment	Steel Lined Concrete	9.0	13.6	9.6

Miscellaneous Surfaces	Material	Thickness (in.)	Percent of Total Miscellaneous Area	Percent of Total Area ^[a]
Flat Slab 1	steel	0.25	13.3	4.4
Flat Slab 2	steel	0.50	8.3	2.7
Flat Slab 3	steel	0.75	8.3	2.7
Flat Slab 4	steel	1.00	25.0	8.3
Flat Slab 5	steel	1.50	16.7	5.6
Flat Slab 6	steel	2.00	28.4	9.4

[a] Total area equals building area plus area of miscellaneous surfaces.

3. VARIATIONS IN THE CONTAINMENT MODEL

The range of variation of the parameters shown in Table II results from a liberal extension of the range found for recent large PWR's. With the exception of the condensing-steam heat transfer coefficient, each parameter was varied independently to determine the influence on the maximum containment pressure. The maximum value of the condensing-steam heat transfer coefficient was a dependent variable which satisfied the Tagami correlation⁽⁸⁾.

TABLE II

RANGE OF VARIATION OF THE PARAMETERS IN THE ANALYSIS

Parameter	Range of Variation
Energy released per unit of containment volume.	50 to 200 Btu/ft ³
Fluid enthalpy in the primary coolant system.	550 to 650 Btu/ft ³
Time required for decompression of primary coolant system.	5 to 50 sec
Surface area of heat-conducting structures per unit of containment volume.	0 to 0.30 ft ⁻¹
Energy absorbed in steam generators during decompression of primary coolant system.	0 to 10% of the initial stored coolant energy
Maximum condensing-steam heat transfer coefficient (dependent variable).	105 to 710 Btu/hr-ft ² -°F

III. MAXIMUM PRESSURE CORRELATIONS

The paragraphs that follow describe the correlations developed from the sensitivity analysis discussed in the previous section. Subsequent paragraphs illustrate the use of the correlations for predicting maximum containment pressures in large PWRs; also, comparisons are made between the predicted pressures and those published in safety analysis reports.

1. DEVELOPMENT OF MAXIMUM PRESSURE CORRELATIONS

The containment pressure depends on the sum of the partial pressures of the air and the water vapor, and each of the partial pressures depends on the total energy content of the mixture. If the assumption is made that the initial conditions in all dry containment buildings are essentially the same, then the containment pressure will depend primarily on the energy released from the primary system minus the energy absorbed in heat-conducting structures. This reasoning leads to use of the volumetrically-averaged energy addition and the volumetrically-averaged surface areas of the heat-conducting structures as the principal factors with which the maximum containment pressure was correlated.

The relationships between maximum containment pressure and energy released per unit of containment volume as a function of average fluid enthalpy is illustrated in Figure 2 for no heat absorption in heat-conducting regions.

Fig. 2 Relation Between Containment Pressure, Fluid Enthalpy, and Ratio of Energy Released to Volume of the Containment

The pressure obtained from the figure is considered the first approximation to the maximum containment pressure and corrections are later defined which can be applied to this estimate.

Parameters required in Figure 2 to estimate the pressure presuppose that separate blowdown analyses have been done on the plant. However, for cases in which such an analysis is not available, the total energy stored initially in the primary coolant and the initial fluid enthalpy can be used as an approximation to the actual energy released and to the average enthalpy of the released fluid^(a). When these approximations are used, correction to Figure 2 may be desirable to account for energy absorbed in the steam generators during blowdown. This correction is defined in Figure 3 for various percentages of the initially stored energy that is transferred to the steam generators as a function of the initially stored energy per unit of containment volume. An assumption of the percent of the initially stored energy transferred to the steam generators is required; experience has shown that one to three percent is typical of many large PWR's.

Heat absorption in the containment structures during decompression abates the potential buildup of containment pressure. The amount of reduction in maximum containment pressure depends chiefly on the surface area exposed to the air-steam mixture, steam concentration, turbulence within the mixture, and length of time that the surfaces are exposed before the maximum pressure is reached. Length of exposure time approximately equals the time required for the primary system to depressurize to the containment pressure.

Analysis of the interaction of the preceding parameters resulted in correlations that can be used to estimate the reduction in the maximum containment pressure caused by heat absorption in containment structures. An estimate of the adjustment to the maximum pressure requires the combined use of Figures 4 and 5. First, Figure 4 is used to estimate a preliminary maximum pressure adjustment as a function of the total exposed surface area per unit volume and the time required for decompression of the primary coolant system. This adjustment is for a particular value of energy released per unit of containment volume and must be corrected to reflect the actual energy released per unit of containment volume. Hence, the adjustment read from Figure 4 is multiplied by the factor C_T from Figure 5 and the result is subtracted from the estimate obtained from Figure 2. The factor C_T accounts for the particular energy released per unit of containment volume and also reflects the dependence of the Tagami correlation on steam concentration and average turbulence.

Collectively, Figures 2, 3, 4, and 5 can be used to estimate the maximum containment pressure in a large PWR. In summary, a preliminary pressure based on the average fluid enthalpy and the total energy released per unit of containment volume can be estimated from Figure 2. If the energy initially stored in the primary coolant is used as an approximation for the energy released, the preliminary pressure can be modified to account for heat transfer to the steam generators during blowdown by using Figure 3. A second modification to account for heat absorption in the containment structures can be obtained from Figures 4 and 5. The result is the final estimate of the maximum containment pressure. The following illustrative examples are given to demonstrate the method.

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- (a) A method equivalent to approximating the energy released by the energy initially stored in the primary coolant is to base the correlations on the ratio of primary system volume to containment volume.

Adjustment in Maximum Containment Pressure Due to Heat Transferred to Steam Generators During Blowdown (psi)

Fig. 3 Effect of Heat Transferred to Steam Generators during Blowdown on the Maximum Containment Pressure

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Fig. 4 Reduction in Maximum Containment Pressure as a Result of Energy Absorption in Containment Structures for Various Ratios of Surface Area to Volume and Decompression Time

Fig. 5 Correction Factor Versus the Ratio of Energy Released to Volume of the Containment

2. ILLUSTRATIVE EXAMPLES FOR LARGE PRESSURIZED WATER REACTORS

Calculations performed with the RELAP3 computer program⁽⁹⁾ to determine the thermal-hydraulic behavior following a loss-of-coolant accident in a typical four-loop large PWR resulted in the following data:

energy released during decompression, 3.08×10^8 Btu

mass released during decompression, 5.37×10^5 lb_m

time for decompression (to 50 psia), 22 sec

By assuming the blowdown to a containment building with a volume of 1.98×10^6 ft³ and exposed surface areas of 2.16×10^5 ft², the necessary ratios for use in the correlations can be calculated as follows:

$$\frac{\text{Energy released}}{\text{Containment volume}} = 155 \frac{\text{Btu}}{\text{ft}^3}$$

$$\frac{\text{Energy released}}{\text{Mass released}} = 575 \frac{\text{Btu}}{\text{lb}_m}$$

and,

$$\frac{\text{Surface area}}{\text{Containment volume}} = 0.109 \text{ ft}^{-1}$$

Then from Figure 2, a preliminary pressure of 51.5 psig is estimated using 155 Btu/ft³ and 575 Btu/lb_m. No adjustment for heat absorption in the steam generators is required because this energy transfer is considered internally in RELAP3. Modification by - 4.5 psi to account for heat absorption in the containment structures follows from Figures 4 and 5 using 22 sec, 0.109 ft⁻¹, and 155 Btu/ft³ as coordinates. Then the approximate maximum pressure is 51.5 psig minus 4.5 psi, or 47.0 psig. A detailed analysis of this case with CONTEMPT-PS using the actual time-dependent blowdown history and actual heat-absorbing structures resulted in a maximum containment pressure of 47.7 psig (estimate is about 1.5% low).

For the case considered, the mass and energy release histories were known from the RELAP3 analysis. If this information is not available then the assumption is made that the actual totals released can be approximated by the total initial values of mass and energy stored in the primary coolant. The primary system volume, V_p , of about 12,550 ft³ and the average enthalpy, h_f , of 595 Btu/lb, can be found in the safety analysis reports; then from steam tables at 595 Btu/lb, a specific volume for saturated liquid, v_f , of 0.023 ft³/lb_m can be located. Then the approximate mass released can be calculated as follows:

$$m_f = \frac{V_p}{v_f} = 5.44 \times 10^5 \text{ lb}_m$$

and the approximate total energy released, U , is:

$$U = m_f h_f = 3.24 \times 10^8 \text{ Btu.}$$

Using this value to calculate the energy loading per unit of containment volume results in the following ratio:

$$\frac{\text{Energy released}}{\text{Containment volume}} = 163 \text{ Btu/ft}^3.$$

From Figure 2, a preliminary pressure of 55.2 psig can be determined using 163 Btu/ft³ and 595 Btu/lb_m as coordinates. Assuming a 2% energy absorption in the steam generators during blowdown results in a -1.6 psi adjustment to the preliminary containment pressure by using Figure 3. For the heat absorption in the containment structures, a - 4.8 psi adjustment can be estimated from Figures 4 and 5 using 163 Btu/ft³, 0.109 ft²/ft³, and an assumed 20 sec as coordinates. The final estimate is then 48.8 psig which compares reasonably well (within 2.3%) with the 47.7 psig calculated with the CONTEMPT-PS computer program.

For cases in which the containment building normally operates under a slight negative pressure (subatmospheric containment) the preceding procedure can be used with the resulting pressure estimate being interpreted as the rise in pressure rather than the actual gage pressure. Thus, if a containment normally operates at a 4 psig negative pressure, and the correlations are used to estimate a pressure rise of 50 psi, the corrected estimate of the maximum containment pressure would be 46 psig.

3. COMPARISON OF PREDICTIONS WITH VALUES FROM SAFETY ANALYSIS REPORTS

Nearly all safety analysis reports give sufficient information to make at least a preliminary estimate of the maximum containment pressure by using the correlation in Figure 2. Data necessary to correct the preliminary data for heat absorption in the steam generators or in the heat-conducting structures are sometimes lacking. The following paragraphs describe comparisons for both preliminary estimates and final estimates (corrected for heat absorption) with data from safety analysis reports.

Figure 6 illustrates the general agreement between the pressures estimates from Figure 2 and the predictive vendor data from safety analysis reports. The solid line in Figure 6, for an average fluid enthalpy of 590 Btu/lb_m, has no adjustment for heat absorption in the steam generators or heat-conducting regions and is, therefore, slightly higher than the majority of the data points from the vendors.

Sufficient information to compare final pressure estimates from the correlations (including heat absorption) with vendor calculations was available in several safety analysis reports. This comparison is shown in Figure 7. Data points below the diagonal indicate vendor-calculated pressures that are more conservative (higher) than predicted by the correlations; data points above the diagonal indicate pressures less conservative than predicted by the correlations.

The agreement between the calculated curves and the vendor data is good considering that the vendor data reflect many different assumptions relative to the behavior of the primary system and safety systems as well as the different assumptions relative to the containment pressure prediction. As an example of the differences, many vendors use a condensing-steam heat transfer correlation based on the work of Kolflat^(10,11) rather than the Tagami correlation⁽⁸⁾ used in the present analysis.

4. USE OF THE CORRELATIONS BY AEC DIVISIONS OF REACTOR LICENSING AND REACTOR SAFETY

A detailed analysis of the containment building thermodynamic response to a loss-of-coolant accident is required in the licensing process of a nuclear power plant. An approximation to the correlation in Figure 2 is used as the basis for checking these analyses and a 10% margin is required between the maximum calculated containment pressure and the design pressure for the building. The approximation to the correlation of Figure 2 at 590 Btu/lb_m is given by the following expression:

$$P = 1/3 U/V$$

where

- P = peak containment pressure, psig
- U = energy stored in the primary coolant at full power and normal operating liquid levels prior to blowdown (liquid plus pressurizer steam)^(a), Btu
- V = containment free volume, ft³.

The two methods of calculating the containment design pressure that are generally accepted by the AEC are as follows:

- (1) If an applicant's calculations of the containment maximum pressure equals or exceeds that obtained by the preceding expression, then the design pressure of the containment should be ten percent above the applicant's calculation of the maximum pressure.
- (2) If an applicant's calculation of the maximum containment pressure falls below that obtained through use of the preceding expression, then he should establish his containment design pressure by adding 10% to the value obtained by using the expression.

In the event that an applicant feels his maximum pressure justifiably falls below that obtained from the expression, an independent AEC analysis is made using the CONTEMPT-PS computer program.

(a) The assumption is made that the energy sources other than the primary coolant are approximately equal to the energy sinks at the time of peak pressure. This assumption is justified, in part, by the agreement shown in Figure 6.

(a) Estimate of Energy Released Based on Initially Stored Energy in Primary Coolant Minus 2% Absorption in Steam Generators.

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Fig. 6 Comparison of Maximum Pressure Correlation (Without Adjustment for Heat Absorption in Steam Generators or in Heat Conducting Regions) with Vendor Predictive Data from Safety Analysis Reports

- (a) Estimate of Energy Released Based on Initially Stored Energy in Primary Coolant Minus 2% Absorption in Steam Generators.
- (b) Subatmospheric Containment; Vendor Prediction (43 psig) was Increased by 4.7 psi to Convert to Equivalent Atmospheric Containment for Comparative Purposes.

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Fig. 7 Comparison of Maximum Containment Pressures Estimated with Correlations (Adjusted for Heat Absorption) and Pressures Calculated by Vendors

After completion of the AEC analysis, the containment design pressure should be 10% above the AEC calculation or the applicant's calculation, whichever is larger.

IV. CONCLUSIONS

The correlations developed on the basis of a parametric analysis of a simplified containment model provide a method for prediction of the maximum containment pressures in large PWR containments following a loss-of-coolant accident. The figures provide the framework to account for initial fluid enthalpies, heat transfer to the steam generators during blowdown, and heat absorption in the containment structures. The trend of pressure estimated with the correlations agrees with vendor predictive data from safety analysis reports.

The large number of variables involved in predicting the decompression of the primary coolant systems for large PWR's, coupled with the variables involved in the maximum containment pressure prediction makes impractical the analysis of all possible combinations of the variables. However, the assumption can be made reasonably that many of the variables are of secondary importance and simplifying assumptions can be made to derive approximate correlations for a general class of containment problems. As such, the derived correlations are intended to be used to approximate the maximum containment pressure rather than to give an exact solution of the containment pressure.

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