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REVIEW OF HEAT TRANSFER COEFFICIENTS FOR CONDENSING STEAM IN A CONTAINMENT BUILDING FOLLOWING A A LOSS-OF-COOLANT ACCIDENT

D. C. Slaughterbeck

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ABSTRACT

A literature search of available technical publications, and a survey of recent experiments and current practices relevant to the prediction of heat transfer in a containment building following a loss-of-coolant accident have been completed. Very little information with direct applicability to large power reactor containments is available on which to base concrete recommendations. A correlation based on the work of Tagami is suggested for use in safety analyses because its trend is consistent with the Carolinas Virginia Tube Reactor (CVTR) measurements and because its use leads to predicted containment pressures being higher and thus more conservative than those measured at CVTR. This conservatism is desired because of the uncertainty associated with extrapolating results from atypical small-scale experiments to large power plants.

SUMMARY

The containment systems of large nuclear power plants are designed to withstand the pressures that could result from accidental loss of coolant from the primary coolant system of the nuclear reactor. The prediction of the pressure-temperature response of the internal containment atmosphere depends on many primary-system parameters as well as parameters within the containment and on the operation of safety systems. The absorption of energy into the containment building walls and internal structures is an area of particular concern because of its known influence on the containment pressure.

A search of available literature concerning the energy absorption process for condensing steam in the presence of noncondensable gases revealed very little information with direct applicability to the containment analysis of large nuclear power plants following a loss-of-coolant accident. Papers concerning modifications to the classical Nusselt analysis of filmwise condensation as well as information concerning dropwise condensation were reviewed. The data cannot be used directly because of uncertainties in the turbulence, unknown impurities, and unknown surface characteristics.

Several small-scale experiments that relate to containment pressurization were reviewed in detail. Although the experiments had shortcomings (notably size) they collectively lend insight into the physical problem. One experiment, the Carolinas Virginia Tube Reactor In-Plant Containment Test, used an actual reactor containment vessel having a volume of 227,000 ft^3 which is about 1/10 the size of containment vessels of many recent large pressurized water reactors.

As a result of this review, the Tagami heat transfer correlation is recommended for use in the safety analysis of large pressurized water reactors. This correlation is recommended because of its similarities in trend with the CVTR data and its apparent conservatism (that is, it predicts containment pressures higher than those measured at CVTR).

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I. INTRODUCTION

A recent PWR containment analysis[1] demonstrates the sensitivity of the predicted containment pressure to the assumed empirical correlation for the film coefficient for heat transfer from the containment atmosphere to the building walls and other heat conducting structures following a loss-of-coolant accident. Considerable uncertainty exists in the selection of an accurate empirical correlation for these heat transfer coefficients. This report documents a survey of the recent experiments, technical publications, and current practices relevant to the prediction of the heat transfer process. Conclusions and recommendations are given on the applicability of the available data to the containment analysis of large power reactors following a loss-of-coolant accident.

The heat transfer from the containment atmosphere occurs principally as a result of the condensation of steam on the heat conducting structures in the containment building. The local condensing coefficient or film coefficient is defined as follows:

$$h_x = \frac{-k_x \left.\frac{\partial T}{\partial X}\right|_x}{T_b - T_w}$$

where

h_x = the local film coefficient for heat transfer, in the x direction, from the containment atmosphere to a heat conducting structure

k_x = the thermal conductivity, in the x direction, of the heat conducting structure at its exposed surface

$\left.\frac{\partial T}{\partial X}\right|_x$ = the temperature gradient in the heat conducting structure adjacent to its exposed surface, in the x direction

T_b = the bulk temperature of the air-steam mixture

T_w = the surface temperature of the heat conducting structure.

The heat transfer process is dependent on many variables such as condensation mode, steam concentration and distribution, impurities, turbulence, location within the building, time after the accident, wall height, and the thermal resistance of the resultant condensate. These variables, when combined with the necessity for making assumptions on the postulated accident and the action of emergency containment safety systems, complicate the physcial problem and prohibit a detailed space-time solution for the applicable local heat transfer coefficient. For these reasons, the heat transfer coefficients used in the safety analyses of large containment systems generally are defined to be an area-averaged heat transfer coefficient as follows:

$$\bar{h} = \frac{\int h_x \, dA}{A}$$

where

$\bar{h}$ = the average heat transfer coefficient at a particular time

h_x = the local film heat transfer coefficient

dA = the differential area for which the local film coefficient h_x is applicable

A = the total exposed area of heat conducting structures.

The averaged coefficient is intended solely for estimating the total heat flux from the containment atmosphere and, therefore, predicting the pressure transient.

Even though a local heat transfer coefficient may be extremely high (for example, the coefficient for a location near the postulated break may be high a few seconds after rupture), the average heat transfer coefficient may be very low. Thus, the thermal response of the containment atmosphere should not be used to predict thermal loadings on various localized structures because the thermal boundary conditions for a particular structure are likely to be different from the computed average conditions of the containment atmosphere. The importance of these statements is exemplified by the unexpected rupture of a simulated containment vessel used in experiments by Kolflat [2] in which the cause of the rupture was believed to be high localized thermal stresses.

Considerable confusion exists in the literature as to what coefficient is being discussed. In the succeeding paragraphs, "heat transfer coefficients" will refer to the total average coefficients unless specifically referred to as local coefficients.

For containment analysis, two separate time periods are generally considered following a loss-of-coolant accident in which different correlations for condensing steam heat transfer coefficients apply. The first period is characterized by the high turbulence caused by the decompression of the primary coolant system. This period is referred to by various authors as the forced convection portion, the turbulent portion, the blowdown period, or the transient state. The end point of this period is usually not defined explicitly but is the end of the pressurization of the containment resulting from the initial injection of primary coolant into the containment. Later additions of mass and energy from emergency safety systems would not affect the end point of the forced convection region. The second period is referred to as the natural convection portion, the steady state portion, the postblowdown portion, or the stationary state. As the terms imply, this period is characterized by lower turbulence following the decompression of the primary coolant system.

II. REVIEW OF LITERATURE

Considerable effort has been spent in recent years in studying the fundamental modes of heat transfer in condensing steam systems. The literature is generally separated according to the description of the resultant condensate, that is, dropwise or filmwise. Dropwise condensation occurs when vapor comes in contact with a non-wetting surface that is at a temperature lower than the saturation temperature of the vapor. The condensate on the non-wetting surface will collect in growing droplets until they run off the surface due to gravity or other external forces. Very high heat transfer rates have been reported for this type of condensation. If the condensate tends to wet the surface and thereby forms a liquid film, the process is called filmwise condensation. Filmwise condensation is more common and is characterized by lower heat transfer rates than is dropwise condensation.

Past theoretical treatments on these types of condensation have been sufficient for many applications. Most subsequent analyses have been conducted in an effort to generalize the solutions. Many publications relative to these basic heat transfer types are available; however, only a few will be mentioned here -- mainly to enable the reader to gain an understanding of the areas of current research. The following paragraphs discuss filmwise and dropwise condensation and summarize publications written directly for the safety analysis of large nuclear plants.

1. FILMWISE CONDENSATION

Heat transfer rates in laminar film condensation on vertical or near-vertical surfaces can be predicted adequately by Nusselt's [3] analysis, or modifications of it taking into account the effects of interfacial shear, fluid acceleration, nonlinear temperature distributions, and surface instabilities. The Nusselt theories have been extended to provide correlations derived for horizontal and inclined surfaces [4], variations in physical properties [5], and interfacial heat transfer resistance [6]. Fluid effects [7,8] and geometric effects [9] have also been investigated. Turbulent film effects for various degrees of roughness on vertical surfaces have been studied extensively by Medwell and Nicol [10,11,12]. The value of these and other theoretical papers is that they enable the analyst to gain an understanding of the heat transfer processes. However, the results cannot be applied directly to the safety analysis of a reactor containment, largely because of the uncertainties in turbulence in the containment atmosphere. These theoretical papers are based on experiments with highly controlled environments with known impurities unlike the postulated accidents of a large pressurized water reactor. Also, the heat transfer coefficients derived from such analyses are local coefficients only, and generally not applicable to an entire containment building.

2. DROPWISE CONDENSATION

The mechanics of the formation of the liquid drops of dropwise condensation is unclear. Generally, theories can be categorized in two areas. One theory, originally formulated by Jakob[13] in 1936, hypothesized that a very thin film condenses on a surface between visible drops; the film subsequently grows to a critical thickness, and finally, the film fractures to produce drops. Evidence from a microscopic study to support this theory was presented by Welch and Westwater[14]. The second theory suggests that the condensation begins as a consequence of a nucleation phenomenon. Evidence supporting this theory is presented in several papers[15,16,17]. The second theory appears to have the most popular support at this time[18].

The real importance of the dropwise condensation mode of heat transfer is in the possible thermal loadings on localized structures due to the extraordinary heat flux which characterizes such condensation. The effect of dropwise condensation on the pressure response is minimal because this means of condensation is difficult to achieve because of the surface conditions required and probably is not typical for extended periods of the condensation following a loss-of-coolant accident. Even if extensive dropwise condensation did exist immediately after the rupture of the primary coolant system, the duration would likely be short because of the probable buildup of a water film on the containment walls and other equipment.

3. CONDENSATION IN SMALL-SCALE CONTAINMENT VESSELS

One of the earlier works considering condensing-steam heat transfer in containment structures following a loss-of-coolant accident was published by Kolflat and Chittenden in 1957[19]. In their small-scale experiments, a blowdown was simulated in a thin steel containment shell. The volume of the containment structure was about 800 ft^3. Data necessary to compute the heat absorption in the shell were obtained. The authors concluded (for Test 14) that the heat transfer rate for the first few seconds was of the order of 620 Btu/hr-ft^2-°F. Indications are that the 620 Btu/hr-ft^2-°F heat transfer coefficient is the maximum during blowdown because it cannot be obtained from the published temperature profiles nor the comment that 51,000 Btu were absorbed by the shell in the first 10 seconds. In the light of more recent experiments, use of the Kolflat data is probably not conservative during the first few seconds of blowdown. Fuls[20] calculated heat transfer coefficients as a function of time from the published data of Kolflat, and used them in ACT-1, a computer program for predicting containment pressure transients.

In a separate study by Jubb[21], experimental data were obtained and correlations were developed for the heat transfer coefficients due to condensation in a boiler (30 feet long and 8 feet in diameter) after steam was injected from a 120 psig source. The horizontal boiler had scale and rust deposits on the condensing surface. The thermal resistance of these deposits was unknown; a significant resistance was found in separate studies[10,11,12] when similar conditions of surface roughness were studied. The effect of the scale and rust on Jubb's results is that the heat transfer coefficients calculated would be low for scale- and rust-free surfaces and would lead to higher containment pressures than would actually exist. Jubb suggests that the following forced convection correlation based on the experimental data be used for subcooled blowdown:

$$St \cdot Pr^{0.5} = 0.0576/(Re\ P)^{0.25} \qquad (1)$$

where

St = Stanton number = (Nusselt number)/(Re Pr)

Pr = Prandtl number

Re = Reynolds number

P = number of atmospheres.

In an example for a containment building with a volume of 50,000 ft^3, Jubb used this correlation to compute an average heat transfer coefficient of 83 Btu/hr-ft^2-°F.

Another correlation was suggested by Jubb for the natural convection period after the blowdown:

$$q''/\rho = 0.0152 \; \Delta T^{1.25} \qquad (2)$$

where

q'' = heat flux (Btu/ft^2-sec)

ρ = mass density of air-steam mixture (lb/ft^3)

ΔT = difference in the bulk and wall surface temperatures, $T_b - T_w$(°F).

For the same example in the postblowdown period, a heat transfer coefficient of about 24 Btu/hr-ft^2-°F was calculated.

In both correlations, the effect of containment size was not included because the experimental data were obtained from a single size structure. Jubb recommended further experiments to determine the functional relationship for containment size.

The experiments reported by Uchida[22] were modified and extended by Tagami and others[23,24]. In these publications, the experiments were organized according to the time period under consideration. The stationary state referred to the natural convection period after blowdown when condensation on the structures is not influenced by the turbulent decompression of the primary coolant system. The transient state was defined to be the time during blowdown of the primary coolant at which condensation on the structures is characterized by forced convection in the containment atmosphere. The experimental apparatus used consisted of a containment structure about 11 feet in diameter and 21 feet in height. Within the containment structure was an instrumented test surface from which average heat transfer coefficients were measured. This test surface was a water-cooled cylinder about 6 inches in diameter and about 12, 24, or 36 inches in height, depending on the particular test.

Results of the natural convection portions of the tests are described in the Uchida report[22]. The conclusion was that the heat transfer coefficient depends on the weight-ratio of air to steam. These data and the resulting conclusion have had wide industrial usage and are used as an option in the

CONTEMPT code[25]. Tagami further concludes that the heat transfer coefficient on the small test specimens is inversely proportional to the fourth root of the height of the condensing surface. A similar relationship was given by Chapman[26] for natural convection in air with laminar flow, but without condensation. The correlation predicts that the local coefficient would be lower in the upper regions of the containment building than the comparable coefficient near the ground level. This application is beyond the range of the test data and Tagami recognized that the problem of estimation of heat transfer to tall surfaces remains unresolved.

For the heat transfer in the transient or forced convection portion, the Japanese experiments show that the heat transfer to vertical surfaces increases with time after rupture until a maximum coefficient is reached slightly before the end of blowdown. The heat transfer gradually decreases from this maximum and presumably approaches that of the natural convection heat transfer model. As the injection rate was increased, time to reach the maximum coefficient decreased, and the maximum heat flux increased. Tagami was able to correlate these experimental data for the maximum heat transfer coefficient on steel surfaces. The empirical correlation shows that the maximum heat transfer coefficient depends on the total energy released from the primary coolant system during the decompression per unit volume of the containment building, and also depends on the time required for decompression. This heat transfer correlation can be expressed as:

$$h_{max} = C\left(\frac{Q}{Vt_p}\right)^{0.62} \qquad (3)$$

where

h_{max} = the maximum heat transfer coefficient during blowdown (cal/sec-cm^2-°C or Btu/hr-ft^2-°F)

C = a constant equal to 0.185 for metric units or 72.5 for English units

Q = the total energy released from the primary system during blowdown (cal or Btu)

V = the free volume of the containment vessel (cm^3 or ft^3)

t_p = the time interval until peak pressure (sec).

Westinghouse has used the correlation in English units with the constant C as 75 and the exponent as 0.60. (These values result in a maximum heat transfer coefficient about 1% higher than the maximum coefficient calculated by using Equation 3.) In the later Japanese publication[24], Tagami shows a correlation in the following form:

$$q_p \propto \left(\frac{Q}{Vt_p}\right)^{1.3} \qquad (4)$$

where q_p is the maximum heat flux in cal/cm^2-sec and the other terms remain the same. These correlations were presumably derived from the same experimental data. The authors caution that "these equations are not confirmed by experiments with various size geometrical configurations of containers, and the theoretical basis has not been known up to this time ...", and "further investigations are necessary concerning the effect of the size and geometrical configurations of the containers".

Average condensing steam heat transfer coefficients in the range 40 to 400 Btu/hr-ft^2-°F were considered by Voigt [27] in a parametric analysis of large containment building pressure responses. For one case, Voigt estimated a heat transfer coefficient of 400 Btu/hr-ft^2-°F during the forced convection period and decreased this coefficient to 80 Btu/hr-ft^2-°F for the natural convection period. Voigt thought this model would predict a lower containment pressure than the true value because a very high degree of turbulence would be necessary to achieve a heat transfer coefficient of 400 Btu/hr-ft^2-°F [28]. Voigt's results for these coefficients show a maximum pressure about 4 psi lower than the pressure predicted by using a constant coefficient of 80 Btu/hr-ft^2-°F.

4. EMPIRICAL HEAT TRANSFER CORRELATIONS USED IN INDUSTRY

Heat transferred to the containment structures during blowdown of the primary coolant can affect the maximum containment pressure by about 4 to 7 psi, depending on the assumed correlation [1,25]. Heat transfer to the containment walls enables manufacturers to reduce the maximum design pressure of the containment building and, therefore, reduce construction costs. The amount of credit taken for heat transfer depends on the correlation used to estimate the heat transfer coefficient. After the initial pressure peak resulting from the mass and energy released during decompression, the pressure decay depends on natural and forced heat removal from the containment atmosphere. The pressure response during this period is also sensitive to the heat transfer coefficients but may be masked by operation of containment safety systems.

Recent safety analysis reports indicate a preference for a heat transfer model based on the Tagami correlation for the maximum coefficient on steel surfaces (for example, Diablo Canyon 2, PSAR [29]) because of its conservatism. Various assumptions are used to approximate a smooth transition from the pre-accident steady state coefficient to the maximum value as predicted by the Tagami correlation, Equation 3. The natural convection data of Uchida [22] are often used after the decay from the peak heat transfer coefficient.

Little experimental data are available for predicting heat transfer coefficients for concrete surfaces. In Kolflat's experiments [10], the heat transfer coefficient was found equal to 40% of the value measured for steel surfaces. The manufacturers either use this relationship or use a value believed to be conservative (low) to approximate the heat transfer on concrete.

The presence of paint on the concrete surfaces can be significant, although it is not considered in the safety analysis reports. A painted concrete surface can allow dropwise condensation and, therefore, have a heat transfer coefficient comparable to the value for steel. (Griffith and Lee [30] report that the substrate material can influence the heat transfer coefficient during dropwise condensation;

the heat transfer coefficient decreases as the conductivity of the substrate material decreases). Dropwise condensation would lead to lower containment pressures, as more energy is removed from the containment atmosphere. If filmwise condensation occurs on the painted concrete surface, the paint would tend to impede the heat flow from the containment atmosphere. The extent of decreased heat flow, of course, depends on the paint thickness and the thermal characteristics of the paint. Greater emphasis should be placed on the effects of paint on heat transfer surfaces in the future.

Table I shows the correlations recently used by various manufacturers to predict the condensing-steam heat transfer coefficient for steel and concrete surfaces. The time dependence during decompression for these correlations is shown in Figure 1. All correlations are applied to the reference accident of a large PWR [1]. The correlations based on the Japanese data give heat transfer coefficients that are quite low compared to the Kolflat data, and would, therefore, lead to higher containment pressures. Furthermore, as discussed in the following section, the trend and magnitude of the Japanese data are consistent with the preliminary data of the CVTR experiment [31].

TABLE I

CORRELATIONS USED IN INDUSTRY FOR PREDICTING CONDENSING-STEAM HEAT TRANSFER COEFFICIENTS

		WESTINGHOUSE ELECTRIC CORPORATION		BABCOCK & WILCOX		COMBUSTION ENGINEERING
Material	Time Covered by Correlation	Diablo Canyon 2	Indian Point 2	Davis-Besse	Rancho-Seco	Calvert Cliffs
Steel	During Decompression	$h = h_{max}(t/t_p)$	h = 620 Btu/hr-ft^2-°F decreasing linearly to h = 40 Btu/hr-ft^2-°F	Published as using modified Tagami correlation similar to that of Westinghouse	620 Btu/hr-ft^2-°F until 110 Btu/ft^2 has been transferred, 40 Btu/hr-ft^2-°F thereafter	Published as using modified Tagami correlation, similar to h_{max} of Westinghouse; transitions to and from h_{max} expressed as $h = h_{max}(t/t_p)$
	At end of Decompression	$h = h_{max} = 75\left(\frac{Q}{Vt_p}\right)^{0.60}$	h = 40 Btu/hr-ft^2-°F			
	After Decompression	$h = h_{stag} + (h_{max} - h_{stag})Y$	h = 40 Btu/hr-ft^2-°F	h = f (air-to-steam ratio of Uchida)		
Concrete	Throughout Accident	40% of value calculated for steel	h = 240 Btu/hr-ft^2-°F decreasing to 40 Btu/hr-ft^2-°F at end of blowdown	Unpublished	40 Btu/hr-ft^2-°F	40 Btu/hr-ft^2-°F

t = time after rupture of primary system

t_p = time when containment reaches peak pressure

Q = energy released to containment during decompression

$Y = \exp^{-0.05}(t - t_p)$

V = volume of containment

$h_{stag} = 2 + 50x$

x = steam-to-air mass ratio

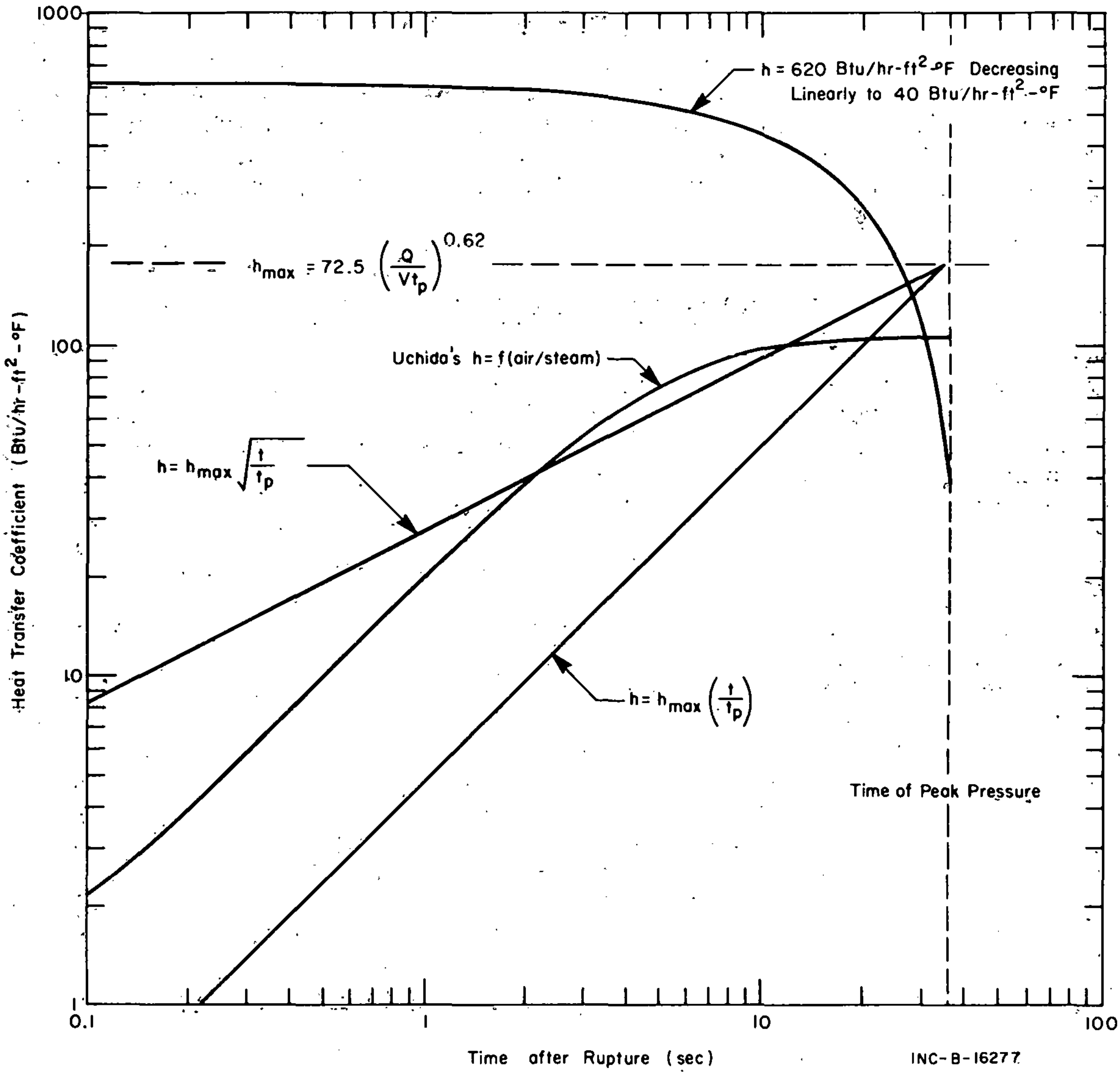

FIG. 1 FILM COEFFICIENTS AS FUNCTIONS OF TIME FOR REFERENCE ACCIDENT [1].

III. CONTAINMENT EXPERIMENTS

Several experimental containment programs have been considered that could provide information on the thermal behavior of a containment building following a loss-of-coolant accident. In the case of the CVTR experiments described in the following section, considerable information has been obtained. Brief descriptions of the programs and objectives have been reported [32,33].

1. CVTR IN-PLANT TESTING PROGRAM

Simulated loss-of-coolant accident tests were recently performed in the Carolinas Virginia Tube Reactor (CVTR) containment system. The simulations were achieved by injecting slightly superheated steam into the containment volume (227,000 ft^3). Pressure reduction sprays were operated following steam injection for part of the tests.

Measurements were made of the pressure-temperature response of the containment system. Preliminary data evaluations and comparisons of experimental and analytically predicted responses have been documented [31]. Although meaningful heat transfer data were obtained from the CVTR tests, the tests were somewhat atypical with respect to large PWR containment systems. The containment volume was divided by an operating floor that could have appreciably affected condensation and flow patterns. The simulated decompression was accomplished with superheated steam rather than a two-phase mixture as predicted from the analysis of the primary coolant systems of large PWR's. Also, the injection period was long (180 seconds) compared to the short blowdowns (20 seconds) predicted for double-ended ruptures of of primary system piping. In spite of these inherent limitations, the CVTR tests provide the only data from a containment of this size (very large in comparison to other sources of experimental containment data but only about 1/10 the volume of large PWR containments).

Figure 2 shows the condensing steam heat transfer coefficients versus time for two-point locations in the CVTR containment. The trends established by these data indicate that the film coefficients for heat transfer from the containment atmosphere to the heat conducting structures had the following characteristics: The coefficients were very low at initiation of the simulated accident, increased sharply as the presence of steam became widespread, and reached maximums near the end of the steam injection period. In the case of the upper location, the maximum value was reached somewhat before the end of steam injection, possibly because either a conduction-limited heat transfer process occurred in the concrete or a localized diffusion-limited mass transfer process occurred in the boundary layer. Following steam injection, the coefficients dropped rapidly as the turbulence decreased. This trend is similar to that indicated by the use of the modified Tagami correlation, Equation 3; however, the magnitudes of the measured coefficients are higher than the Tagami prediction.

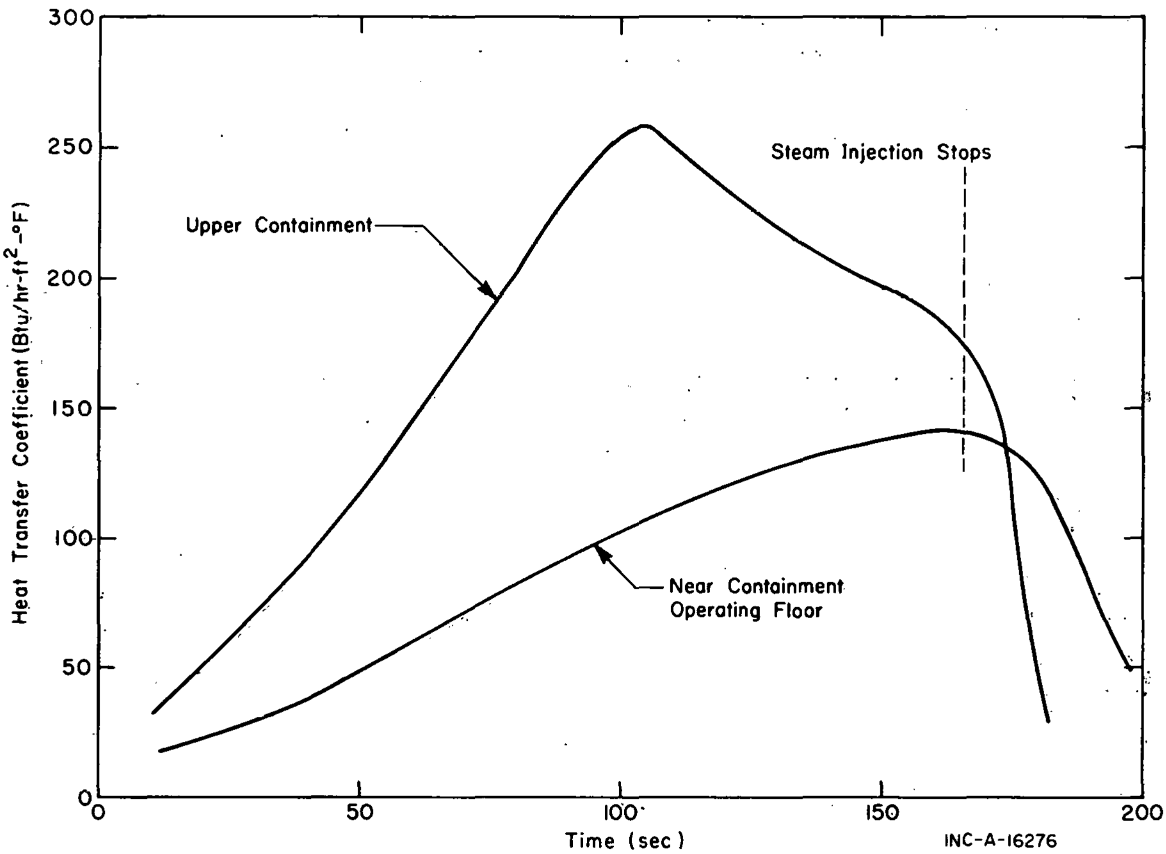

FIG. 2. HEAT TRANSFER COEFFICIENTS FROM MEASURED CVTR DATA.

2. CONTAINMENT SYSTEMS EXPERIMENTS (CSE)

The CSE program was designed to accurately determine the leakage rate and associated fission product release under simulated accident conditions from a small-scale containment building. As part of the experiments, pressure and temperature data were to be taken to correlate the leakage with the containment conditions. Average heat transfer coefficients were to be calculated from these data. Funding of these experiments has been discontinued, and no applicable heat transfer data are available.

3. LOSS-OF-FLUID TEST (LOFT)

The simulated accident conditions of the LOFT tests[34] will provide an excellent opportunity to obtain containment response data under actual blowdown conditions. Heat transfer-coefficients for the various structures will be determined from the collected data. Condensate traps for fission-product analysis will also be used to relate the condensation rates and the heat transfer process. The effects of containment spray systems on the heat transfer process will be studied. The LOFT containment will have an externally insulated liner that is atypical of recent large PWR's. Current schedules indicate that the first LOFT nuclear test will occur in FY-1973.

IV. CONCLUSIONS

The following statements summarize the previous sections and indicate the state-of-the-art for the prediction of condensing steam heat transfer coefficients used in large pressurized water reactors following a loss-of-coolant accident:

(1) The maximum predicted pressure in a typical containment building following a loss-of-coolant accident can vary by about 4 to 7 psi depending on the assumptions made for the condensing steam coefficients [1,25].

(2) The heat transfer for large containment buildings should be defined clearly to avoid misuse of the various correlations.

(3) The classical Nusselt analysis with modifications for filmwise condensation is not suitable for predicting gross heat removal in a large containment building because of uncertainties in turbulence in the atmosphere and unknown surface characteristics of the heat conducting structures.

(4) Dropwise condensation, although probably not characteristic of the whole containment, could occur on localized surfaces. The extraordinary heat flux typical of dropwise condensation can cause serious thermal loadings on the affected structures.

(5) The heat transfer coefficients measured by Kolflat and Chittenden [19] are from gross measurements in a small-scale containment shell and do not accurately reflect the time dependence early in the blowdown.

(6) Empirical correlations suggested by Jubb [21] for the forced convection and natural convection portions of the containment response were undefined with respect to containment size. Presence of scale and rust deposits in the simulated containment caused an unknown resistance to heat flow at the vessel boundary and led to correlations that give low heat transfer coefficients.

(7) Results from the experiments completed by the Japanese [22,23,24] indicate differences for the forced convection and natural convection portions of the containment response. Correlations proposed from these experiments predict the maximum heat transfer coefficient near the end of primary-system blowdown. (The proposed correlation is not confirmed for large containment buildings.)

(8) PWR manufacturers prefer the Japanese data [22,23,24] because of its apparent conservatism. Various approximations are used to provide a smooth transition to and from the peak film coefficient as predicted by the Tagami correlation (Table I and Figure 1). The peak containment pressure is not sensitive to these approximations.

(9) Painted surfaces may tend to promote dropwise condensation that would greatly enhance the heat transfer during the early portion of blowdown and result in a lower peak pressure.

(10) For filmwise condensation, the presence of paint would cause an added resistance and would tend to impede the heat transfer.

(11) The following experiments are expected to provide information on the thermal behavior of containment structures following loss-of-coolant accidents: CVTR and LOFT [31,34]. The CVTR tests have been completed. The LOFT experiments (FY-1973), and the completed CVTR experiments will provide information necessary to establish the relationship between containment size and condensing-steam heat transfer coefficient.

V. RECOMMENDATIONS

The rationale and recommendations that follow are based on the preceding conclusions and the available literature. Usage of the recommended correlations is believed to predict maximum containment pressures slightly higher than the actual pressures.

1. RATIONALE

The film coefficient for heat transfer is expected to behave as follows: The average coefficient should start at values of about 5 Btu/hr-ft^2-°F and increase as the blowdown progresses. This increase would depend on the concentration of steam and the level of turbulence caused by the decompression of the primary system. The average film coefficient would reach a maximum near the end of blowdown because both the steam concentration and turbulence are at their maximums. The magnitude at the maximum would have a strong dependence on the turbulence and the steam concentration, and possibly the containment configuration. Maximum values of 200 to 600 Btu/hr-ft^2-°F appear reasonable[31]. The average film coefficient would then drop rapidly as the turbulence decays which would require the water vapor to diffuse to the containment walls through noncondensable gases. Experimental evidence of these trends is seen in the preliminary CVTR results[31], and the results of the Japanese experiments [22,23,24].

2. CORRELATIONS FOR SAFETY ANALYSIS

The Tagami correlation, $h_{max} = C\left(\frac{Q}{Vt_p}\right)^{0.62}$, is recommended for the maximum heat transfer coefficient. For the transition to the maximum coefficient, the equation

$$h = h_{max}\left(\frac{t}{t_p}\right)$$

is recommended because of its conservatism relative to Uchida's natural convection data early in the blowdown (Figure 1). For the natural convection portion, after decompression of the primary coolant system, the use of Uchida's data is recommended. These recommendations are consistent with the rationale outlined and, as evidenced by comparisions with the preliminary CVTR results, the recommended correlations will give conservative (low) heat transfer coefficients.

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