WESTINGHOUSE CLASS 3

WCAP-10987
Addendum 1

RE-ANALYSIS OF WATTS BAR AND CATAWBA CONTAINMENT TEMPERATURES IN RESPONSE TO LANL EVALUATION OF LOTIC-III HEAT TRANSFER MODELS

AUGUST, 1988

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SUMMARY

This report addresses the concerns expressed in the Los Alamos National Laboratory (LANL) Evaluation of the Revised LOTIC-III Drain Flow Heat Transfer Models, and presents the results of re-analyses of containment temperatures and pressures of the Watts Bar and Catawba ice-condenser plants using LOTIC-III with modifications which incorporate the LANL concerns. The results demonstrate that, during a postulated steam line break with superheated steam releases, the peak containment temperatures will remain below the environmental qualification temperature of 327 ^{o}F and the peak containment pressure will remain below the design pressure of 15 psig.

The LOTIC-III re-analysis peak containment temperature results are as follows:

Plant	Original Peak Temp (^{o}F)	LANL Mods Effect (net) (^{o}F)	Modified h_c + A Effect (^{o}F)	Revised Peak Temp (^{o}F)	E-Q Temp Limit (^{o}F)	Margin (^{o}F)
			a,c			
Watts Bar				313.0	327	14.0
Catawba				322.0	327	5.0

a,c

The LOTIC-III re-analysis resulted in 7.1 and 6.8 psia peak containment pressures for Watts Bar and Catawba, respectively.

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1.0 INTRODUCTION

Reference 1 documents the modification of the LOTIC-III ice condenser containment code which was done to include the effects of the drain flow which falls from the ice beds through the lower compartment into the containment sump. The water which drains from the ice beds is initially subcooled and exits the ice condenser drain pipe flapper valve as a turbulent, rough liquid sheet. Significant condensation occurs in this sheet and heats the drain water to nearly saturation. The liquid sheet breaks into droplets which then evaporate in the superheated containment atmosphere. The droplet field impacts the equipment and structures within the containment and can de-entrain into liquid films, re-entrain as a drop field, and shatter into finer size drops.

Full-scale experiments were conducted to help quantify the drain hydraulic behavior, and the key interfacial area parameters such as droplet size, velocity, sheet areas, and droplet trajectories were measured (Reference 1). Relatively simple heat transfer models were constructed using existing, well documented correlations from the literature for condensation and droplet evaporation. The experiments also considered the types of equipment the drain flow could impact such that the drain flow could be classified into different categories. Specific models were developed for each piece of equipment that the drains could impact and were incorporated into the analysis.

The Los Alamos National Laboratory (LANL), at the request of the NRC, reviewed several of these drain flow models and prepared an independent assessment on how the drain flow should be modeled (Reference 2). The main concern that LANL had was that the drain flow will induce a convective flow of the containment steam-air atmosphere because of the drag of the falling drops on the atmosphere. The induced convective air flow will reduce the relative drop-to-containment atmosphere velocity which will reduce the droplet convective heat transfer. Also, if the containment atmosphere is flowing, the absolute velocity of the droplets will be increased such that the residence time in the containment, i.e., the time available for heat transfer will be reduced. Both of these effects are heat transfer penalties because the droplet heat transfer is a,c

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The detailed responses to the LANL questions are covered in the following sections as well as the revised LOTIC-III drain and heat transfer model.

2.0 LANL EVALUATION OF LOTIC-III DRAIN MODEL

In Reference 2 the Los Alamos National Laboratory reviewed the LOTIC-III Ice Condenser Heat Transfer Models (Reference 1) and identified several questions on the models used in the methodology. These may be summarized as follows.

A. Falling-Drop-Flow-Field Velocity Analysis - Appendix A of Reference 2 presented the results of a simplified analysis of the drain flow which indicated that the droplet flow-field will cause steam entrainment, resulting in significant steam velocities. Therefore, the heat transfer from the droplet flow-field should be based on the velocity of the droplets relative to the moving steam, not on the absolute velocity of the droplets.

B. Drop Sizes - Appendix B of Reference 2 assessed drop size development for a spray from different theoretical models.

C. Drop Sizes from an Aerodynamically-Unstable Inviscid Liquid Sheet Appendix C of Reference 2 assessed liquid sheet breakup length from theoretical considerations as well as the drop size generated from the unstable liquid sheet.

D. Heat Transfer from Entrained Atmosphere to Spray - Appendix D of Reference 2 discussed the heat transfer from entrained atmosphere to spray. A correction factor, T, was derived to take into account the reduced effective temperature difference potential, $T-T_L$. The argument in the appendix is that the air/steam entrained in the spray has less communication to the ambient atmosphere. Therefore, the entrained air/steam temperature should be lower than the ambient temperature, hence lower $T-T_L$.

E. Turbulent-Diffusion Heat Transfer to a Uniform Distribution of Drops Appendix E of Reference 2 discussed the effectiveness of the heat transfer to a dispersion of drops. Such condition may be created by drain-flow spray interaction with cable trays. The argument is that the effective heat transfer is therefore less than the maximum heat transfer when the maximum temperature potential available applies everywhere.

F. Splash Analysis - Appendix F of Reference 2 concluded that the trajectory of the drain flow in a steam environment could significantly differ from the trajectory observed in the air tests. Hence, the angle of impact with equipment (e.g., steam generator), would be different, and so the splashing fraction of the drain flow would be different than indicated by the measurements.

3.0 WESTINGHOUSE RESPONSES TO LANL COMMENTS ON THE LOTIC-III DRAIN FLOW MODELS

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A. Falling-Drop-Flow-Field Velocity Analysis -

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B. Drop Sizes -

C. Drop Sizes from an Aerodynamically-Unstable Inviscid Liquid Sheet
The LANL analysis in Appendix C was to determine the sheet length at which the sheet would become unstable and break into a droplet field. Two types of liquid sheet instability were investigated: sinuous or flutter instability, and an aerodynamic liquid sheet tracing type of instability. The sinuous instability was investigated and the resulting drop sizes from a sheet breakup from a nozzle were larger than the data which LANL claims is as good as could be expected considering the gross assumptions.

LANL also looked at an analytical model for the breakup of a liquid sheet using the model they developed from the liquid sheet breakup from a nozzle. LANL used the gravitational acceleration applied to a sheet to calculate the sheet velocity as it falls. [

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The end result of the analysis does support the range of drop sizes observed in the tests as well as the liquid sheet lengths. Since a measurement basis was used in the LOTIC-III model development, the LANL calculations serve as a useful check that the experimental values were consistent with other drop size and liquid sheet information from similar situations.

D. <u>Heat Transfer from Entrained Atmosphere to Spray</u> - The derivation of the correction factor described in Appendix D of Reference 2 was reviewed. With the given assumptions and considerations in the derivation of the correction factor, it is the reviewer's opinion that the correction factor is appropriate for the stated purpose. A 0.96 factor will be applied to the temperature difference, as suggested by Reference 2. (See Appendix II for additional details.)

E. <u>Turbulent-Diffusion Heat Transfer to a Uniform Distribution of Drops</u> The model described in Appendix E of Reference 2 is judged to be appropriate only for the condition where uniform distribution of drops exists. For LOTIC-III applications, the penalty factor of 0.948 suggested in Reference 2 for steam atmosphere (instead of the 0.96 factor quoted above), should be applied to the temperature difference for drain flows impinging on cable trays. The numerical value of the effectiveness is affected by the expression of eddy momentum diffusivity and the turbulent Prandtl number. More solid reference should be provided to support the correctness of the current expression. (See Appendix III for additional details.)

F. <u>Splash Analysis</u> - Appendix F of Reference 2 examined the drain flow splashing fraction from a mechanistic point of view and obtained reasonable agreement between analysis and <u>W</u> measurement.

Appendix F of Reference 2 also commented that the angle of impact between the drain flow and a vertical surface could be affected by the drag on the drain water trajectory, and suggested that the fraction of the impacted drain flow going into film flow could be significantly greater in a steam atmosphere than in the air tests. a,c

4.0 REVISED LOTIC-III DRAIN MODEL METHODOLOGY

The paragraphs below describe the changes that were made to the Reference 1 LOTIC-III drain flow methodology to obtain the Revised LOTIC-III Methodology used in the Watts Bar and Catawba containment re-analysis presented in Section 5.0.

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Revised Droplet Flow-Field Velocities -

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5.0 LOTIC-III RE-ANALYSIS, RESULTS, AND DISCUSSION

LOTIC-III containment analyses were performed for the Watts Bar and Catawba plants incorporating the drain flow model modifications discussed in Section 4.0. To recapitulate, these model modifications consist of the following:

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The same mass and energy releases are used in the re-analysis as given in Reference 1. Also, the classification of the drains, shown in Figure 5-1 for Watts Bar and in Figure 5-4 for Catawba, is the same as used in Reference 1.

The re-analyzed containment pressures are shown in Figure 5-2 for Watts Bar and in Figure 5-5 for Catawba. As shown in these figures, the re-analysis resulted in 7.1 and 6.8 psig peak containment pressures for Watts Bar and Catawba, respectively, which are below the design pressure of 15 psig for the containment.

The re-analyzed containment temperatures are shown in Figure 5-3 for Watts Bar and Figure 5-6 for Catawba. As shown in these figures, the peak temperatures in the containment during a main steamline break with superheated steam release will remain below the environmental qualification temperature of 327 ^{o}F. The LOTIC-III containment temperature re-analysis results may be summarized as follows.

Plant	Original Peak Temp (^{o}F) (Ref.1)	LANL Mods Effect (net) (^{o}F)	Modified h_c + A Effect (^{o}F)	Revised Peak Temp (^{o}F)	E-Q Temp Limit (^{o}F)	Margin (^{o}F)
	[		]a,c			
Watts Bar				313.0	327	14.0
Catawba				322.0	327	5.0

The "LANL Mods Effect" represents the net penalty which results from incorporating the LANL-suggested modifications in the LOTIC-III drain model methodology. [

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Figure 5-1. Classification of Drains for Watts Bar

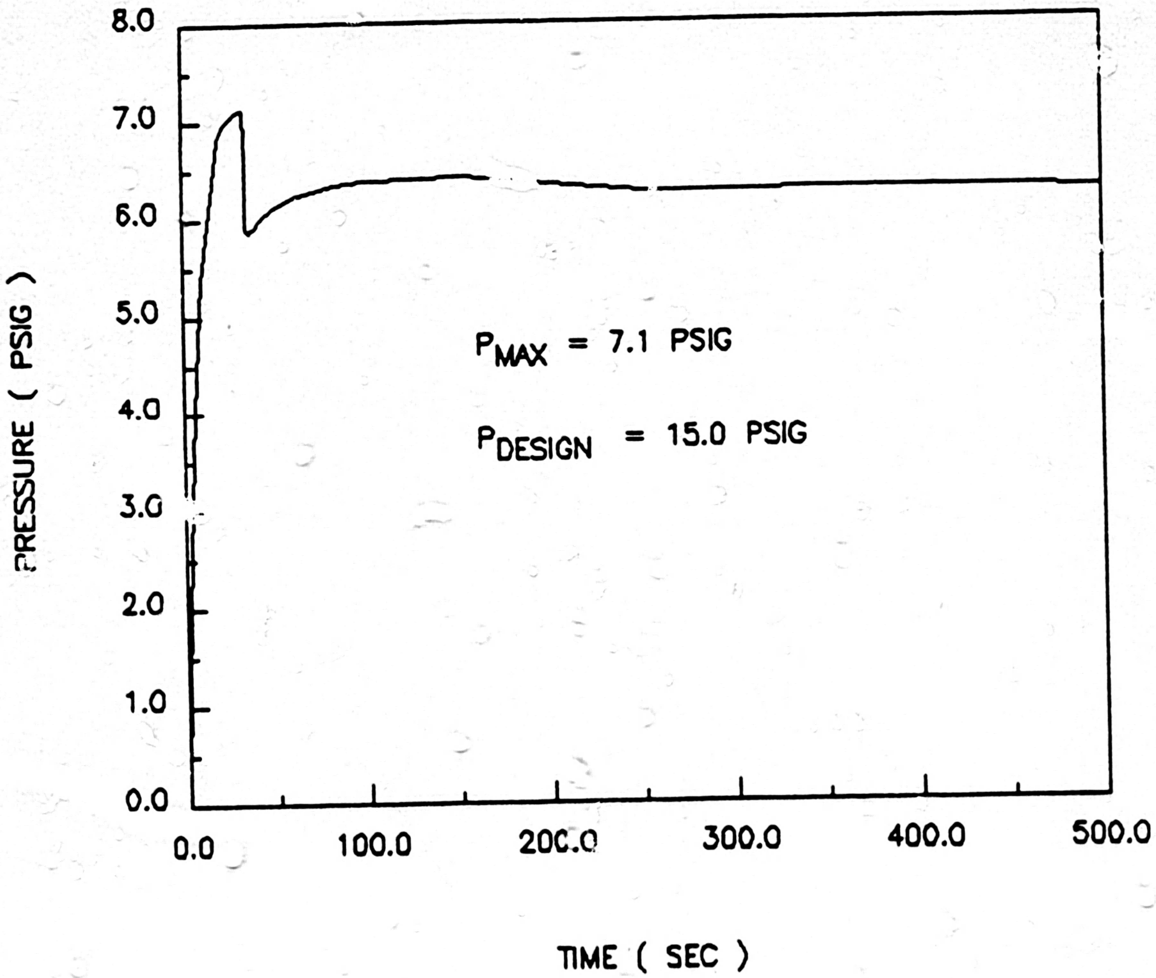

Figure 5-2. Watts Bar Containment Pressure Transient Calculated with Revised LOTIC-III Model

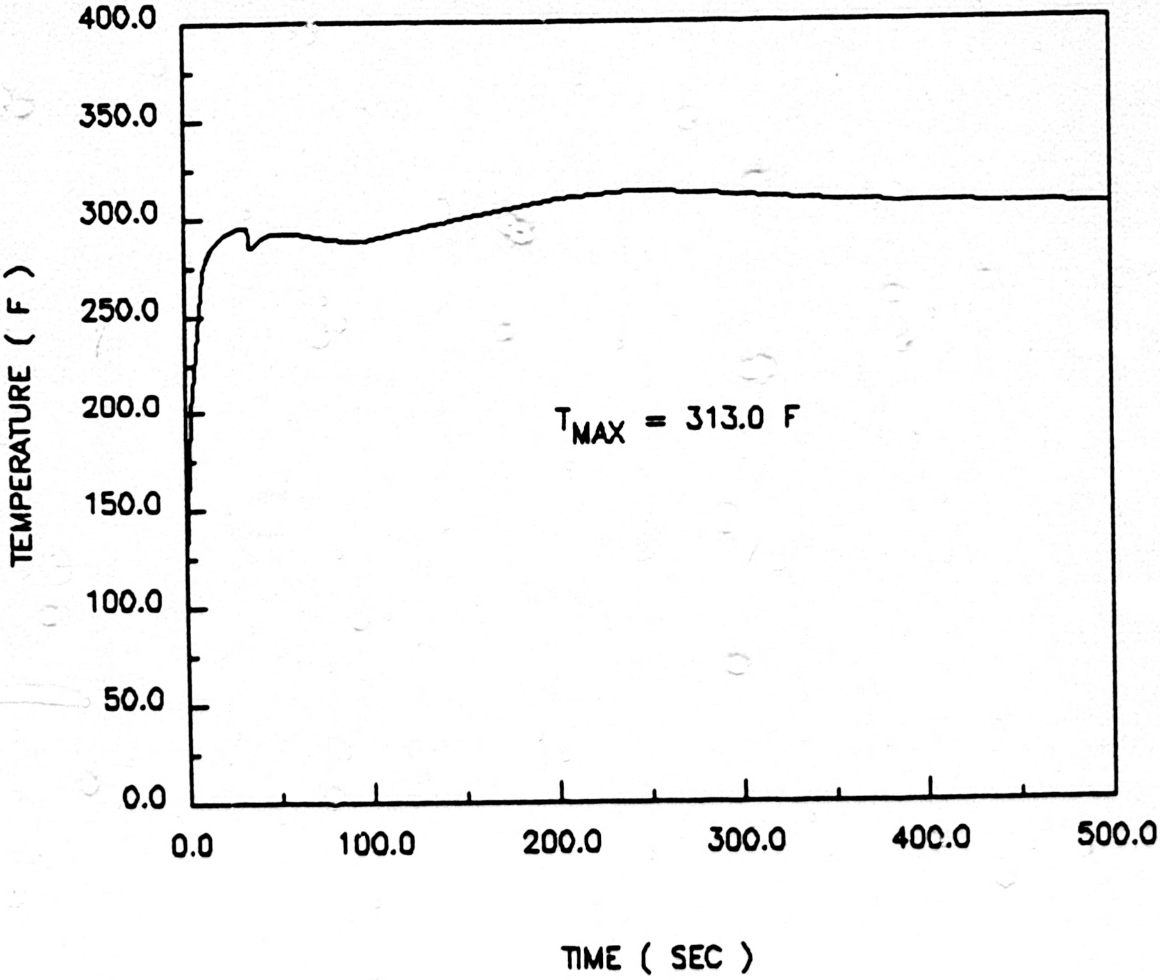

Figure 5-3. Watts Bar Containment Temperature Transient Calculated with Revised LOTIC-III Model

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Figure 5-4. Classification of Drains for Catawba

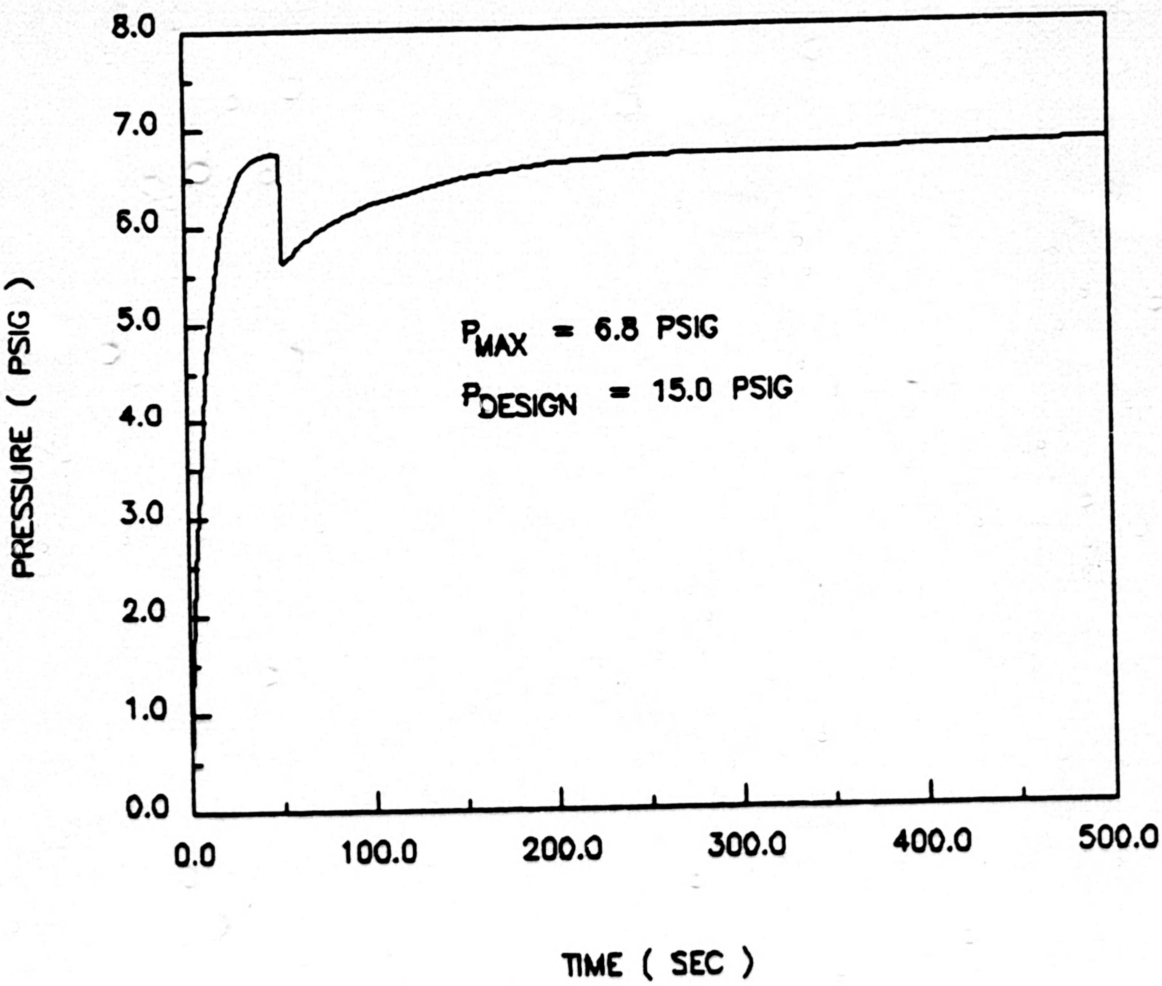

Figure 5-5. Catawba Containment Pressure Transient Calculated with Revised LOTIC-III Model

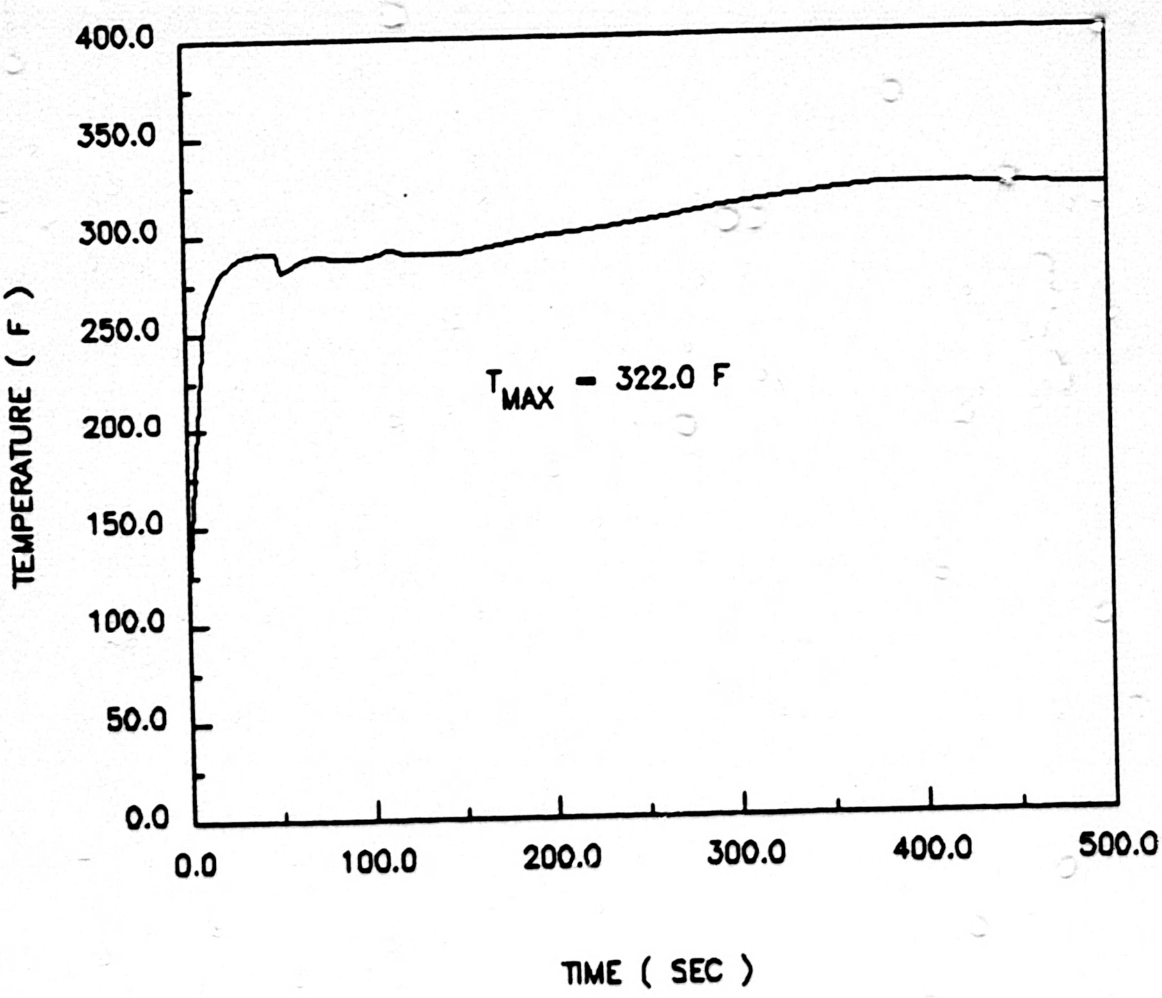

Figure 5-6. Catawba Containment Temperature Transient Calculated with Revised LOTIC-III Model

6.0 CONCLUSIONS

The evaluation conducted by LANL of the LOTIC-III ice-condenser containment drain flow and heat transfer models (Reference 1) produced several suggestions for the modification of these models (Reference 2). Incorporation of these modification in LOTIC-III resulted in higher peak containment temperatures. Most of the temperature penalty came from consideration of drain-flow-induced vapor velocities in the containment. a,c

7.0 NOMENCLATURE

A - Area, ft^2

A' - Droplet flow-field surface area per unit volume, ft^{-1}

A_T - Droplet surface area per unit volume integrated along flow trajectory, ft

C_{pG} - Specific heat of vapor, Btu/lbm-^oF

d_o - Droplet diameter, ft

f - Friction factor

h - Heat transfer coefficient, Btu/s-ft^2-^oF

k_G - Thermal conductivity of vapor, Btu/s-ft-^oF

L - Trajectory length, ft

$\dot{m}$ - Droplet mass flow rate, lbm/s

T_{cont} - Containment temperature, ^oF

U_G - Volocity of vapor/gas, ft/s

U_L - Velocity of liquid (droplet), ft/s

V_a - Absolute velocity of droplet ($V_a = U_L$), ft/s

V_r - Velocity of droplet relative to vapor/gas ($V_r = U_L - U_G$), ft/s

Z_1 - Liquid sheet breakup length, ft

Greek Symbols

μ_G - Viscosity of vapor/gas lbm/ft-s

ρ_G - Density of vapor/gas, lbm/ft^3

ρ_L - Density of liquid, lbm/ft^3

8.0 REFERENCES

(1) R. J. Davis, et al., "Ice Condenser Drain Test Results, Data Analysis, a' ' Development of Drain Flow Models for the LOTIC-III ˆondenser Code," WCAP-10986P, November 1985.

(2) A. Koestel and R. G. Gido, "Evaluation of Revised LOTIC-3 Drain Flow Heat Transfer Models," LA-UR-86-2053 (1987)

(3) R. B. Bird, W. E. Stuart, and E. N. Lightfoot, Transport Phenomena, John Wiley & Sons, Inc., 1960, pg. 401.

(4) C. L. Wheeler, et al., "COBRA-NC: A Thermal-Hydraulic Code for Transient Analysis of Nuclear Reactor components," NUREG/CR-3262, PNL-4710, Vol. 1, pg. 34.

Appendix I

VELOCITIES IN DROPLET FLOW-FIELD

Analysis

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Force balance on a droplet gives:

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Comparisons with Reference 2 Results

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Table I-1

Comparison of Computed Drain Flow-Field Velocities with Those Presented in Ref. 2

Velocities at 32 ft. (ft/s)	Atmos.	Drain Flow Rate 400 GPM Ref. 2	W(1)	1200 GPM Ref. 2	W	Steam/Air Ratio Ref. 2	W

a,c

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(1) W = This analysis

(2) 400 GPM/1200 GPM

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Figure I-1 Drain Flow Velocities at 400 gpm:
U_L= Droplet Velocity;
U_G= Gas Velocity;
U_L-U_G= Relative Velocity

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Figure I-2 Drain Flow Velocities at 1200 gpm:
U_L= Droplet Velocity;
U_G= Gas Velocity;
U_L-U_G= Relative Velocity

Appendix II
Review of Appendix D of Reference 2: Heat Transfer From Entrained Atmosphere To Spray

Introduction

Appendix D of Reference 2 discusses the heat transfer from entrained atmosphere to spray. (The references quoted in this appendix are listed in Section 8.0 of this report.) The appendix derived a correction factor, T, to take into account the reduced effective temperature difference potential, $T-T_\ell$. The argument in the appendix is that the air/steam entrained in the spray has less communication to the ambient atmosphere. Therefore, the entrained air/steam temperature should be lower than the ambient temperature, hence lower $T-T_\ell$.

The objectives of the review are to

1.) list the assumptions used in the derivation;

2.) check experimental procedure of the heat transfer coefficient correlation and identify if the experiment was a single droplet or a spray test;

3.) perform calculations for the correction factor with different drop velocities.

Based on the conclusion of the above tasks, one can determine if the correction factor is appropriate.

Review of the Derivation

The derivation employed the following assumptions:

1.) it is a 1-D model;

2.) the droplet number density is based on the assumption that drag force equals the drop weight;

3.) heat transfer coefficient employed considers primarily sensible heat only.

The derivation considers the upstream air/steam temperature and includes an entrainment term which accounts for the mixing from the ambient air/steam (with temperature T_0).

The derivation is found to be correct except that 4th equation on page 40 should be

$$(T_0-T)*(dm_g/m_g) = 12h/(c\alpha\delta\rho_\ell g)(T-T_\ell)du_g + dT$$

The Ranz-Marshall heat transfer coefficient is employed in the calculation. The original paper was reviewed. The experiment was conducted with single droplet at different air temperatures and velocities. Therefore, it is necessary to include the correction factor for the temperature difference potential.

With the above assumptions and considerations, it is the reviewers opinion that the derivation is appropriate for the entrained air/steam temperature calculation.

Calculations with Different U_g

Curves 1 and 2 in Figure II-1 show the correction factor, T, v.s. u_g without the correction of α mentioned earlier. For both air and steam, T is decreasing with increasing u_g. This is reasonable since higher u_g leads to better heat transfer between the droplet and the surrounding air/steam, hence lower air/steam temperature.

Curves 3 and 4 in Figure II-1 show the correction factor, T, v.s. u_g with the correction of α for steam and air, respectively. The value of α used in these calculations is 0.9. It is found that with α included, T is smaller.

Conclusion

The derivation of the correction factor described in the Appendix D of Reference 2 is reviewed. With given assumptions and considerations in the derivation of the correction factor, it is the reviewer's opinion that the correction factor is appropriate for the stated purpose. A value of T=0.96 is used for steam case as suggested by Reference 2.

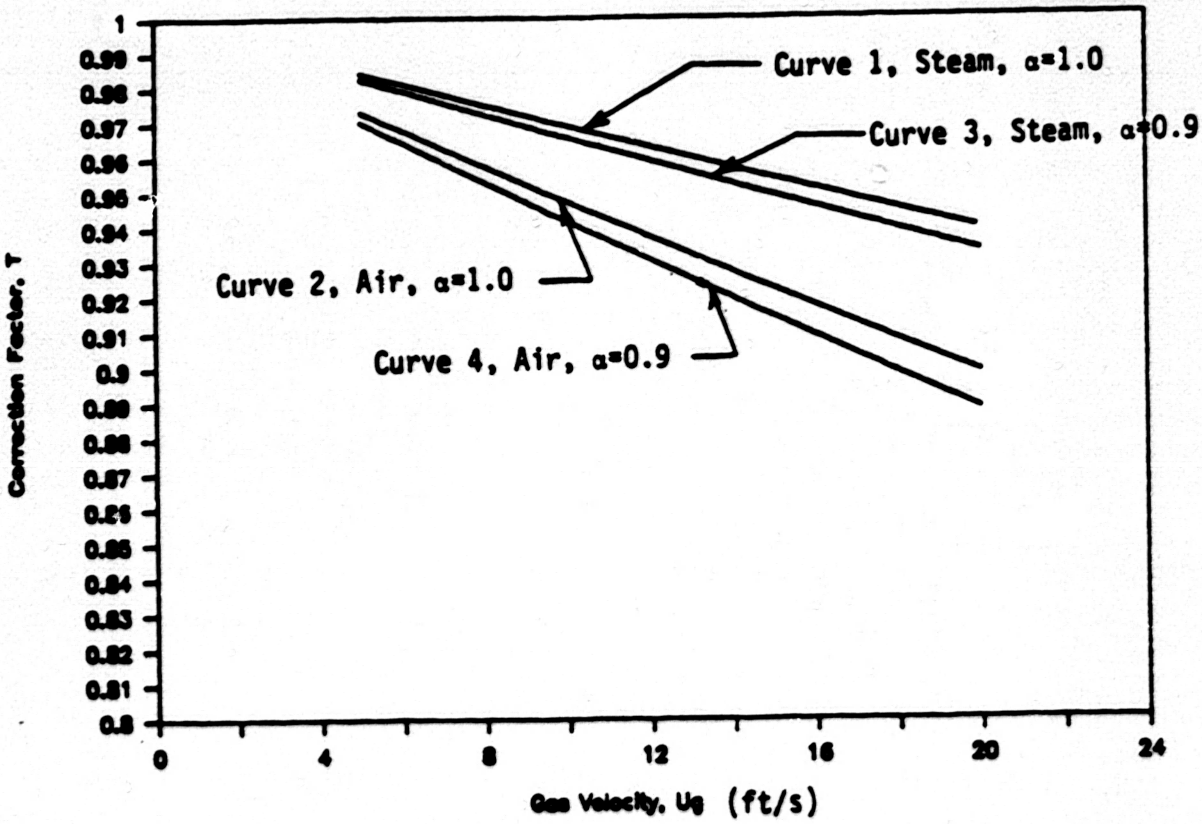

Figure II-1 Correction Factor, T, vs. Gas Velocity, u_g

Appendix III
Review of Appendix E of Reference 2: Turbulent-Diffusion Heat Transfer to a Uniform Dispersion of Drops

Introduction

Appendix E of Reference 2 discusses the effectiveness of the heat transfer to a dispersion of drops. (The references quoted in this Appendix are listed in Section 8.0 of this report.) Such condition may be created by drain-flow spray interaction with cable trays. The argument is that the effective heat transfer is therefore less than the maximum heat transfer when the maximum temperature potential available applies everywhere.

The objectives of the review are to:

1.) list the assumptions used in the derivation;

2.) review the derivation;

3.) review the eddy diffusivity used in the derivation.

Based on the results of the above objectives, one can determine if the model presented in Appendix E is appropriate.

Review of the Derivation

The derivation employed the following assumptions:

1.) it is a 1-D model;

2.) the heat transfer is assumed to be controlled by turbulent propagation only;

3.) uniform distribution of drop heat sinks is assumed.

4.) round turbulent jet is assumed

With the above assumptions the derivation is judged to be correct except typos in the equation above Equation E-4, and Equation E-6. The correct expressions should be:

$$(\theta)_{x=\ell L} = \theta_0$$

and

$$q_t = (A_\ell h \epsilon \rho c/V)^{1/2} \theta_0 \tanh[(A_\ell h/V\epsilon\rho c)^{1/2} L]$$

for Equation above Equation E-4, and Equation E-6, respectively.

It is not clear how the eddy diffusivity ϵ and the Pr_t=0.7 were obtained by the authors (Equation E-10). Reference 14 has been reviewed and there is no direct connection between the equation and the referenced document. However, the authors stated to this reviewer (Tsai) that they had been using Equation E-10 in the past and have confidence in the correctness of the expression of eddy diffusivity and the value of the turbulent Prandtl number. The definition of Equation E-11 stated on page 46 should be changed to "ϕ is the dissipation <u>rate</u> per <u>unit gas mass</u> of the potential energy of the falling spray". The expression of Equation E-11 would then be consistent with the definition.

The mixing length used in Appendix E is for a free round turbulent jet (ℓ = 0.075 δ, where δ is the width of the spray, see paper 2 in Reference 14).

<u>Conclusion</u>

The model described in Appendix E is judged to be appropriate only for the condition where uniform distribution of drops exists. For LOTIC-III applications, the penalty (as suggested by Reference 2 for steam case, 0.948) should be taken where cable trays exist only. The numerical value of the effectiveness is affected by the expression of eddy momentum diffusivity and the turbulent Prandtl number. More solid reference should be provided to support the correctness of the current expression.

Appendix IV

DRAIN FLOW TRAJECTORY

Analysis

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Results/Conclusions

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Figure IV-1 Droplet Trajectory for 400 gpm Drain Flow

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Figure IV-2 Droplet Trajectory for 1200 gpm Drain Flow