UEC-TR-006-SUP
JUNE, 1979

CONTRAST-S MOD1

A DIGITAL COMPUTER PROGRAM TO PREDICT CONTAINMENT PRESSURE-TEMPERATURE RESPONSES

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1. INTRODUCTION

The CONTRAST-S MOD1 is an extension of the basic computer program CONTRAST-S[1] to include the capability for predicting containment pressure-temperature transients following high energy line ruptures which result in superheated conditions in the containment atmosphere following the accidents. A Main Steam Line Break (MSLB) is an example of such an accident. The proper treatment of superheated conditions in the containment atmosphere required some modifications in the mathematical modeling of CONTRAST-S. The modifications have been described in the following sections.

2. MATHEMATICAL MODELING

Modeling of the containment has been extensively described in Reference 1. In this section only the deviations from the basic model to simulate the superheated conditions in the containment atmosphere have been outlined.

2.1 Containment Heat Removal By Sprays

The spray droplets traveling through the containment atmosphere absorb energy before being collected in the sump. The amount of energy absorbed is limited by the final temperature of the spray droplets which is expressed as (See Reference 1):

$$T_s = T_i + \eta(T_c - T_i) \tag{1}$$

where T_i = Spray droplet initial temperature (^oF),

T_s = Spray droplet final temperature before entering sump (^oF),

T_c = Containment atmospheric temperature (^oF),

η = Spray efficiency (fractional).

In a saturated containment atmosphere the spray droplets approaches the containment temperature (Refs. 2,3) within a few seconds depending on the droplet sizes.

In the superheated containment atmosphere the determination of the final temperature of spray droplets is somewhat different. It can be demonstrated by considering heat and mass transfer between the spray droplet and the containment atmosphere that the final droplet temperature regardless of the droplet size approaches the containment saturation temperature which can be much lower than the containment atmospheric temperature for highly superheated containment environments. Hence, the droplet reach a final temperature which can be expressed as:

$$T_s = T_i + \eta(T_{sat} - T_i), \tag{2}$$

where T_{sat} is the containment saturation temperature at the partial pressure of vapor. If the final temperature of the spray droplets is assumed to be the containment saturation temperature,the spray efficiency remains unity for all degrees of superheat.

The energy removal rate from the containment atmosphere is given by

$$q_s = \eta c M_s (T_s - T_i), \tag{3}$$

where q_s = Spray energy removal rate (Btu/hr),

M_s = Spray flow rate (lbm/hr),

c = Specific heat of spray water (Btu/lbm-°F),

2.2 Containment Heat Removal By Fan Coolers

The heat removal rate in a superheated containment atmosphere is expressed as follows:

$$q_c = \sum_{n=0}^{N} A_n T^n_{sat} + \sum_{n=0}^{M} B_n T^n_{sup}, \tag{4}$$

where T_{sat} and T_{sup} are containment saturation temperature and degree of superheat, respectively. A's and B's are constants for a particular fan cooler system and are usually obtained from manufacturer's performance data for a specific application.

2.3 Heat Transfer Model for Passive Heat Sinks

The heat transfer to the passive heat sink is considered to be consisting of a condensing part and a convective part. The heat flux to a heat sink is expressed as follows:

$$q_{hs} = f\ (h_{cond} - h_{conv})\ (T_{sat} - T_{wall}) + h_{conv}\ (T_{con} - T_{wall}), \quad (4)$$

where

q_{hs} = Heat flux (Btu/hr-ft^3)

h_{cond} = Condensing heat transfer coefficient (Btu/hr-ft^2-^{o}F),

h_{conv} = Convective heat transfer coefficient (Btu/hr-Ft^2-^{o}F),

T_{sat} = Containment saturation temperature (^{o}F),

T_{wall} = Heat sink surface temperature (^{o}F),

T_{con} = Containment dry bulb temperature (^{o}F),

f = 1 if $T_{sat} > T_{wall}$, otherwise zero .

When the heat sink temperature exceeds the saturation temperature the condensing heat transfer vanishes. The condensing heat transfer coefficient has been discussed in Appendix D of Reference 1.

2.4 Condensate Removal From Containment Atmosphere

The condensate produced by the condensation of vapor on the heat sink surface or on the fan cooler coils is assumed to fall to the sump. The condensate removal rate is calculated as follows:

$$M_c = q/h_{fg}, \quad (5)$$

where

M_c = Condensate removal rate (lbm/hr),

q = Heat transfer to the heat sink or the fan cooler due to condensation (Btu/hr),

h_{fg} = Latent heat of vaporization of steam at containment saturation temperature (Btu/lbm).

In a superheated containment if the passive heat sink surface temperature exceeds the saturation temperature no condensate is produced.

The condensate removal from the bulk containment atmoshphere is described in Reference 1.

4. REFERENCES

1. Niyogi, K. K. and Rathi, J. S., "Prediction of Containment Pressure-Temperature Transients Using CONTRAST-S - A Digital Computer Program," UEC-TR-006-0, March 1976.

2. Chung, J. N. and Ayyaswamy, P. S., "The Effect of Internal Circulation on the Heat Transfer of a Nuclear Reactor Containment Spray Droplet", Nuclear Technology Vol. 35, October 1977, pp 603-610.

3. Parsly, L. E.,"Design Considerations of Reactor Containment Spray Systems Part VI - The Heating of Spray Drops in Air-Steam Atmosphere", ORNL-TM-2412, Part VI, January 1970.

ATTACHMENT II

RESPONSES
TO REQUEST FOR ADDITIONAL
INFORMATION ON TOPICAL REPORT: CONTRAST-S
(UEC-TR-006-0)

RAI 1.

On page 2, reference is made to other containment heat removal devices. Identify the specific devices that are considered.

RESPONSE

The containment heat removal devices other than the sprays and the fan coolers are the Containment Spray (CS) heat exchangers, Residual Heat Removal (RHR) heat exchangers and the Primary Component Cooling Water (PCCW) heat exchanger. A detailed description of these devices can be found in Section 3.2.2.3 of the Topical Report.

RAI 2.

In Section 3.2.1, spray efficiency is indicated to be a function of air-steam content of the containment atmosphere. Provide the analytical model and/or empirical data which are used and the supporting basis. In addition, discuss how the nozzle design, droplet size and fall height are considered in the determination of spray efficiency. Note all parameters that must be considered on a case-by-case basis.

RESPONSE

The temperature reached by the spray droplets with respect to the containment atmosphere temperature is dictated by the spray efficiency. Reference 1 shows that the spray efficiency can be expressed as a function of steam-air mass ratio in the containment, and it approaches unity when the ratio reaches slightly over unity. For a typical LOCA this occurs within a few seconds after the accident and much earlier than the time when the sprays are initiated.

Reference 2 has demonstrated that in the case of saturated containment atmosphere the spray droplets with sizes ranging from 100μ to 1500μ which represent a typical spectrum of droplet sizes, reach practically containment atmosphere temperature within 0.1 to 3 seconds. During this period the droplets fall a height of approximately 0.1 to 60 ft, estimated on the basis of their respective terminal velocities. For a typical PWR containment virtually all of the droplets experience fall heights that are larger than those required to reach thermal equilibrium with the containment atmosphere.

RAI 3.

For superheated containment conditions, describe how the spray efficiency is determined. If the final spray water temperature is allowed to exceed the saturation temperature, supporting data should be provided.

RESPONSE

In the situations where the containment atmosphere is superheated the degree of superheating has a very pronounced effect on the equilibrium temperature of the spray droplets. By considering heat and mass transfer between the spray droplet and the containment atmosphere it can be demonstrated that the final droplet temperature approaches only the containment saturation temperature regardless of the droplet size and the air-steam ratio of the containment atmosphere. Therefore the final droplet temperature can be much lower than the containment atmospheric temperature for highly superheated environments. The cold spray droplets are heated up during their initial fall primarily through condensation of the containment vapor then the droplets start evaporating at a constant equilibrium temperature, which is essentially the saturation temperature corresponding to the partial pressure of vapor.

The spray efficiency, η, for the superheated environment is expressed as follows:

$$\eta = \frac{T_s - T_i}{T_{sat} - T_i} ,$$

T_s = spray droplet final temperature,

T_i = spray droplet initial temperature,

T_{sat} = containment saturation temperature.

According to the definition, the spray water temperature is not allowed to exceed the saturation temperature. However, it is to be noted that the saturation temperature is approached faster in the case of a superheated atmosphere than a saturated atmosphere.

RAI 4.

The fan cooler model as described in Section 3.2.2.2 does not appear to adequately address several areas. Therefore, provide additional information in the following areas:

a. The heat transfer to the fan cooler coils does not differentiate between saturated and superheated containment conditions, Therefore, for superheated containment conditions, provide justification for using vapor temperature rather than the saturation temperature (Equation 3.2.2.2.1)).

b. Provide the basis for not considering the condensate removed from the fan cooler coils.

c. Since fan cooler designs may differ, identify the interface parameters which must be considered on a case-by-case basis.

RESPONSE

4a. The heat removal rate by the fan coolers expressed in Eq. 3.2.2.2.1 corresponds to a saturated containment atmosphere where the vapor temperature is equal to the saturation temperature. In the case of superheated containment conditions, the heat transfer to the fan cooler coils is determined as a function of the saturation temperature and the degree of superheat. The model has been described in Reference 3.

b. Provisions exist to consider the condensate removal from the fan cooler coils. The method has been described in Reference 3.

c. The parameters which contribute most in the heat transfer to the fan cooler coils are the atmospheric saturation temperature, degree of superheat, steam-air ratio and the containment pressure. It might be difficult to develop performance characteristics of a fan cooler as explicit functions of all the above parameters. However, for a specific application, considering the ranges of interest of the above parameters a simplified but conservative expression can be established for the heat removal rate of the fan cooler as a sum of functions of saturation temperature and the degree of superheat.

RAI 5.

Provide the basis for not considering condensate removal from the atmosphere due to condensation on the heat sink surfaces when the containment atmosphere is superheated. Additionally, provide justification for using vapor rather than saturation temperature when computing heat transfer to sinks in a superheat condition.

RESPONSE

Reference 3 outlines the model used to consider the condensate removal from the atmosphere due to condensation on the heat sink surfaces. When the containment atmosphere is superheated, the condensation of water vapor on the passive heat sink surface occurs as long as the heat sink surface temperature is lower than the containment saturation temperature. This condensate is added to the sump without accounting for any re-evaporation.

The heat transfer to passive heat sinks is a combination of condensing heat transfer and convective heat transfer. The condensing heat transfer rates are usually much higher than the convective heat transfer rates until the heat sink surface temperature approaches the containment saturation temperature. When the heat sink temperature exceeds the saturation temperature the condensing heat transfer ceases. For the condensing heat transfer the saturation temperature is used and for the convective heat transfer the containment atmospheric temperature is considered.

RAI 6.

The heat transfer correlations of Tagami and Uchida are based on experiments considering saturated steam-air mixtures. Discuss the effect on heat transfer to the passive heat sinks when (1) the containment atmosphere is superheated and the heat sink surface temperature is less than the temperature of saturated steam and (2) the heat sink's surface temperature is greater than the temperature of saturated steam.

RESPONSE

The heat transfer to the passive heat sinks is partly due to condensation and partly due to convection when the heat sink surface temperature is below the saturation temperature as explained in (5), above. The heat transfer correlations of Tagami and Uchida are used to calculate the condensing heat transfer part whereas a convective heat transfer coefficient is used to calculate the convective part. When the heat sink temperature exceeds the saturation temperature no condensing heat transfer occurs and only the convective heat transfer is calculated.

RAI 7.

The coefficients within equation A-3 appear to be low. Verify the correctness of the values provided.

RESPONSE

Equation A-3 has typographical errors and the corrected form is as follows:

$$P_s = 3206.18232 \exp \left(\frac{-Y}{T + 459.58}\right) .$$

RAI 8.

Appendix D provides the heat transfer models used for LOCA containment analysis. Clarify whether or not the same models are used for a MSLB. If different, provide similar information for the MSLB. Include the models used when the heat sink temperature exceeds the saturation temperature.

RESPONSE

The heat transfer to a passive heat sink is calculated following a MSLB as follows :

$$q_{hs} = f \, (h_{cond} - h_{conv}) \cdot (T_{sat} - T_{wall}) + h_{conv} \, (T_{con} - T_{wall}) ,$$

where

q_{hs} = heat flux,

h_{cond} = condensing heat transfer coefficient from Appendix D of Reference 1,

h_{conv} = convective heat transfer coefficient,

T_{sat} = containment saturation temperature,

T_{wall} = heat sink surface temperature,

T_{con} = containment dry bulb temperature,

f = 1 if $T_{sat} > T_{wall}$, otherwise, zero.

It is to be noted that if the containment atmosphere is saturated the above expression becomes identical to Equation 3.2.2.4.1 used for LOCA analysis.

RAI 9.

Provide the models and assumptions used to compute the condensate associated with the heat transfer to passive heat sinks. The information should include the methods used to compute mass and temperature for both saturated and superheated containment conditions.

RESPONSE

The condensate mass associated with the heat transfer to passive heat sinks is computed as follows:

$$M = q/h_{fg} ,$$

where

M = condensation rate on passive heat sinks,

q = heat flux to heat sink by condensation,

h_{fg} = latent heat of vaporization of steam at containment saturation temperature.

In a superheated containment atmosphere the condensation ceases as soon as a heat sink surface reaches containment saturation temperature. The condensate is added to the sump at the containment saturation temperature.

RAI 10.

Provide the criteria and bases used to determine the heat sink nodalization for both steel and concrete structures.

RESPONSE

The heat transfer to the passive heat sinks is computed in the CONTRAST-S code by solving the partial differential heat conduction equation using a fully implicit finite difference scheme which is unconditionally stable. The expression for the truncation error indicates, however, that one should limit the grid spacings and the time steps. By decreasing the grid spacing and the time increment the accuracy of the solution can be improved. On the other hand, Reference 4 suggests that in order to avoid large meaningless fluctuations in the solution the grid spacings should be limited by the following criterion for a preselected time step :

$$M = \frac{\Delta x^2}{\alpha \Delta t} \geq 1 + \frac{h \Delta x}{K},$$

where

Δx = grid spacing,

Δt = time increment,

α = thermal diffusivity of the material,

h = heat transfer coefficient for the heat sink surface,

K = thermal conductivity of the material.

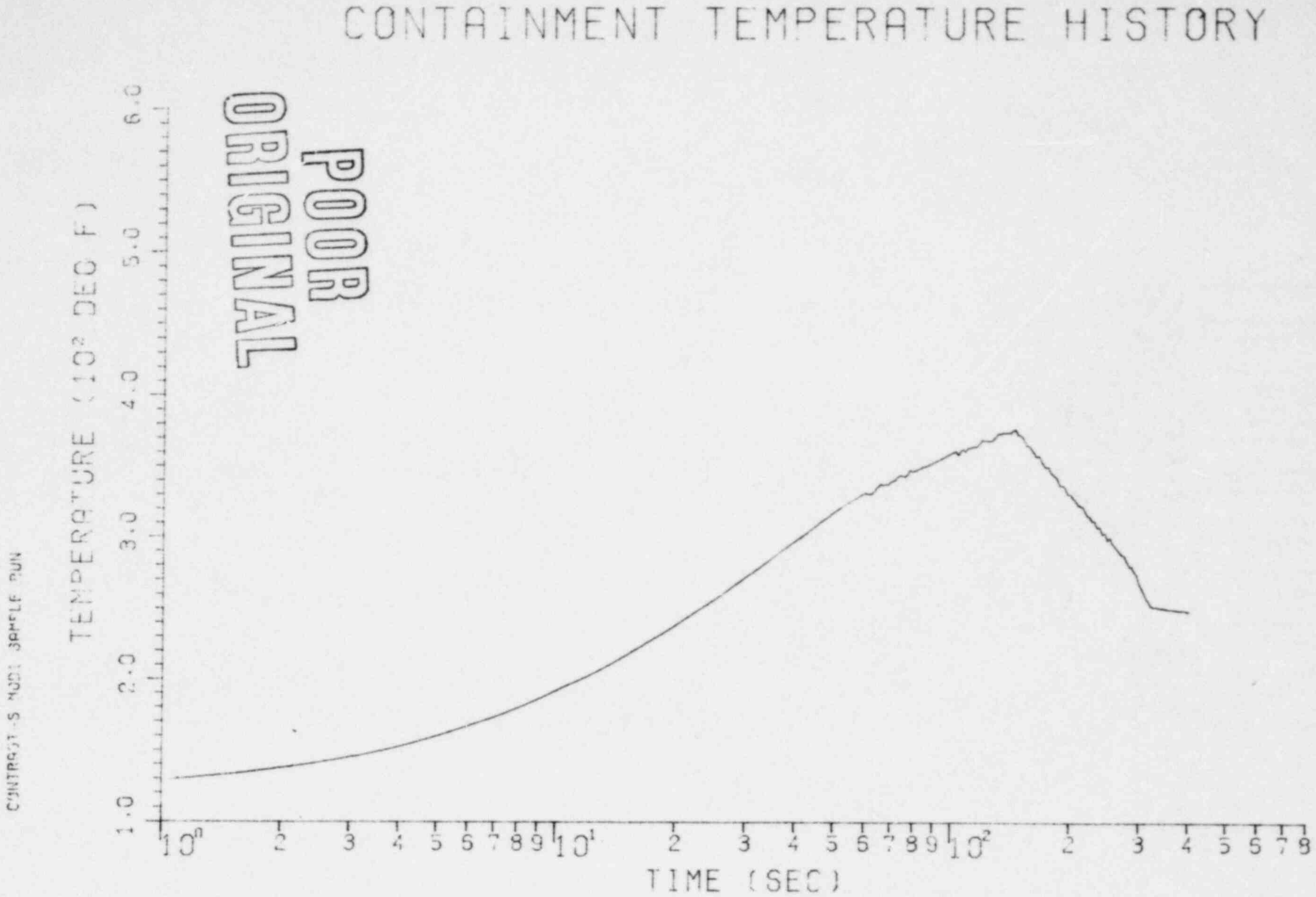

Figure 2 Containment Temperature Response Following a MSLB

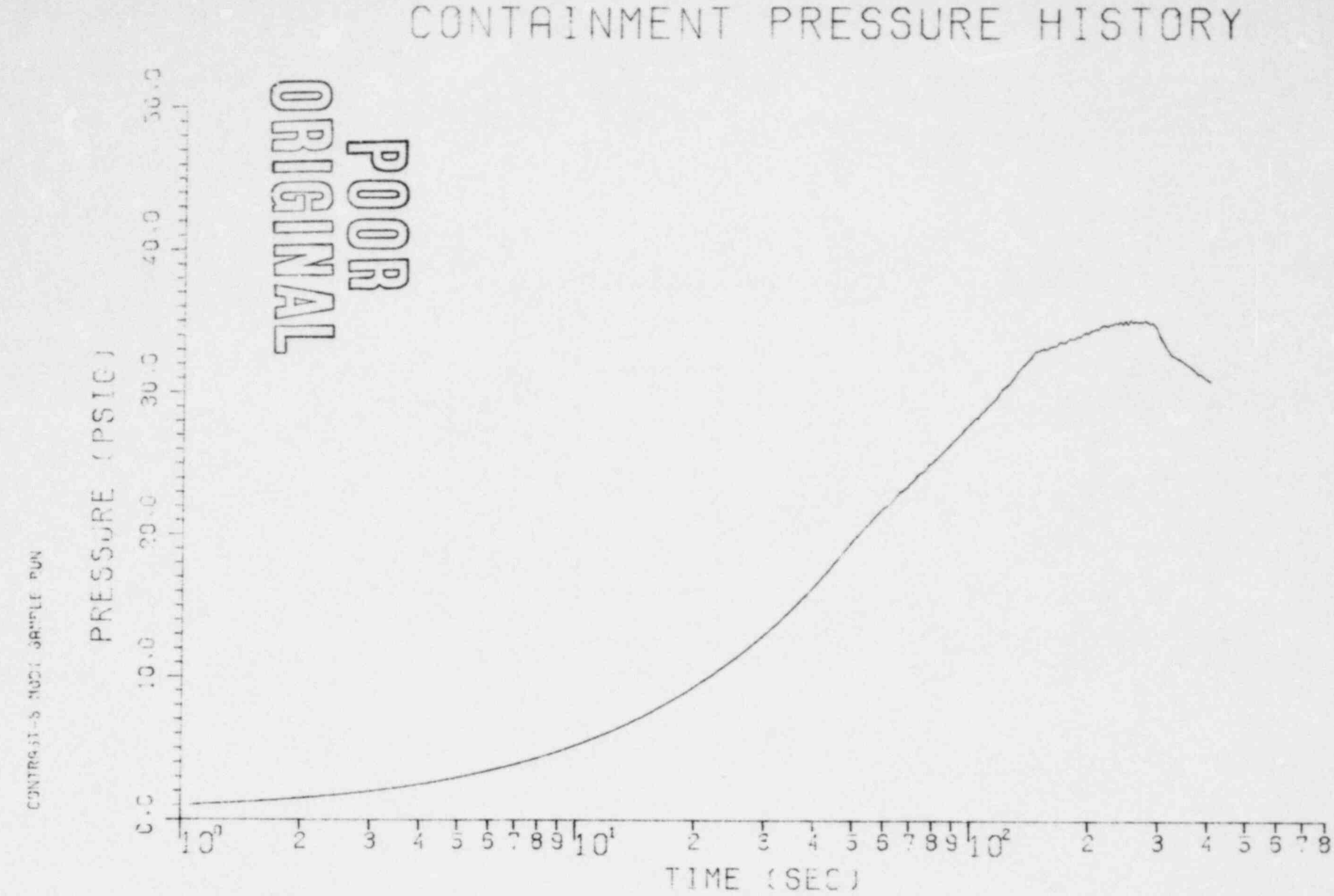

Figure 1 Containment Pressure Response Following a MSLB

TABLE 3

MASS AND ENERGY RELEASE DATA FOR

SAMPLE PROBLEM

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 TIME(SEC)          FLOW RATE(LBS/SEC)     ENTHALPY(BTU/LB)        TIME(SEC)          FLOW RATE(LBS/SEC)     ENTHALPY(BTU/LB)
0.                     2.15600E 03          1.18810E 03          1.00000E 00             2.13600E 03          1.18870E 03
2.00000E 00            2.10800E 03          1.18930E 03          3.00000E 00             2.08000E 03          1.18980E 03
4.00000E 00            2.05200E 03          1.19030E 03          5.00000E 00             2.02800E 03          1.19080E 03
6.00000E 00            2.00800E 03          1.19120E 03          7.00000E 00             1.98400E 03          1.19160E 03
8.00000E 00            1.96400E 03          1.19200E 03          9.00000E 00             1.94800E 03          1.19230E 03
1.00000E 01            1.93200E 03          1.19260E 03          1.10000E 01             1.91600E 03          1.19290E 03
1.20000E 01            1.90000E 03          1.19320E 03          1.30000E 01             1.88400E 03          1.19340E 03
1.40000E 01            1.87200E 03          1.19370E 03          1.50000E 01             1.85600E 03          1.19390E 03
1.75000E 01            1.82800E 03          1.19440E 03          2.00000E 01             1.80000E 03          1.19490E 03
2.25000E 01            1.77600E 03          1.19530E 03          2.50000E 01             1.75200E 03          1.19570E 03
2.75000E 01            1.73200E 03          1.19600E 03          3.00000E 01             1.71600E 03          1.19630E 03
3.50000E 01            1.68800E 03          1.19670E 03          4.00000E 01             1.67200E 03          1.19690E 03
4.50000E 01            1.66400E 03          1.19710E 03          4.58000E 01             1.66300E 03          1.19710E 03
4.58010E 01            1.66300E 03          1.20500E 03          4.68000E 01             1.63100E 03          1.20500E 03
4.78000E 01            1.57700E 03          1.20500E 03          4.88000E 01             1.52800E 03          1.20500E 03
4.98000E 01            1.48500E 03          1.20500E 03          5.09000E 01             1.44500E 03          1.20500E 03
5.18000E 01            1.41000E 03          1.20500E 03          5.28000E 01             1.37900E 03          1.20500E 03
5.38000E 01            1.34700E 03          1.20500E 03          5.48000E 01             1.31500E 03          1.20500E 03
5.58000E 01            1.28500E 03          1.20500E 03          5.68000E 01             1.25400E 03          1.20500E 03
5.78000E 01            1.22600E 03          1.20500E 03          5.88000E 01             1.19700E 03          1.20500E 03
5.98000E 01            1.17200E 03          1.20500E 03          6.08000E 01             1.14900E 03          1.20500E 03
6.33000E 01            1.09900E 03          1.20500E 03          6.58000E 01             1.05900E 03          1.20500E 03
6.83000E 01            1.02600E 03          1.20500E 03          7.08000E 01             9.96000E 02          1.20500E 03
7.33000E 01            9.75000E 02          1.20500E 03          7.58000E 01             9.55000E 02          1.20500E 03
8.08000E 01            9.20000E 02          1.20500E 03          8.58000E 01             8.93000E 02          1.20500E 03
9.08000E 01            8.70000E 02          1.20500E 03          9.58000E 01             8.48000E 02          1.20500E 03
1.05800E 02            8.17000E 02          1.20500E 03          1.15800E 02             7.85000E 02          1.20500E 03
1.25800E 02            7.58000E 02          1.20500E 03          1.35800E 02             7.35000E 02          1.20500E 03
1.45800E 02            7.12000E 02          1.20500E 03          1.65800E 02             6.74000E 02          1.20500E 03
1.85800E 02            6.37000E 02          1.20500E 03          2.05800E 02             5.79000E 02          1.20500E 03
2.25800E 02            4.74000E 02          1.20500E 03          2.45800E 02             4.07000E 02          1.20500E 03
2.88700E 02            3.06000E 02          1.20500E 03          2.88701E 02             0.                   1.20500E 03
4.01000E 02            0.                   1.20500E 03
```

POOR
ORIGINAL

TABLE 2
(Cond't)

HEAT SINK	MATERIAL	AREA(Ft^2)	THICKNESS(in.)
Miscellaneous Steel (Cont'd)			
Heat sink #11	Polar crane & tracks	19,920[a]	
	Paint		0.008
	Carbon steel		0.717
Heat sink #12	Equipment steels	5,960[a]	
	Paint		0.008
	Steel		1.12
Containment Floor	Painted concrete	11,640[b]	
	Paint		0.008
	Concrete		48
	Steel liner		1/4
	Concrete		108
Containment Sump	Painted concrete	884[b]	
	Paint		0.008
	Concrete		108

MATERIAL DATA

Material	Conductivity (Btu/hr-ft-^{o}F)	Volumetric Heat Capacity (Btu/ft^3-^{o}F)
Paint	6.0	36.05
Carbon Steel	26.0	521.0
Stainless Steel	9.3	56.0
Air Gap	0.0184	0.0173
Concrete	0.83	29.0

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a - one side exposed to containment atmosphere and the area corresponds to one side

b - one side exposed to containment sump water and the area corresponds to one side

c - two sides exposed to containment atmosphere and the area corresponds to two sides

d - two sides exposed to containment atmosphere and the area corresponds to one side

TABLE 2

STRUCTURAL HEAT SNIKS AND MATERIAL DATA

HEAT SINK	MATERIAL	AREA(ft^2)	THICKNESS(in.)
Containment Cylinder	Steel-lined concrete	63,774[a]	
	Paint		0.008
	Carbon Steel		3/8
	Air gap		1/16
	Concrete		54
Containment Dome	Steel-lined concrete	30,788[a]	
	Paint		0.008
	Carbon steel		1/2
	Air gap		1/16
	Concrete		42
Miscellaneous Concrete			
Heat sink #3	Painted concrete	5,900[c]	
	Paint		0.008
	Concrete		12
	Paint		0.008
Heat sink #4	Unlined concrete	12,559[c]	
	Concrete		24
Heat sink #5	Painted concrete	8,382[c]	
	Paint		0.008
	Concrete		36
	Paint		0.008
Heat sink #6	Unpainted concrete	6,747[c]	
	Concrete		36
Heat sink #7	Unlined concrete	53,688[c]	
	Concrete		48
Heat sink #8	SS-lined refueling canal	7,157[d]	
	Stainless steel		0.198
	Concrete		48
Miscellaneous Steel			
Heat sink #9	Galvanized duct & trays	67,654[a]	
	Steel		0.0875
Heat sink #10	Painted steel structures	61,085[a]	
	Paint		0.008
	Steel		0.269

TABLE 1

GENERAL CONTAINMENT INFORMATION

Pressure, psig	.5
Inside Temperature, ^{o}F	120
Outside Temperature, ^{o}F	90
Relative Humidity, %	90
Refueling Water Temperature, ^{o}F	88
Containment Free Volume, Ft^3	2.715×10^6
Containment Spray Flow Rate, gpm	3000

3. SAMPLE PROBLEM

The pressure-temperature transients are analyzed in a typical PWR containment following a Main Steam Line Break accident. The containment physical data and the passive heat sink information are provided in Tables 1 and 2. The mass and energy release for a split rupture in a main steam line are given in Table 3.

The containment pressure-temperature responses are illustrated in Figures 1 and 2.

For a typical situation in computing the containment pressure-temperature transients (say, h = 80 Btu/hr-ft^2-^{o}F, K = 0.83 Btu/hr-ft-^{o}F for concrete, α = 0.028 ft^2/hr) with time steps of one second, the grid spacings in concrete should be greater than .038 inch to satisfy the above criterion.

In order to establish the upper limit of the grid spacings in concrete a sensitivity study[5] has been performed. It has been observed that the heat sink surface temperature is underestimated and as a consequence the containment heat removal rate is overestimated resulting in lower prediction of the containment pressure, unless the grid spacings considered are small enough. Grid spacings of 0.05 inch for a few inches in concrete is considered to be adequate. Relatively larger grid spacing have been found to be adequate for steel heat sinks, due to decreased temperature gradients.

RAI 11.

Specify whether or not the gap heat transfer coefficient between liner and concrete is to be determined on a case-by-case basis. If on a generic basis, provide the value and the supporting basis.

RESPONSE

In order to predict maximum pressure in the containment a hypothetical gap is considered which accounts for the interfacial resistance. Because of the nature of the hypothesis a case-by-case determination is utilized.

In the heat conduction model used in CONTRAST-S, the interface conductance is modeled as an equivalent air gap of constant thickness (typically, 1/16 inch). Experiemental data (References 6 and 7) show values of interface conductance varying fromm 100,000 Btu/hr-ft^2-^{o}Ffor a very good contact to 10 Btu/hr-ft^2-^{o}F for a very poor contact in vacuum. The lower limit corresponds to an equivalent conductance of an approximately 20 mil thick air gap.

RAI 12.

Provide the basis for the mass transfer models used between the pool and containment vapor region.

RESPONSE

The following are the mechanisms of mass transfer between the vapor region and the sump in the containment:

a. The condensation of vapor on the passive heat sink surfaces and on the fan cooler coils.

b. The bulk condensation of vapor in the containment atmosphere to attain thermal equilibrium.

c. The boiling of the sump water when the containment pressure drops below the saturation pressure corresponding to the sump water temperature.

Items (a) and (b) above, are significant for the estimation of the maximum containment atmospheric temperature and item (c) may be important for the long term containment pressure analysis.

REFERENCES

1. Tagami, T., "Interim Report on Safety Assessment and Facilities Establishment Project", Hitachi Ltd. Tokyo, Japan, Feb. 1966.

2. Chung, J. N. and Ayyaswami, P. S., "The Effect of Internal Circulation on the Heat Transfer of a Nuclear Reactor Containment Spray Droplet", Nuclear Technology, Vol. 35, October 1975.

3. Niyogi, K. K., Lin, S. D., and Rathi, J. S., "Predictions of Containment Pressure-Temperature Transients Using CONTRAST-S MC[illegible] - A Digital Computer Program". UEC-TR-006-SUP, June 1979.

4. Clausing, A. M., "Practical Techniques for Estimating the Accuracy of Finite Difference Solutions to Parabolic Equations", J. Appl. Mech., March 1973.

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6. Roshenow, W. M. and Hartnett, J. P., "Handbook of Heat Transfer, McGraw-Hill, New York, 1973.

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In Section 3.2.1, spray effieiency is indicated to be a function of air-steam content of the containment atmosphere. Provide the analytical model and/or empirical data which are used and the supporting basis. In addition, discuss how the nozzle design, droplet size and fall height are considered in the determination of spray efficiency. Note all parameters that must be considered on a case-by-case basis.

RESPONSE

The temperature reached by the spray droplets with respect to the containment atmosphere temperature is dictated by the spray efficiency. Reference 1 shows that the spray efficiency can be expressed as a function of steam-air mass ratio in the containment, and it approaches unity when the ratio reaches slightly over unity. For a typical LOCA this occurs within a few seconds after the accident and much earlier than the time when the sprays are initiated.

Reference 2 has demonstrated that in the case of saturated containment atmosphere the spray droplets with sizes ranging from 100μ to 1500μ which represent a typical spectrum of droplet sizes, reach practically containment atmosphere temperature within 0.1 to 3 seconds. During this period the droplets fall a height of approximately 0.1 to 60 ft, estimated on the basis of their respective terminal velocities. For a typical PWR containment virtually all of the droplets experience fall heights that are larger than those required to reach thermal equilibrium with the containment atmosphere.

R A I 3.

For superheated containment conditions, describe how the spray efficiency is determined. If the final spray water temperature is allowed to exceed the saturation temperature, supporting data should be provided.

RESPONSE

In the situations where the containment atmosphere is superheated the degree of superheating has a very pronounced effect on the equilibrium temperature of the spray droplets. By considering heat and mass transfer between the spray droplet and the containment atmosphere it can be demonstrated that the final droplet temperature approaches only the containment saturation temperature regardless of the droplet size and the air-steam ratio of the containment atmosphere. Therefore the final droplet temperature can be much lower than the containment atmospheric temperature for highly superheated environments. The cold spray droplets are heated up during their initial fall primarily through condensation of the containment vapor then the droplets start evaporating at a constant equilibrium temperature, which is essentially the saturation temperature corresponding to the partial pressure of vapor.

The spray efficiency, η, for the superheated environment is expressed as follows:

$$\eta = \frac{T_s - T_i}{T_{sat} - T_i}$$

T_s = spray droplet final temperature
T_i = spray droplet initial temperature
T_{sat} = containment saturation temperature

According to the definition, the spray water temperature is not allowed to exceed the saturation temperature. However, it is to be noted that the saturation temperature is approached faster in the case of a superheated atmosphere than a saturated atmosphere.

RAI 4.

The fan cooler model as described in Section 3.2.2.2 does not appear to adequately address several areas. Therefore, provide additional information in the following areas:

a. The heat transfer to the fan cooler coils does not differentiate between saturated and superheated containment conditions, Therefore, for superheated containment conditions, provide justification for using vapor temperature rather than the saturation temperature (Equation 3.2.2.2.1)).

b. Provide the basis for not considering the condensate removed from the fan cooler coils.

c. Since fan cooler designs may differ, identify the interface parameters which must be considered on a case-by-case basis.

RESPONSE

4a. The heat removal rate by the fan coolers expressed in Eq. 3.2.2.2.1 corresponds to a saturated containment atmosphere where the vapor temperature is equal to the saturation temperature. In the case of su superheated containment conditions, the heat transfer to the fan cooler coils is determined as a function of the saturation temperature and the degree of superheat. The model has been described in Reference 3.

b. Provisions exist to consider the condensate removal from this fan cooler coils. The method has been described in Reference 3.

c. The parameters which contribute most in the heat transfer to the fan cooler coils are the atmospheric saturation temperature, degree of superheat, steam-air ratio and the containment pressure. It might be difficult to develop performance characteristics of a fan cooler as explicit functions of all the above parameters. However, for a specific application, considering the ranges of interest of the above parameters a simplified but conservative expression can be established for the heat removal rate of the fan cooler as a sum of functions of saturation temperature and the degree of superheat.

RAI 5.

Provide the basis for not considering condensate removal from the atmosphere due to condensation on the heat sink surfaces when the containment atmosphere is superheated. Additionally, provide justification for using vapor rather than saturation temperature when computing heat transfer to sinks in a superheat condition.

RESPONSE

Reference 3 outlines the model used to consider the condensate removal from the atmosphere due to condensation on the heat sink surfaces. When the containment atmosphere is superheated, the condensation of water vapor on the passive heat sink surface occurs as long as the heat sink surface temperature is lower than the containment saturation temperature. This condensate is added to the sump without accounting for any re-evaporation.

The heat transfer to passive heat sinks is a combination of condensing heat transfer and convective heat transfer. The condensing heat transfer rates are usually much higher than the convective heat transfer rates until the heat sink surface temperature approaches the containment saturation temperature. When the heat sink temperature exceeds the saturation temperature the condensing heat transfer ceases. For the condensing heat transfer the saturation temperature is used and for the convective heat transfer the containment atmospheric temperature is considered.

RAI 6.

The heat transfer correlations of Tagami and Uchida are based on experiments considering saturated steam-air mixtures. Discuss the effect on heat transfer to the passive heat sinks when (1) the containment atmosphere is superheated and the heat sink surface temperature is less than the temperature of saturated steam and (2) the heat sink's surface temperature is greater than the temperature of saturated steam.

RESPONSE

The heat transfer to the passive heat sinks is partly due to condensation and partly due to convection when the heat sink surface temperature is below the saturation temperature as explained in (5), above. The heat transfer correlations of Tagami and Uchida are used to calculate the condensing heat transfer part whereas a convective heat transfer coefficient is used to calculate the convective part. When the heat sink temperature exceeds the saturation temperature no condensing heat transfer occurs and only the convective heat transfer is calculated.

R A I 7.

The coefficients within equation A-3 appear to be low. Verify the correctness of the values provided.

RESPONSE

Equation A-3 has typographical errors and the corrected form is as follows:

$$P_s = 3206.18232 \exp \left(\frac{-Y}{T + 459.58}\right)$$

R A I 8.

Appendix D provides the heat transfer models used for LOCA containment analysis. Clarify whether or not the same models are used for a MSLB. If different, provide similar information for the MSLB. Inlcude the models used when the heat sink temperature exceeds the saturation temperature.

RESPONSE

The heat transfer to a passive heat sink is calculated following a MSLB as follows :

$$q_{hs} = f\,(h_{cond} - h_{conv}) \cdot (T_{sat} - T_{wall}) + h_{conv}\,(T_{con} - T_{wall})$$

where

q_{hs} = heat flux

h_{cond} = condensing heat transfer coefficient from Appendix D of Reference 1.

h_{conv} = convective heat transfer coefficient

T_{sat} = containment saturation temperature

T_{wall} = heat sink surface temperature

T_{con} = containment dry bulb temperature

f = 1 if $T_{sat} > T_{wall}$, otherwise, zero

It is to be noted that if the containment atmosphere is saturated the above expression becomes identical to Equation 3.2.2.4.1 used for LOCA analysis.

RAI 9.

Provide the models and assumptions used to compute the condensate associated with the heat transfer to passive heat sinks. The information should include the methods used to compute mass and temperature for both saturated and superheated containment conditions.

RESPONSE

The condensate mass associated with the heat transfer to passive heat sinks is computed as follows:

$$M = q/h_{fg}$$

where,

M = condensation rate on passive heat sinks

q = heat flux to heat sink by condensation

h_{fg} = latent heat of vaporization of steam at containment saturation temperature

In a superheated containment atmosphere the condensation ceases as soon as a heat sink surface reaches containment saturation temperature. The condensate is added to the sump at the containment saturation temperature.

R A I 10.

Provide the criteria and bases used to determine the heat sink nodalization for both steel and concrete structures.

RESPONSE

The heat transfer to the passive heat sinks is computed in the CONTRAST-S code by solving the partial differential heat conduction equation using a fully implicit finite difference scheme which is unconditionally stable. The expression for the truncation error indicates, however, that one should limit the grid spacings and the time steps. By decreasing the grid spacing and the time increment the accuracy of the solution can be improved. On the other hand, Reference 4 suggests that in order to avoid large meaningless fluctuations in the solution the grid spacings should be limited by the following criterian for a preselected time step :

$$M = \frac{\Delta x^2}{\alpha \Delta t} \geq 1 + \frac{h \Delta x}{K}$$

where,

Δx = grid spacing

Δt = time increment

α = thermal diffusivity of the material

h = heat transfer coefficient for the heat sink surface

K = thermal conductivity of the material

For a typical situation in computing the containment pressure-temperature transients (say, $h = 80$ Btu/hr-ft^2-$^\circ$F, $K = 0.83$ Btu/hr-ft-$^\circ$F for concrete, $\alpha = 0.028$ ft^2/hr) with time steps of one second, the grid spacings in concrete should be greater than .038 inch to satisfy the above criterion.

In order to establish the upper limit of the grid spacings in concrete a sensitivity study[5] has been performed. It has been observed that the heat sink surface temperature is underestimated and as a consequence the containment heat removal rate is overestimated resulting in lower prediction of the containment pressure, unless the grid spacings considered are small enough. Grid spacings of 0.05 inch for a few inches in concrete is considered to be adequate. Relatively larger grid spacing have been found to be adequate for steel heat sinks, due to decreased temperature gradients.

RAI 11.

Specify whether or not the gap heat transfer coefficient between liner and concrete is to be determined on a case-by-case basis. If on a generic basis, provide the value and the supporting basis.

RESPONSE

In order to predict maximum pressure in the containment a hypothetical gap is considered which accounts for the interfacial resistance. Because of the nature of the hypothesis a case-by-case determination is utilized.

In the heat conduction model used in CONTRAST-S, the interface conductance is modeled as an equivalent air gap of constant thickness (typically, 1/16 inch). Experiemental data (References 6 and 7) show values of interface conductance varying fromm 100,000 Btu/hr-ft^2-^{o}Ffor a very good contact to 10 Btu/hr-ft^2-^{o}F for a very poor contact in vacuum. The lower limit corresponds to an equivalent conductance of an approximately 20 mil thick air gap.

RAI 12.

Provide the basis for the mass transfer models used between the pool and containment vapor region.

RESPONSE

The following are the mechanisms of mass transfer between the vapor region and the sump in the containment:

a. The condensation of vapor on the passive heat sink surfaces and on the fan cooler coils.

b. The bulk condensation of vapor in the containment atmosphere to attain thermal equilibrium.

c. The boiling of the sump water when the containment pressure drops below the saturation pressure corresponding to the sump water temperature.

Items (a) and (b) above, are significant for the estimation of the maximum containment atmospheric temperature and item (c) may be important for the long term containment pressure analysis.

REFERENCES

1. Tagami, T., "Interim Report on Safety Assessment and Facilities Establishment Project", Hitachi Ltd. Tokyo, Japan, Feb. 1966.

2. Chung, J. N. and Ayyaswami, P. S., "The Effect of Internal Circulation on the Heat Transfer of a Nuclear Reactor Containment Spray Droplet", Nuclear Technology, Vol. 35, October 1975.

3. Niyogi, K. K., Lin, S. D., and Rathi, J. S., "Predictions of Containment Pressure-Temperature Transients Using CONTRAST-S MOD1 - A Digital Computer Program". UEC-TR-006-SUP, June 1979.

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ATTACHMENT I

CONTRAST-S MOD1

A DIGITAL COMPUTER PROGRAM TO PREDICT CONTAINMENT PRESSURE-TEMPERATURE RESPONSES

UEC-TR-006-SUP
JUNE, 1979

CONTRAST-S MOD1

A DIGITAL COMPUTER PROGRAM TO PREDICT CONTAINMENT PRESSURE-TEMPERATURE RESPONSES

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A Raytheon Company

1. INTRODUCTION

The CONTRAST-S MOD1 is an extension of the basic computer program CONTRAST-S[1] to include the capability for predicting containment pressure-temperature transients following high energy line ruptures which result in superheated conditions in the containment atmosphere following the accidents. A Main Steam Line Break (MSLB) is an example of such an accident. The proper treatment of superheated conditions in the containment atmosphere required some modifications in the mathematical modeling of CONTRAST-S. The modifications have been described in the following sections.

2. MATHEMATICAL MODELING

Modeling of the containment has been extensively described in Reference 1. In this section only the deviations from the basic model to simulate the superheated conditions in the containment atmosphere, have been outlined.

2.1 Containment Heat Removal By Sprays

The spray droplets traveling through the containment atmosphere absorb energy before being collected in the sump. The amount of energy absorbed is limited by the final temperature of the spray droplets which is expressed as (See Reference 1):

$$T_s = T_i + \eta(T_c - T_i) \qquad (1)$$

where, T_i = Spray droplet initial temperature (^{o}F)

T_s = Spray droplet final temperature before entering sump (^{o}F)

T_c = Containment atmospheric temperature (^{o}F)

η = Spray efficiency (fractional)

In a saturated containment atmosphere the spray droplets approaches the containment temperature (Refs. 2,3) within a few seconds depending on the droplet sizes.

In the superheated containment atmosphere the degree of superheating has a pronounced effect on the final temperature of the spray droplets. It can be demonstrated by considering heat and mass transfer between the spray droplet and the containment atmosphere that the final droplet temperature regardless of the droplet size approaches the containment saturation temperature which can be much lower than the containment atmospheric temperature for highly superheated containment environments. Hence, the droplet reach a final temperature which can be expressed as:

$$T_s = T_i + \eta(T_{sat} - T_i) \qquad (2)$$

where, T_{sat} is the containment saturation temperature at the partial pressure of vapor. If the final temperature of the spray droplets is assumed to be the containment saturation temperature, the spray efficiency remains unity for all degrees of superheat.

The energy removal rate from the containment atmosphere is given by

$$q_s = \eta c M_s (T_s - T_i) \qquad (3)$$

where, q_s = Spray energy removal rate (Btu/hr)

M_s = Spray flow rate (lbm/hr)

c = Specific heat of spray water (Btu/lbm-°F)

2.2 Containment Heat Removal By Fan Coolers

The heat removal rate in a superheated containment atmosphere is expressed as follows:

$$q_c = \sum_{h=0}^{N} A_n T_{sat}^{n} + \sum_{h=0}^{M} B_n T_{sup}^{n} \qquad (4)$$

where, T_{sat} and T_{sup} are containment saturation temperature and degree of superheat, respectively. A's and B's are constants for a particular fan cooler system and are usually obtained from manufacturer's performance data for a specific application.

2.3 Heat Transfer Model for Passive Heat Sinks

The heat transfer to the passive heat sink is considered to be consisting of a condensing part and a convective part. The heat flux to a heat sink is expressed as follows:

$$q_{hs} = f\,(h_{cond} - h_{ccnv})\,(T_{sat} - T_{wall}) + h_{conv}\,(T_{con} - T_{wall}) \qquad (4)$$

where,

q_{hs} = Heat flux (Btu/hr-ft^3)

h_{cond} = Condensing heat transfer coefficient (Btu/hr-ft^2-^{o}F)

h_{conv} = Convective heat transfer coefficient (Btu/hr-Ft^2-^{o}F)

T_{sat} = Containment saturation temperature (^{o}F)

T_{wall} = Heat sink surface temperature (^{o}F)

T_{con} = Containment dry bulb temperature (^{o}F)

f = 1 if $T_{sat} > T_{wall}$, otherwise zero

When the heat sink temperature exceeds the saturation temperature the condensing heat transfer vanishes. The condensing heat transfer coefficient has been discussed in Appendix D of Reference 1.

2.4 Condensate Removal From Containment Atmosphere

The condensate produced by the condensation of vapor on the heat sink surface or on the fan cooler coils is assumed to fall to the sump. The condensate removal rate is calculated as follows:

$$M_c = q/h_{fg} \qquad (5)$$

where,

M_c = Condensate removal rate (lbm/hr)

q = Heat transfer to the heat sink or the fan cooler due to condensation (Btu/hr)

h_{fg} = Latent heat of vaporization of steam at containment saturation temperature (Btu/lbm)

In a superheated containment if the passive heat sink surface temperature exceeds the saturation temperature no condensate is produced.

The condensate removal from the bulk containment atmoshphere is described in Reference 1.

3. SAMPLE PROBLEM

The pressure-temperature transients are analyzed in a typical PWR containment following a Main Steam Line Break accident. The containment physical data and the passive heat sink information are provided in Tables 1 and 2. The mass and energy release for a split rupture in a main steam line are given in Table 3.

The containment pressure-temperature responses are illustrated in Figures 1 and 2.

where, M_c = Condensate removal rate (lbm/sec)

q = Heat transfer to the heat sink or the fan cooler due to condensation (Btu/hr)

h_{fg} = Latent heat of vaporization of steam at containment saturation temperature (Btu/lbm)

In a superheated containment if the passive heat sink surface temperature exceeds the saturation temperature no condensate is produced.

The condensate removal from the bulk containment atmosphere is described in Reference 1.

4. REFERENCES

1. Niyogi, K. K. and Rathi, J. S., "Prediction of Containment Pressure-Temperature Transients Using CONTRAST-S - A Digital Computer Program," UEC-TR-006-0, March 1976.

2. Chung, J. N. and Ayyaswamy, P. S., "The Effect of Internal Circulation on the Heat Transfer of a Nuclear Reactor Containment Spray Droplet", Nuclear Technology Vol. 35, October 1977, pp 603-610.

3. L. F. Parsly, "Design Considerations of Reactor Containment Spray Systems Part VI - The Heating of Spray Drops in Air-Steam Atmosphere", ORNL-TM-2412, Part VI, January 1970.

TABLE 1

GENERAL CONTAINMENT INFORMATION

Pressure, psig	.5
Inside Temperature, °F	120
Outside Temperature, °F	90
Relative Humidity, %	90
Refueling Water Temperature, °F	88
Containment Free Volume, Ft^3	2.715×10^6
Containment Spray Flow Rate, gpm	3000

TABLE 2

STRUCTURAL HEAT SNIKS AND MATERIAL DATA

HEAT SINK	MATERIAL	AREA(ft^2)	THICKNESS(in.)
Containment Cylinder	Steel-lined concrete	63,774[a]	
	Paint		0.008
	Carbon Steel		3/8
	Air gap		1/16
	Concrete		54
Containment Dome	Steel-lined concrete	30,788[a]	
	Paint		0.008
	Carbon steel		1/2
	Air gap		1/16
	Concrete		42
Miscellaneous Concrete			
Heat sink #3	Painted concrete	5,900[c]	
	Paint		0.008
	Concrete		12
	Paint		0.008
Heat sink #4	Unlined concrete	12,559[c]	
	Concrete		24
Heat sink #5	Painted concrete	8,382[c]	
	Paint		0.008
	Concrete		36
	Paint		0.008
Heat sink #6	Unpainted concrete	6,747[c]	
	Concrete		36
Heat sink #7	Unlined concrete	53,688[c]	
	Concrete		48
Heat sink #8	SS-lined refueling canal	7,157[d]	
	Stainless steel		0.198
	Concrete		48
Miscellaneous Steel			
Heat sink #9	Galvanized duct & trays	67,654[a]	
	Steel		0.0875
Heat sink #10	Painted steel structures	61,085[a]	
	Paint		0.008
	Steel		0.269

TABLE 2
(Cond't)

HEAT SINK	MATERIAL	AREA(Ft^2)	THICKNESS(in.)
Miscellaneous Steel (Cont'd)			
Heat sink #11	Polar crane & tracks	19,920[a]	
	Paint		0.008
	Carbon steel		0.717
Heat sink #12	Equipment steels	5,960[a]	
	Paint		0.008
	Steel		1.12
Containment Floor	Painted concrete	11,640[b]	
	Paint		0.008
	Concrete		48
	Steel liner		1/4
	Concrete		108
Containment Sump	Painted concrete	884[b]	
	Paint		0.008
	Concrete		108

MATERIAL DATA

Material	Conductivity (Btu/hr-ft-°F)	Volumetric Heat Capacity (Btu/ft^3-°F)
Paint	6.0	36.05
Carbon Steel	26.0	521.0
Stainless Steel	9.3	56.0
Air Gap	0.0184	0.0173
Concrete	0.83	29.0

---

a - one side exposed to containment atmosphere and the area corresponds to one side

b - one side exposed to containment sump water and the area corresponds to one side

c - two sides exposed to containment atmosphere and the area corresponds to two sides

d - two sides exposed to containment atmosphere and the area corresponds to one side

TABLE 3

MASS AND ENERGY RELEASE DATA FOR

SAMPLE PROBLEM

TIME(SEC)	FLOW RATE(LBS/SEC)	ENTHALPY(BTU/LB)	TIME(SEC)	FLOW RATE(LBS/SEC)	ENTHALPY(BTU/LB)
0.	2.15600E 03	1.18810E 03	1.00000E 00	2.13600E 03	1.18870E 03
2.00000E 00	2.10800E 03	1.18930E 03	3.00000E 00	2.08000E 03	1.18980E 03
4.00000E 00	2.05200E 03	1.19030E 03	5.00000E 00	2.02800E 03	1.19080E 03
6.00000E 00	2.00800E 03	1.19120E 03	7.00000E 00	1.98400E 03	1.19160E 03
8.00000E 00	1.96400E 03	1.19200E 03	9.00000E 00	1.94800E 03	1.19230E 03
1.00000E 01	1.93200E 03	1.19260E 03	1.10000E 01	1.91600E 03	1.19290E 03
1.20000E 01	1.90000E 03	1.19320E 03	1.30000E 01	1.88400E 03	1.19340E 03
1.40000E 01	1.87200E 03	1.19370E 03	1.50000E 01	1.85600E 03	1.19390E 03
1.75000E 01	1.82800E 03	1.19440E 03	2.00000E 01	1.80000E 03	1.19490E 03
2.25000E 01	1.77600E 03	1.19530E 03	2.50000E 01	1.75200E 03	1.19570E 03
2.75000E 01	1.73200E 03	1.19600E 03	3.00000E 01	1.71600E 03	1.19630E 03
3.50000E 01	1.68800E 03	1.19670E 03	4.00000E 01	1.67200E 03	1.19690E 03
4.50000E 01	1.66400E 03	1.19710E 03	4.58000E 01	1.66300E 03	1.19710E 03
4.58010E 01	1.66300E 03	1.20500E 03	4.68000E 01	1.63100E 03	1.20500E 03
4.78000E 01	1.57700E 03	1.20500E 03	4.88000E 01	1.52800E 03	1.20500E 03
4.98000E 01	1.48500E 03	1.20500E 03	5.09000E 01	1.44500E 03	1.20500E 03
5.18000E 01	1.41000E 03	1.20500E 03	5.28000E 01	1.37900E 03	1.20500E 03
5.33000E 01	1.34700E 03	1.20500E 03	5.48000E 01	1.31500E 03	1.20500E 03
5.58000E 01	1.28500E 03	1.20500E 03	5.68000E 01	1.25400E 03	1.20500E 03
5.78000E 01	1.22600E 03	1.20500E 03	5.88000E 01	1.19700E 03	1.20500E 03
5.98000E 01	1.17200E 03	1.20500E 03	6.08000E 01	1.14900E 03	1.20500E 03
6.33000E 01	1.09900E 03	1.20500E 03	6.58000E 01	1.05900E 03	1.20500E 03
6.83000E 01	1.02600E 03	1.20500E 03	7.08000E 01	9.98000E 02	1.20500E 03
7.33000E 01	9.75000E 02	1.20500E 03	7.58000E 01	9.55000E 02	1.20500E 03
8.08000E 01	9.20000E 02	1.20500E 03	8.58000E 01	8.93000E 02	1.20500E 03
9.08000E 01	8.70000E 02	1.20500E 03	9.58000E 01	8.48000E 02	1.20500E 03
1.05800E 02	8.17000E 02	1.20500E 03	1.15800E 02	7.85000E 02	1.20500E 03
1.25800E 02	7.58000E 02	1.20500E 03	1.35800E 02	7.35000E 02	1.20500E 03
1.45800E 02	7.12000E 02	1.20500E 03	1.65800E 02	6.74000E 02	1.20500E 03
1.85800E 02	6.37000E 02	1.20500E 03	2.05800E 02	5.79000E 02	1.20500E 03
2.25800E 02	4.74000E 02	1.20500E 03	2.45800E 02	4.07000E 02	1.20500E 03
2.88700E 02	3.06000E 02	1.20500E 03	2.88701E 02	0.	1.20500E 03
4.01000E 02	0.	1.20500E 03			

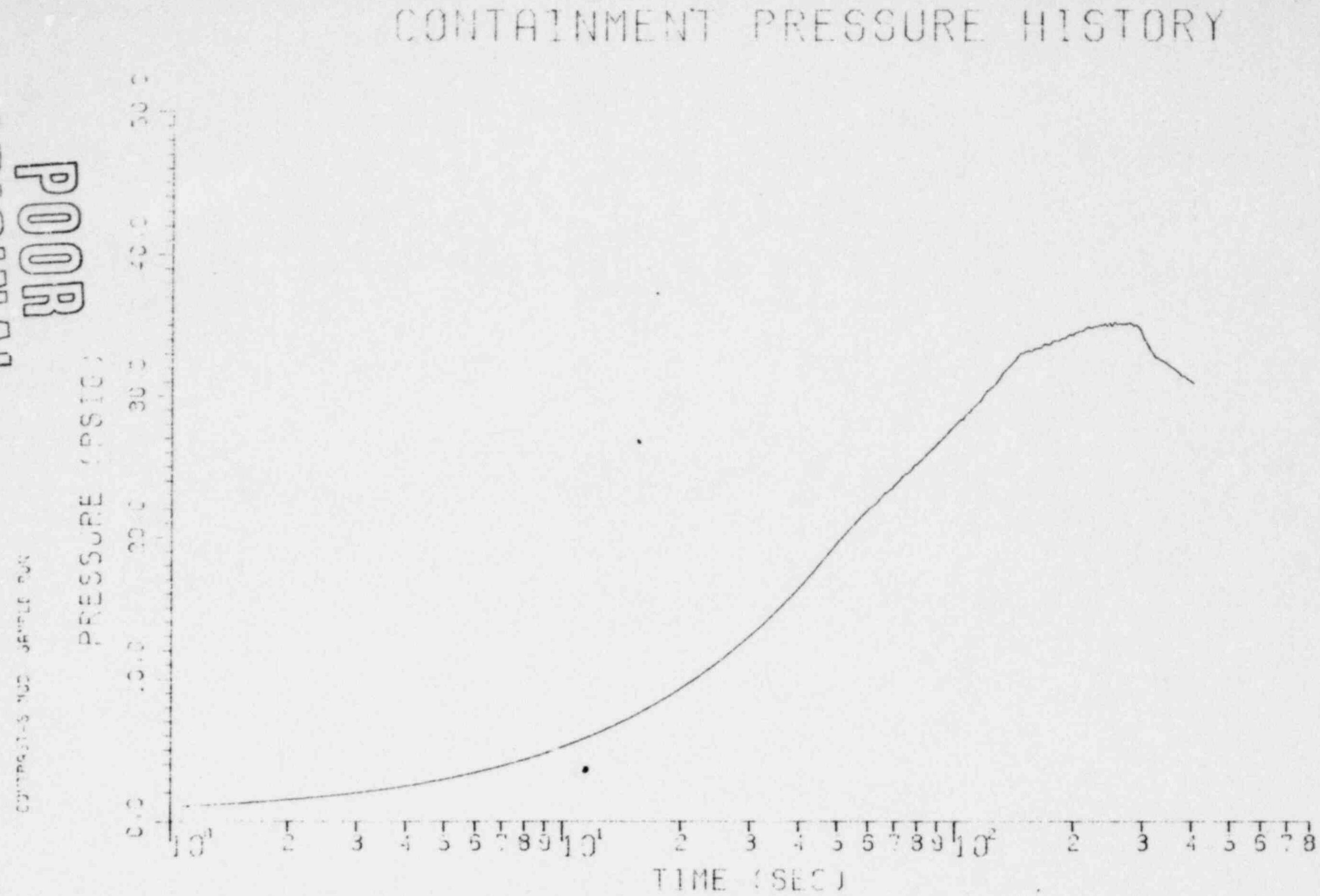

Figure 1 Containment Pressure Response Following a MSLB

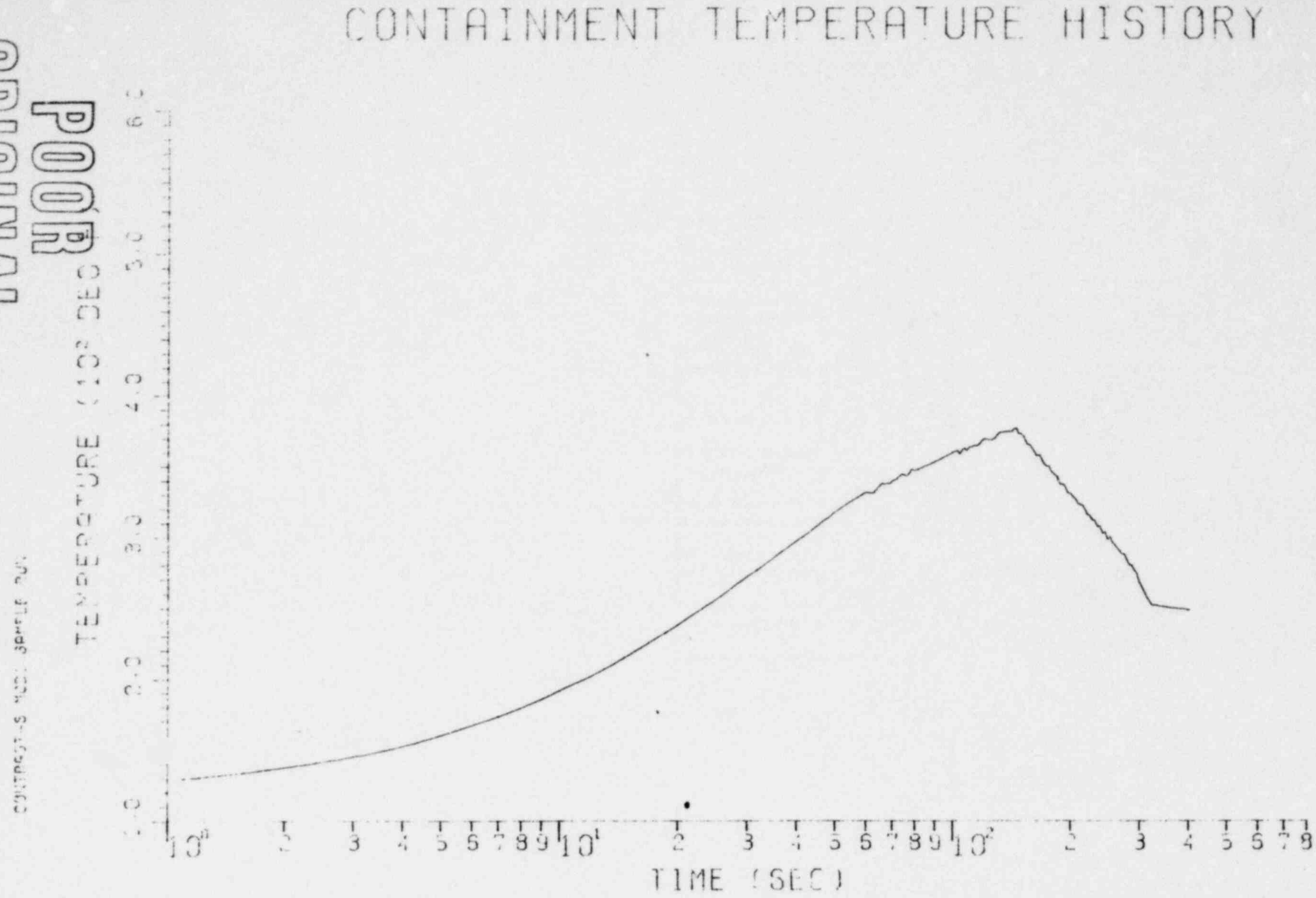

Figure _ Containment Temperature Response Following a MSLB

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