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MILLER.C.L. Project Directorate I-2

See Rpt.

SUBJECT: Forwards util revised response to Station Blackout Rule per NRC 920114 Safety Evaluation w/answers attached to all but one NRC recommendation.Query on CR instrument cabinet temp to be answered no later than 920501.

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MAR 13 1992

Director of Nuclear Reactor Regulation
Attention: Mr. C.L. Miller, Project Director
Project Directorate I-2
Division of Reactor Projects
U.S. Nuclear Regulatory Commission
Washington, D.C. 20555

**SUSQUEHANNA STEAM ELECTRIC STATION**
**RESPONSE TO STATION BLACKOUT SAFETY EVALUATION**
**PLA-3745 FILE R41-2**

***Reference:*** *RESPONSE TO THE STATION BLACKOUT RULE FOR SUSQUEHANNA STEAM ELECTRIC STATION, UNIT 1 AND 2 (TAC NOS. M68613 AND M68614) Dated January 14, 1992.*

Dear Mr. Miller:

This letter provides the Pennsylvania Power & Light Company (PP&L) revised response to the Station Blackout (SBO) Rule as required by the referenced NRC Safety Evaluation.

This response (attached) revises diesel generator target reliability to 0.975 based on your position, and provides the requested justification to support PP&L's original position that SSES is only required to cope with a SBO event for 4 hours. However, it should be noted that a thorough evaluation was undertaken to review the staff's concerns regarding the need and ability for SSES to cope for 8 hours. Results of this evaluation concluded SSES has the capability to cope for 8 hours and longer if required.

With the exception of a final technical resolution to your question regarding Control Room instrument cabinet temperatures, the attachment responds in full to each of your recommendations. Our resolution to the cabinet temperature concern will be forwarded to you no later than May 1, 1992.

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Questions regarding this revised response should be directed to Mr. A.K. Maron at (215) 774-7852.

Very truly yours,

H. W. Keiser

Attachment

cc: NRC Document Control Desk (original)
NRC Region I
Mr. G. S. Barber, NRC Sr. Resident Inspector - SSES
Mr. J. J. Raleigh, NRC Project Manager - Rockville

# STATION BLACKOUT RULE
# RESPONSE TO NRC SAFETY EVALUATION

## INTRODUCTION

The Station Blackout Rule (10 CFR 50.63) was instituted in 1988 and required licensees to assess their ability to cope with a station blackout (SBO) of a specified duration. In 1989, PP&L submitted the results of our coping study to the NRC, concluding that Susquehanna SES (SSES) must be able to cope with a station blackout for 4 hours and maintain an Emergency Diesel Generator (EDG) reliability of 0.975 (97.5%). In February of 1991, PP&L revised its EDG target reliability value from 0.975 to 0.95 based on a spray pond bypass valve modification. On January 14, 1992, NRC issued its Safety Evaluation of the SSES SBO submittal concluding that SSES was an 8 hour coping plant requiring EDG reliability be maintained at 0.975. The following is an item by item response to the recommendations identified in the NRC Safety Evaluation.

## STATION BLACKOUT DURATION

NRC RECOMMENDATION: The licensee needs to change the EDG reliability target from 0.95 to 0.975 and the coping duration from 4 hours to 8 hours.

### PP&L RESPONSE

**A) Coping Duration**

One input to the determination of required SBO coping duration is the "return time" of extremely high winds(>125 mph). As part of our original coping assessment, PP&L contracted with Dames & Moore Consulting Engineers for the calculation of this "return time" for SSES. Dames & Moore determined this value to be ~6.7E-4/yr. (about once in 1500 years) using data specific to SSES. Any return time value less than 1.OE-3/yr, coupled with our severe weather and off-site power design classification, places SSES in a 4 hour coping category.

The NRC evaluation did not credit use of site specific data due to this data being applicable for winds at 10 meters off the ground, rather than the required assessment height of 30 meters from the ground (average transmission tower height). It was therefore concluded, based on NUMARC Table 3.2, that the return time for SSES was more frequent than once per 1000 years and that SSES must cope with a SBO for 8 hours.

To address this coping duration concern, PP&L investigated the basis of Table 3.2 in NUMARC 87-00 and contracted again with Dames & Moore to determine the return time of wind speeds at 30 meters. Conversations with both NUMARC personnel and NRC staff indicated that the use of site specific data is acceptable. The NRC cautioned that the use of such data should account for wind speeds of 125 mph at 30 meters and consider National Bureau of Standards (NBS) publications 118 and 124, as well as several National Oceanic and Atmospheric Administration (NOAA) documents. Note that the use of site specific data is encouraged in NUMARC 87-00.

NBS 118 provides a method of scaling wind speeds to various heights and provides measured weather data from 129 meteorological stations across the US mainland. It is this data which PP&L and Dames & Moore believe provides the best estimates of wind speed return times at SSES. Using the method of NBS 118, the 125 mph "fastest mile" wind speed at 30 meters is scaled to a "fastest mile" wind speed of 107 mph at 10 meters (the normalized height of all reported weather data). Using the data for meteorological stations closest to SSES, NBS 118 provides the following "return times" for various fastest mile speeds:

**TABLE 1**

| Return Time (years) | Fastest Mile Wind Speed (mph) | |
|---|---|---|
| | Scranton | Harrisburg |
| 100 | 60.86 | 70.57 |
| 500 | 67.34 | 80.49 |
| 1,000 | 70.12 | 84.75 |
| 5,000 | 76.58 | 94.64 |
| 10,000 | 79.36 | 98.90 |
| 50,000 | 85.82 | 108.79 |
| 100,000 | 88.60 | 113.05 |
| 500,000 | 95.06 | 122.95 |
| 1,000,000 | 97.84 | 127.21 |

In addition, Dames & Moore have calculated the probability of exceeding various wind speeds within 1000 years, also based on the data and methods in a paper by H.C.S.Thom:

**TABLE 2**

| Probability of Exceedance in 1000 yrs | Fastest Mile Wind Speed (mph) | |
|---|---|---|
| | Scranton | Harrisburg |
| 0.500 | 72 | 87 |
| 0.250 | 75 | 92 |
| 0.100 | 79 | 99 |
| 0.050 | 82 | 103 |
| 0.005 | 92 | 117 |

From the first table above, one can see that the return time of a wind speed of 107 mph at 10 meters is expected to be greater than 1 million years at Scranton and almost 50,000 years at Harrisburg. Table 2 shows that the probability of exceeding the 107 mph wind speed within 1000 years is less than 1% at Scranton and about 3% at Harrisburg. Using the data from Harrisburg in Table 1, the expected return time of a 125 mph wind at 30 meters is ~37,500 years. PP&L also reviewed NBS 124 for applicability. NBS 124 relies on the extrapolation of coastal weather data to infer wind speeds inland. Further, this method of extrapolation assumes intervening terrain to be open and grass covered. Since SSES is located within a valley separated from the coast by approximately 100 miles of hills and forest, the extrapolation is highly inaccurate. Thus, PP&L views NBS 124 as valid only for scoping calculations and should only be used in the absence of better techniques/data.

PP&L considers the preceding arguments and data sufficient justification for not using Table 3.2 of NUMARC 87-00 for determining our ESW category. Further, this data shows that the return time of winds in excess of 125 mph at SSES is highly likely to be greater than 1000 years. Thus, it is concluded that the ESW category of "2" originally reported in our coping study is fully justified (the data actually justifies an ESW classification of "1"), and that SSES remains a "P1" plant (per NUMARC 87-00) requiring a SBO coping time of 4 hours.

## B) EDG Target Reliability

In 1991, PP&L informed the NRC that for purposes of complying with the SBO rule our target EDG reliability was to be 0.95 (95%). In making this determination, PP&L relied on the use of "staggered operation" of RHR pumps to cool both suppression pools. Staggered operation is required because, although in principle any two EDG's can cool both units, in actuality there are two combinations of EDG's (A and C, or B and D) which result in only one RHR pump in each unit available to alternately cool the suppression pools.

The NRC noted that the use of staggered operation did not meet the "connectability criterion" and was determined to be an unacceptable increase in operator burden. This criterion was explained in documentation provided by the NRC to NUMARC after submittal of the SSES SBO analysis. The NRC concluded that to avoid use of staggered operation, 3 of the 4 EDG's would be required.

Further, the NRC noted that if only diesels A and B start, no control structure HVAC would be available. PP&L has performed a calculation of steady state control room temperature using the method in NUMARC 87-00 and assuming that the measured, normal control room heat load exists. The result of this calculation is that the control room temperature will not rise above 111°F in the absence of normal HVAC. Because temperature remains less than 120°F, the control structure environment remains acceptable.

Based on the inability to take credit for staggered operation, PP&L concurs with the staff's position in requiring 3 of 4 EDGs and the reliability target value of 0.975.

## STATION BLACKOUT COPING CAPABILITY

### NRC RECOMMENDATIONS:

The NRC made the following four recommendations based on their previous determination that PP&L had to address the need for SSES to cope with an 8 hour Station Blackout.

1) The licensee needs to conform to an 8 hour coping duration and increase the EDG reliability target from 0.95 to 0.975.

2) The licensee should provide a procedure to refill the CST from the RWST during an SBO event.

3) The licensee should add the portable AC generator to the list of SBO equipment, provide procedures for its utilization, and apply to it an appropriate QA program. The portable ac generator should meet the criteria in Appendix B of NUMARC 87-00. Also the licensee should replace battery 1D650 with a higher capacity battery or provide charging capability to the existing battery to extend its support for the 8 hour SBO duration, and recovery thereafter. The licensee should include all the analyses and related information in supporting documentation that is to be maintained by the licensee for possible staff review.

4) The licensee should provide for staff review a full description, including the nature and objectives of any modification required. The analyses and related information should also be included in the supporting documentation that is to be maintained by the licensee in support of the SBO submittals.

PP&L RESPONSE

As addressed in the initial section of this response, PP&L concludes that SSES must cope with a SBO event for 4 hours. This conclusion is supported by the use of site specific weather data (at the required assessment height). As for the EDG reliability target value, PP&L has reviewed the NRC concerns and has concurred with the staff's finding that the configuration of SSES mandates an EDG reliability target value of 0.975. This reliability value has been included in the EDG Reliability Program developed in accordance with NUMARC 87-00 Appendix D.

PP&L has thoroughly evaluated the ability of SSES to cope 8 hours with an SBO event, including all areas of concern identified in the NRC Safety Evaluation. PP&L is confident that SSES has the ability to cope for 8 hours and longer if required. Since PP&L has demonstrated that SSES is a 4 hour coping plant this information will not be provided in support of our revised submittal, but is available for review.

## EFFECTS OF LOSS OF VENTILATION

NRC RECOMMENDATION: The licensee should: 1) provide additional information and/or technical justification for the initial conditions and assumptions used in the heat-up analysis for each area of concern, 2) with regard to COTTAP computer code, provide detailed information to address the staff's concerns as identified above, and 3) re-perform the heat-up analysis for each area of concern and for an 8 hour coping duration taking into account the non-conservatism as identified in the SAIC TER.

PP&L RESPONSE - COTTAP2 Calculations

The use of the Compartment Temperature Transient Analysis Program (COTTAP) computer code has been presented to the staff as part of our submittals to resolve steam leak detection Technical Specification changes. Attachment A contains a user's manual for the COTTAP computer code and a copy of a recent paper published in Nuclear Technology which describes the methodology used in the COTTAP program and presents some of the verification calculations which have been performed. The user's manual presents some of the calculations which were performed against problems that have exact analytical solutions. The referred paper presents the methodology along with calculations which have been benchmarked against calculations performed with the CONTAIN computer program. In addition, the program and computation package have been independently reviewed by Gilbert Associates. PP&L also maintains a Quality Assurance file/package for the COTTAP computer code.

In the original coping assessment, two basic COTTAP2 calculations were performed: an assessment of Dominant Areas of Concern (DACs); and an evaluation of control room cabinets. For BWRs, the DACs are the HPCI and RCIC rooms, and the main steam tunnel (NUMARC 87-00). The main steam tunnel is considered because, apparently at some plants, HPCI and RCIC are isolated on high temperature in the tunnel. At SSES, the HPCI/RCIC isolations do not come from main steam tunnel temperature but from sensors located on the 683 foot elevation of the reactor building common to both HPCI and RCIC piping. During SBO, only the RCIC isolation logic is powered. Thus, for SSES, the main steam tunnel is not a true DAC. The common piping area, called the RHR piping area in the calculation, is a DAC.

PP&L recalculated the DAC temperatures using COTTAP2 and "conservative" inputs. Inputs included use of "maximum normal" room temperatures per the FSAR. Outside air temperature was assumed to be a constant 95°F. The influence of hot piping (including flued heads) was added to the HPCI, RCIC, RHR piping area, and the main steam tunnel. (The absence of this hot pipe loading caused the cooldown of the main steam tunnel noted in the SAIC Technical Evaluation Report). No engineering reference for a concrete thermal conductivity of 0.7 could be found. However, this value was changed from 1.0 to 0.7 per the TER. The actual input deck, and the justification for all input values used, appears in the detailed calculation.

The results of the COTTAP2 calculations are presented in the tables below.

Table 3: COTTAP2 DAC Room Temperatures

| ROOM | Temperature (°F) | | | |
|---|---|---|---|---|
| | Original Submittal: | | New Calculation: | |
| | 8 hours | 72 hours | 8 hours | 72 hours |
| HPCI | 113 | 114 | 114 | 119 |
| RCIC | 106 | 109 | 107 | 111 |
| RHR Piping | 118 | 117 | 125 | 130 |
| MS Tunnel | 123 | 117 | 150 | 171 |

From Table 3, the temperatures of the DACs remain less than the 180°F operability limit, even at 72 hours. The inclusion of the hot pipe loads does cause significant increases in tunnel temperatures.

| Table 4: Comparison of COTTAPs and NUMARC Results | | |
|---|---|---|
| ROOM | Temperature (°F) | |
| | COTTAP2 at 72 hours | NUMARC 87-00 |
| RHR Piping | 130 | 144 |
| MS Tunnel | 171 | 176 |

Table 4 presents a comparison of the two hottest DAC temperatures as calculated by both COTTAP2 and the method of NUMARC 87-00. While it appears that the NUMARC method produces "conservative" results, it must be noted that the NUMARC calculation produces a steady state, infinite time result. The COTTAP2 results are not steady state but time dependent, and at 72 hours the temperatures in these rooms are still increasing. At longer and longer times, one would expect better agreement between the two methods. The results of the above table show that the agreement between the two methods is quite good.

The TER made reference to "oscillatory" temperature profiles. Review of the original COTTAP2 work revealed no such profiles. The reviewers may be referring to temperature profiles which peak and drop in the short term, then continue a long term temperature rise (Figure 1). The large early peak is caused by AC motor heat loads which decay away. At later times, the room is heated by surrounding walls. This result is consistent with expected behavior.

The reviewers questioned PP&L's use of COTTAP2 for calculation of instrument cabinet temperatures and several assumptions used in these calculations. The original impetus for using COTTAP2 to calculate cabinet temperatures was the desire to avoid opening control structure cabinet doors and not impose unnecessary operator burden.

PP&L concurs with the NRC that modifications are needed to two assumptions used in the cabinet temperature calculations. The NRC questioned our use of 120°F as the control room temperature, implying such a temperature was overly conservative. In response, the infinite time control room temperature, assuming measured normal operating heat loads, has been calculated using the method of NUMARC 87-00. The resulting control room temperature is 111°F. The TER questioned use of 180°F as the operability limit of control room instruments. Based on information received from equipment manufacturers, we currently believe the correct limit is 140°F, and are performing a reevaluation on this basis. This evaluation will be completed and submitted to the NRC no later then May 1, 1992.

## CONTAINMENT ISOLATION

NRC RECOMMENDATION: The licensee should list the valves identified in an appropriate procedure and identify the actions necessary to ensure that these valves can be fully closed, if containment isolation is required during an SBO event. The valve closure should be confirmed by position indication (local, mechanical, remote, process information, etc.)

PP&L RESPONSE

The penetrations which have been identified by the NRC as requiring to be proceduralized are the Residual Heat Removal (RHR) and Core Spray (CS) suction lines along with the Containment Spray line. Containment isolation of these lines has been addressed and approved by the NRC prior to this submittal. The following identifies that approved approach.

Susquehanna SES FSAR section 6.2.4.3.6 states in part that "Containment isolation provisions for certain lines in engineered safety feature or engineered safety feature-related systems may consist of a single isolation valve outside containment. A single isolation valve is considered acceptable if it can be shown that the system reliability is greater with only one isolation valve in the line, the system is closed outside containment, and a single active failure can be accommodated with only one isolation valve in the line." Additionally, section 6.2.4.3.6.3 states, "Although strictly speaking the HPCI, RCIC, CS, and RHR pump suction lines do not connect directly to the primary containment, they are nevertheless evaluated to 10 CFR 50 Appendix A, General Design Criteria 56. These lines are each provided with one remote manually motor operated gate valve external to the containment and use the respective piping systems as the second isolation barrier. For the RHR and CS valves the hand switches are key locked".

Further investigation into this issue reveals that section 6.2.4 of the NRC Safety Evaluation Report (NUREG 0776) for Susquehanna SSES documents the NRC approval of meeting the alternative acceptance criteria specified in section 6.2.4 of the Standard Review Plan. This section summarizes these alternative acceptance criteria along with specifically identifying the lines found acceptable via this method.

Based on the above explanation we believe that containment isolation is established and containment integrity will be maintained.

## PROCEDURES AND TRAINING

**NRC RECOMMENDATION:** The staff expects the licensee to implement the appropriate training to assure an effective response to an SBO event.

**PP&L RESPONSE**

Appropriate plant personnel will be trained on any new or revised procedures in accordance with the requirements of Initiative 2, NUMARC 87-00 and Reg.Guide 1.155, section 3.4.

## QUALITY ASSURANCE AND TECHNICAL SPECIFICATION

**NRC RECOMMENDATION:** The staff expects that the plant procedures will reflect the appropriate testing and surveillance requirements to ensure the operability of the necessary SBO equipment.

**PP&L'S RESPONSE**

It is PP&L's intent to satisfy the Quality Assurance (QA) requirements of Reg. Guide 1.155 by upgrading an existing procedure to incorporate Station Blackout. This procedure addresses all the Reg. Guide QA requirements and will require the necessary Inspections and Tests to be performed in accordance with the Operational Quality Assurance Program.

## EDG RELIABILITY PROGRAM

**NRC RECOMMENDATION:** The licensee should complete the implementation of an EDG reliability program which meets the guidance of RG 1.155, Section 1.2 and provide a schedule for its completion. Confirmation that such a program is in place or will be implemented should be included in the documentation supporting the SBO submittals that is to be maintained by the licensee.

PP&L RESPONSE

Reg. Guide 1.155 specifies that each utility establish an EDG performance monitoring program. NUMARC 87-00 Appendix D contains guidance for the development and implementation of such a program. PP&L has committed to implement a program of reliability monitoring and, as indicated above, PP&L must maintain an EDG reliability at or above 97.5% as part of our SBO coping strategy.

The Reg. Guide and NUMARC provide "trigger values" for determining compliance with target reliability. NRC reviewers indicated that lack of this data in our submittal hindered assessment of SSES EDG reliability. At the 97.5% reliability level, compliance is assumed if the failures to start/load are less than or equal to 3, 4, and 5 out of the last 20, 50 and 100 start attempts, respectively. As of 2/10/92 the failures to start/load in each category were 0,0, and 3, respectively. Thus, today, PP&L can accept the increased reliability target of 97.5%.

PP&L's Emergency Diesel Generator reliability monitoring program has been developed and documented in Nuclear Department Administrative Procedure-QA-0401 entitled "Emergency Diesel Generator Monitoring Program." This procedure complies with the reliability requirements delineated in Appendix D of NUMARC 87-00, Rev. 1. Reliability will be monitored against a set of "trigger values" with actions specified for various levels of trigger value exceedance.

# ROOM TEMPERATURE RESPONSE TO A STATION BLACKOUT

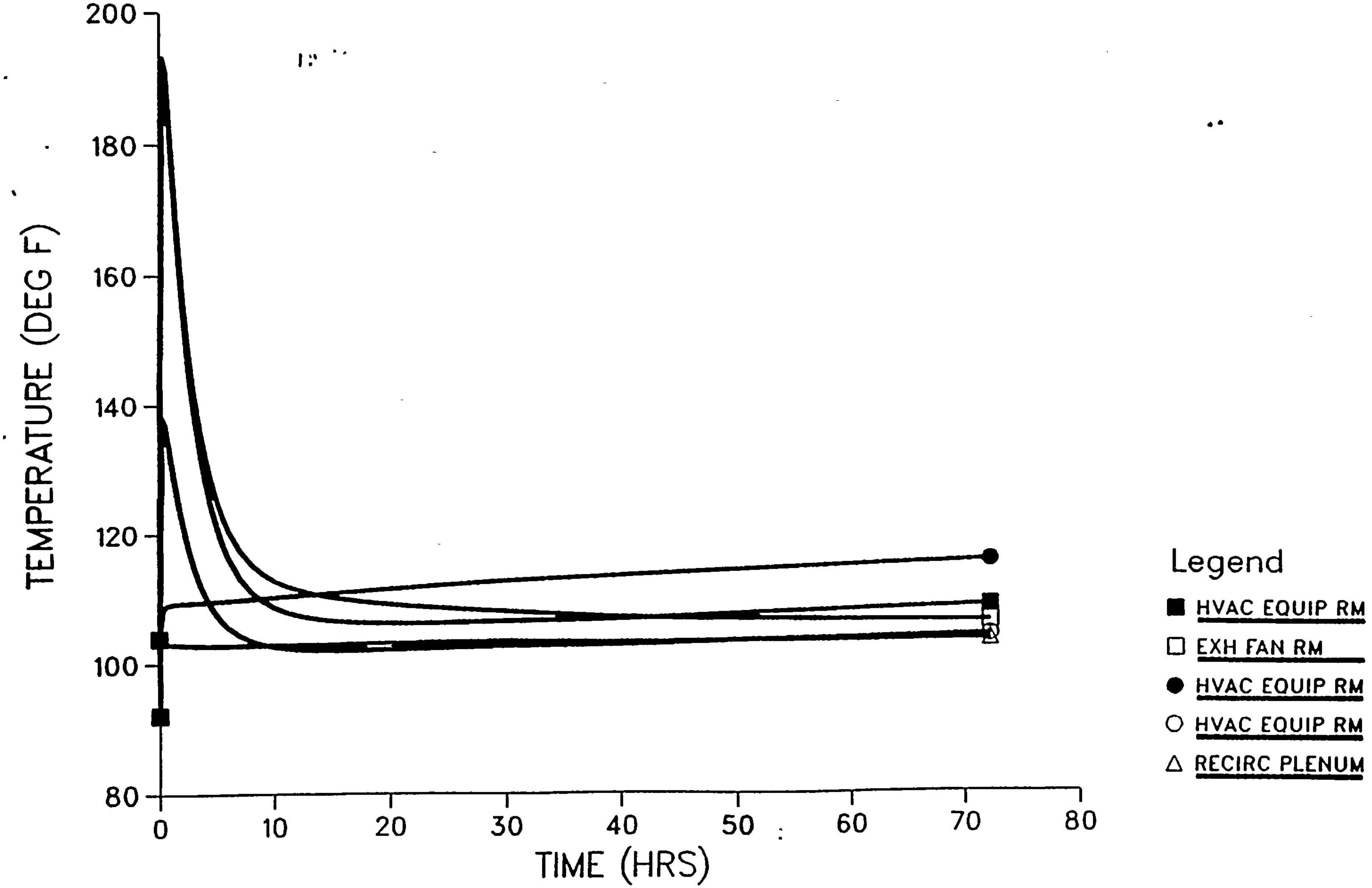


Figure 1

ANS Reprint

NUCLEAR REACTOR SAFETY

# COTTAP: A COMPUTER CODE FOR SIMULATION OF THERMAL TRANSIENTS IN SECONDARY CONTAINMENTS OF BOILING WATER REACTORS

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*The Compartment Transient Temperature Analysis Program (COTTAP) was developed by the Pennsylvania Power & Light Company for postaccident boiling water reactor (BWR) secondary containment thermal analysis. The code makes use of previously developed implicit temporal integration methods and sparse matrix inversion techniques to allow modeling of an entire BWR secondary containment. Investigations were made with a model consisting of 121 compartments and 767 heat-conducting slabs. The simulation presented involves the numerical integration of 20 101 ordinary differential equations over a 30-h simulation period. Two hours of CPU time were required to carry out the calculation on an IBM 3090 computer. The COTTAP code considers natural convection and radiation heat transfer between compartment air and walls through a detailed finite difference solution of the slab conduction equations. Heat addition from hot piping and operating equipment, and cooling effects associated with ventilation flows and compartment heat removal units are also included. Additional capabilities of COTTAP include modeling of compartment heatup resulting from steamline breaks and simulation of natural circulation cooling in compartments with flow paths at differing elevations.*

## I. INTRODUCTION

Under postaccident conditions, boiling water reactor (BWR) secondary containment ventilation systems typically isolate to prevent fission product release to the environment. Since cooled air is no longer circulated through the secondary containment, increased compartment temperatures result. Predictions of postaccident compartment temperatures are necessary to determine whether safety-related equipment is subjected to temperatures that exceed its maximum design values. Safety-related equipment must be operable under postaccident conditions in order to effect the safe shutdown of the reactor.

After an accident, the secondary containment ventilation system operates in a recirculation mode to promote air mixing between compartments and to dilute locally concentrated radioactive isotopes. Original design calculations for Pennsylvania Power & Light Company's (PP&L) Susquehanna Steam Electric Station (SSES) assumed that air recirculation provided enough mixing to produce a fairly uniform temperature distribution throughout all secondary containment compartments. For this reason, a single-compartment transient model was used in the simulation of postaccident conditions. Recent investigations based on steady-state calculations have shown, however, that significant temperature variations can exist between compartments. These temperature variations were large enough to prompt a detailed multicompartment transient analysis of the secondary containment.

To reanalyze the postaccident transient behavior of the SSES secondary containment, PP&L developed the Compartment Transient Temperature Analysis Program (COTTAP). Development of this program began after an evaluation of available codes revealed that none were capable of performing a sufficiently detailed simulation owing to the large number of heat-conducting structures found in the SSES secondary containment. For example, the CONTEMPT code,[1] which is probably the most widely used containment analysis program, can model as many as 999 compartments but is limited to 99 heat-conducting slabs. In contrast, COTTAP can model up to 1200 heat-conducting slabs and 300 compartments. It also contains models that describe heat dissipation from operating electrical equipment and process piping. A COTTAP model of the SSES-1 and -2 secondary containment structures consists of ~120 compartments and 800 heat-conducting slabs.

The CONTAIN code[2] is a more recently developed containment simulation program with complex modeling capabilities. It is, however, designed specifically for primary containment simulation and is not well suited for secondary containment modeling because it has no provisions for energy input to compartments from heat loads such as electrical panels, lighting, motors, and hot piping.

A description of the COTTAP code, including assumptions, governing equations, numerical solution methods, and code limitations is given in Sec. II. Representative results of the SSES-1 and -2 secondary containment analysis are presented in Sec. III, and code verification is discussed in Sec. IV.

## II. DESCRIPTION OF THE COTTAP CODE

### II.A. Compartment Mass and Energy Balances

The COTTAP code allows for air and water vapor mass transfer between compartments by means of forced ventilation, leakage, and natural circulation flows. A forced ventilation flow model describes heating/ventilating/air conditioning systems, and a leakage model simulates intercompartment flows that are generated by pressure differentials. In addition, a natural circulation model simulates gravity-driven flows between compartments connected by flow paths at differing elevations. Steam can also be added to a compartment as a result of pipe breaks or removed through condensation and rain-out. Air and water vapor mass conservation equations for a compartment with $N_v$ ventilation paths, $N_l$ leakage paths, and $N_c$ natural circulation paths are given by

$$V\frac{d\rho_a}{dt} = \sum_{j=1}^{N_v} W_{vj}Y_{vj} + \sum_{j=1}^{N_l} W_{lj}Y_{lj} + \sum_{j=1}^{N_c} W_{cj}(Y_{cj} - Y) \qquad (1)$$

and

$$V\frac{d\rho_w}{dt} = \sum_{j=1}^{N_v} W_{vj}(1 - Y_{vj}) + \sum_{j=1}^{N_l} W_{lj}(1 - Y_{lj}) + \sum_{j=1}^{N_c} W_{cj}(Y - Y_{cj}) + W_{bs} - W_{cond} - W_{ro} \ , \qquad (2)$$

where

$V$ = compartment volume ($m^3$)

$t$ = time (s)

$\rho_a, \rho_w$ = compartment air and water vapor densities, respectively ($kg/m^3$)

$W_{vj}, W_{lj}, W_{cj}$ = mass flow rates associated with $j$'th ventilation, leakage, and circulation paths, respectively (kg/s)

$Y$ = mass fraction of air within compartment

$Y_{vj}, Y_{lj}$ = air mass fractions in donor compartments for ventilation path $j$ and leakage path $j$, respectively

$Y_{cj}$ = mass fraction of air in adjoining compartment associated with circulation path $j$

$W_{bs}$ = rate of steam addition due to pipe breaks (kg/s)

$W_{cond}$ = steam condensation rate (kg/s)

$W_{ro}$ = rain-out rate (kg/s).

The values $W_{vj}$ and $W_{lj}$ are positive for flow into the compartment and negative for flow out of the compartment, whereas the circulation rate $W_{cj}$ is always a positive quantity. Ventilation paths are described by their associated mass flow rates and identification numbers of source and receiving compartments. Ventilation flows can be tripped off or on at any time during a transient by supplying appropriate trip-logic data. Leakage, circulation, and pipe break models are discussed in Sec. II.C along with other special purpose models.

In formulating the compartment energy balance, it is assumed that air behaves as an ideal gas. Moreover, for the transients of interest, partial pressures of water vapor are typically <1 atm. Therefore, it is assumed that the steam specific enthalpy depends only on temperature, i.e., the vapor enthalpy is equal to the enthalpy of saturated steam at the temperature of the gas mixture. The partial pressure of water vapor within a compartment is computed from the ideal gas equation of state, and the total compartment pressure is calculated as the sum of the air and water vapor partial pressures. With these assumptions, the compartment energy balance becomes

$$V\left[\rho_a T \frac{dC_{pa}(T)}{dT} + \rho_a C_{pa}(T) + \rho_w \frac{dh_g(T)}{dT} - \rho_w R_w - \rho_a R_a\right]\frac{dT}{dt}$$
$$= -VTC_{pa}(T)\frac{d\rho_a}{dt} - Vh_g(T)\frac{d\rho_w}{dt}$$
$$+ VT\left(R_w \frac{d\rho_w}{dt} + R_a \frac{d\rho_a}{dt}\right)$$
$$+ Q_{light} + Q_{panel} + Q_{motor} + Q_{cooler} + Q_{piping}$$
$$+ Q_{misc} + Q_{slab} + Q_{break} + W_{bs}h_g(P_{break})$$
$$- W_{ro}h_f(T) - W_{cond}h_f(T)$$
$$+ \sum_{j=1}^{N_v} W_{vj}[Y_{vj}T_{vj}C_{pa}(T_{vj}) + (1 - Y_{vj})h_g(T_{vj})]$$
$$+ \sum_{j=1}^{N_l} W_{lj}[Y_{lj}T_{lj}C_{pa}(T_{lj}) + (1 - Y_{lj})h_g(T_{lj})]$$
$$+ \sum_{j=1}^{N_c} W_{cj}[Y_{cj}T_{cj}C_{pa}(T_{cj}) - YTC_{pa}(T) + (1 - Y_{cj})h_g(T_{cj}) - (1 - Y)h_g(T)] \ , \quad (3)$$

where

$T$ = compartment gas temperature (K)

$C_{pa}(T)$ = specific heat of air at temperature $T$ (J/kg·K)

$h_g(T)$ = specific enthalpy of saturated water vapor at temperature $T$ (J/kg)

$R_a$ = ideal gas constant for air (288.7 J/kg·K)

$R_w$ = ideal gas constant for water (461.4 J/kg·K)

$Q_{light}, Q_{panel}, Q_{motor}, Q_{cooler}, Q_{piping}, Q_{misc}$ = compartment heat loads due to lighting, electrical panels, motors, air coolers, hot piping, and miscellaneous equipment (J/s)

$Q_{slab}$ = rate of heat transfer to compartment air/water vapor mixture from surrounding slabs (J/s)

$Q_{break}$ = heat transfer rate to air/water vapor mixture from liquid exiting break as it cools to compartment temperature (J/s)

$W_{bs}$ = mass flow rate of steam exiting break (kg/s)

$P_{break}$ = total compartment pressure if pipe contains saturated liquid (Pa)

$P_{break}$ = pipe fluid pressure if pipe contains saturated steam (Pa)

$h_g(P_{break})$ = specific enthalpy of saturated water vapor at pressure $P_{break}$ (J/kg)

$h_f(T)$ = specific enthalpy of saturated liquid water at temperature $T$ (J/kg)

$T_{vj}, T_{lj}$ = donor compartment temperatures for ventilation path $j$ and leakage path $j$, respectively (K)

$T_{cj}$ = temperature in adjoining compartment associated with circulation path $j$ (K).

Compartment heat loads from lighting, electrical panels, motors, and miscellaneous equipment are maintained constant unless they are tripped on, off, or exponentially decayed during the transient. Hot piping and room cooler loads vary with compartment temperature and can also be tripped on or off. In addition, hot piping heat loads can be exponentially decayed using the heat load decay model discussed in Sec. II.C.7.

### II.B. Slab Model

In the secondary containment of a BWR, compartment walls, ceilings, and floors are generally concrete slabs that range in thickness from ~0.3 to ~2 m. To determine the heat transfer rate between a compartment atmosphere and the bounding concrete slabs, the one-dimensional heat conduction equation

$$\frac{\partial T_s}{\partial t} = \alpha_s \frac{\partial^2 T_s}{\partial x^2} \quad (4)$$

is solved for each slab. Here, $T_s$ (K) is the slab temperature, and $x$ (m) is the spatial coordinate. Since the thermal diffusivity $\alpha_s$ (m$^2$/s) is supplied as input for each slab, materials other than concrete can be modeled provided that slabs are of uniform material composition. This one-dimensional description assumes that slab edge effects do not significantly affect the overall rate of heat transfer.

Boundary conditions on slab temperature are given by

$$\left.\frac{\partial T_s}{\partial x}\right|_{x=0} = -\frac{h_1}{k_s}[T_1(t) - T_s(0,t)] \quad (5)$$

and

$$\left.\frac{\partial T_s}{\partial x}\right|_{x=L_s} = -\frac{h_2}{k_s}[T_s(L_s,t) - T_2(t)] \ , \quad (6)$$

where

$T_1(t), T_2(t)$ = temperatures of compartments adjacent to the slab

$k_s$ = slab conductivity (J/m·s·K)

$L_s$ = slab thickness (m)

$h_1, h_2$ = heat transfer coefficients (J/m$^2$·s·K).

The solution of Eq. (4) subject to Eqs. (5) and (6) gives the rates of energy transfer from the slab surfaces to the adjacent gas mixtures.

The coefficients $h_1$ and $h_2$ account for natural convection, radiation, and condensation heat transfer. In the absence of condensation, the coefficient $h_1$ can be expressed as

$$h_1 = h_{1n} + h_{1r} \ , \tag{7}$$

where $h_{1n}$ and $h_{1r}$ are the natural convection and radiation components, respectively.

Natural convection coefficients are expressed in terms of the Nusselt number, which in turn is a function of the Rayleigh and Prandtl numbers. For the coefficient $h_{1n}$, the appropriate relation is

$$\mathrm{Nu} = \frac{h_{1n} C_L}{k} = f(\mathrm{Ra}, \mathrm{Pr}) \ , \tag{8}$$

where

$C_L$ = slab characteristic length

$k$ = gas thermal conductivity

and the Rayleigh and Prandtl numbers for the gas mixture are, respectively, defined by

$$\mathrm{Ra} = \frac{g\beta C_L^3 |T_s(0,t) - T_1(t)|}{\nu\alpha} \quad \text{and} \quad \mathrm{Pr} = \frac{\mu C_p}{k} \ , \tag{9}$$

where

$g$ = acceleration due to gravity (9.8 m/s$^2$)

$\beta$ = coefficient of thermal expansion (K$^{-1}$)

$\nu$ = kinematic viscosity (m$^2$/s)

$\alpha$ = thermal diffusivity (m$^2$/s)

$\mu$ = dynamic viscosity (kg/m·s)

$C_p$ = specific heat of the air/water vapor mixture (J/kg·K).

Gas mixture properties used in the calculation of free convection coefficients are evaluated at the thermal boundary layer temperature, which is taken as the average of the slab surface temperature and the bulk gas temperature.

For vertical slabs, coefficients are calculated from the correlation proposed by Churchill and Chu[3] for free convection from a vertical plate. For horizontal slabs, free-convection coefficients depend on whether the surface is being heated or cooled by the surrounding gas mixture. As recommended by Holman,[4] the correlation of Fujii and Imura[5] is used with the modified characteristic length proposed by Goldstein et al.[6] to compute the coefficient for an arbitrarily shaped slab with heated surface facing upward or cooled surface facing downward. In cases where the upper surface is cooled or the lower surface is heated, the correlations of Lloyd and Moran[7] are used.

Diatomic gases such as nitrogen and oxygen are essentially transparent to thermal radiation; however, the emissivity of water vapor with respect to thermal radiation is significant.[8] In COTTAP, radiant energy exchange between a slab surface and water vapor contained within the surrounding gas mixture is modeled through the use of an effective radiation heat transfer coefficient [see Eq. (7)]. For the applications of interest, temperature differences between a slab surface and the surrounding gas mixture are relatively small (typically <5 K). Therefore, the following approximate relation proposed by Hottel and Sarofim[9] for small temperature differences is used to compute the radiation coefficient:

$$h_{1r} = \frac{(\epsilon_s + 1)}{2} (4 + a + b - c)\epsilon_{w,av}\sigma T_{av}^3 \ , \tag{10}$$

where

$\sigma$ = Stefan-Boltzmann constant ($5.669 \times 10^{-8}$ J/m$^2$·s·K$^4$)

$\epsilon_s$ = slab emissivity

$T_{av}$ = average temperature, which is defined by

$$T_{av} = [(T^4 + T_{surf}^4)/2]^{1/4} \ , \tag{11}$$

where

$T$ = gas temperature (K)

$T_{surf}$ = slab surface temperature (K)

$\epsilon_{w,av}$ = emissivity of water vapor evaluated at $T_{av}$.

The Cess-Lian[10] equations, which give an analytical approximation to the emissivity charts of Hottel and Egbert,[11] are used to compute the water vapor emissivity. In Eq. (10), $c$ has the value 0.45, and $a$ and $b$ are obtained through differentiation of the Cess-Lian emissivity equations

$$a = \frac{\partial \ln[\epsilon_w(T, P_a, P_w, P_w L_m)]}{\partial \ln(P_w L_m)} \tag{12}$$

and

$$b = \frac{\partial \ln[\epsilon_w(T, P_a, P_w, P_w L_m)]}{\partial \ln(T)} \ , \tag{13}$$

where

$P_a$ = air partial pressure (Pa)

$P_w$ = water vapor partial pressure (Pa)

$L_m$ = average mean beam length (m).

Condensation on a slab surface occurs when the surface temperature drops below the dew point (the saturation temperature of water evaluated at the partial pressure of water vapor in the compartment) of the air/water vapor mixture. Heat transfer coefficients for condensation conditions are calculated using the experimentally determined Uchida[1,12] correlation, which includes the diffusional resistance effect of noncondensible gases on steam condensation rates.

In COTTAP, initial compartment temperatures, pressures, and relative humidities are specified as input data. An initial slab temperature profile is determined by computing the steady solution to Eqs. (4), (5), and (6) corresponding to the initial compartment conditions. This implies that compartments have been maintained at their initial conditions long enough for slabs to attain steady-state temperature profiles.

### II.C. Special Purpose Models

The COTTAP code includes specialized models to simulate the effects of pipe breaks, hot piping, and compartment air coolers. Leakage and natural circulation models are also included to describe intercompartment mass transfer. In addition, the code includes a simplified slab model, a heat load decay model, and a compartment model in which temperature, pressure, and relative humidity are specified as a function of time.

#### *II.C.1. Pipe Break Model*

Within the scope of the present model, pipes may contain steam or saturated liquid water. Input data define the total mass flow through the break $W_{bt}$ (kg/s) along with the time at which the break develops and the length of time over which fluid loss occurs. For pipes containing saturated liquid, the steam flow rate $W_{bs}$ exiting the pipe (kg/s) is calculated from the energy balance

$$W_{bt}h_f(P_p) = W_{bs}h_g(P) + (W_{bt} - W_{bs})h_f(P) \quad , (14)$$

which describes the isenthalpic expansion of fluid from pipe pressure $P_p$ to compartment pressure $P$. The liquid fraction, which does not flash as it leaves the pipe, is assumed to cool to compartment temperature, and the dissipated sensible heat is transferred directly to the compartment air/water vapor mixture. For the case where a pipe contains steam, all of the mass and energy exiting the break is deposited directly into the compartment gas mixture.

Rain-out phenomena can be important in compartments containing pipe breaks. For example, following isolation of a pipe break (due to valve closure, for instance) a compartment begins to cool and condensation continues to occur on surrounding walls. For a sufficiently fast cooldown rate, condensation alone does not prevent compartment air from becoming saturated, and thus moisture droplets (rain-out) form within the gas mixture. To maintain compartment relative humidity less than or equal to unity, the rainout rate $W_{ro}$ (kg/s) is calculated from the following empirical model:

$$W_{ro} = 200\ (RH - 0.99)\max(W_s, C_{r1}) \quad \text{if } RH > 0.99 \qquad (15)$$

and

$$W_{ro} = 0.0 \quad \text{if } RH \leq 0.99 \ , \qquad (16)$$

where

$RH$ = relative humidity

$W_s$ = total steam flow rate into the compartment (kg/s)

$C_{r1}$ = constant that is supplied as part of the input data (kg/s).

#### *II.C.2. Hot Piping Model*

In many secondary containment compartments, the major heat source consists of piping that contains reactor steam or coolant. The heat addition rate to a compartment air/water vapor mixture from a hot pipe is calculated from

$$Q_{piping} = U_p \pi L_p D_p [T_f - T(t)] \ , \qquad (17)$$

where

$U_p$ = overall heat transfer coefficient ($J/m^2 \cdot s \cdot K$)

$L_p$ = pipe length (m)

$D_p$ = outside diameter of the pipe (or insulation if the pipe is insulated) (m)

$T_f$ = pipe fluid temperature (K)

$T$ = compartment temperature.

The overall heat transfer coefficient is calculated by the code based on initial compartment conditions; the coefficient is then maintained constant throughout the transient.

#### *II.C.3. Air Cooler Model*

Cooling units are used in a number of secondary containment compartments to remove heat generated by equipment such as emergency core cooling systems (ECCS) injection pumps and high-voltage buses and transformers. Heat removal rates of cooling units are calculated from

$$Q_{cool}(t) = C_{cool}[T(t) - \bar{T}_{cool}(t)] \ , \qquad (18)$$

where

$\bar{T}_{cool}(t)$ = average of the inlet and outlet cooling water temperatures

$C_{cool}$ = constant that is computed from specified initial values of the cooling load $Q_{cool}$, the inlet cooling water temperature, the cooling water flow rate, and the compartment temperature $T$.

An energy balance on the cooling water yields the outlet cooling water temperature.

*II.C.4. Leakage Models*

The COTTAP leakage model simulates pressure-induced intercompartmental mass transfer through openings such as doorways and ventilation ducts. Intercompartment leakage is calculated by balancing the pressure differential between the compartments with an irreversible pressure loss. Thus, the leakage rate satisfies

$$P_2(t) - P_1(t) = \frac{K_{lk} W_{lk}(t)|W_{lk}(t)|}{2\rho_{lk}(t) A_{lk}^2} , \quad (19)$$

where

$P_1, P_2$ = pressures of the compartments associated with the leakage path (Pa)

$W_{lk}$ = leakage rate (kg/s)

$K_{lk}$ = irreversible pressure loss coefficient

$A_{lk}$ = leakage area ($m^2$)

$\rho_{lk}$ = gas density within the compartment supplying the leakage flow ($kg/m^3$).

It is assumed that inertial effects do not significantly affect leakage rates.

*II.C.5. Natural Circulation Model*

A natural circulation model simulates gravity-driven mixing in compartments connected by flow paths at differing elevations. The circulation rate $W_c$ (kg/s) is obtained from

$$W_c(t) = \left\{ \frac{2g[\rho_2(t) - \rho_1(t)](E_u - E_l)}{K_l/[A_l^2 \rho_2(t)] + K_u/[A_u^2 \rho_1(t)]} \right\}^{1/2} , \quad (20)$$

where

$\rho_1, \rho_2$ = densities of the air/water vapor mixtures within the two adjacent compartments ($kg/m^3$) (here it is assumed that $\rho_2$ is the gas density for the cooler compartment)

$E_u, E_l$ = elevations of the upper and lower flow paths (m)

$A_u, A_l$ = upper and lower flow path areas ($m^2$).

This model also describes intercompartment, gravity-driven circulation flows that can develop at open doorways (see the analysis of Brown and Solvason[13]).

*II.C.6. Thin Slab Model*

The detailed slab model discussed in Sec. II.B is not required to describe heat transfer through thin slabs that have little thermal capacitance. Slabs of this type, e.g., refueling floor walls, have nearly linear temperature profiles, and thus the heat flow through a thin slab can be calculated by the use of an overall heat transfer coefficient $U_{ts}$. The rate of heat transfer through a thin slab is obtained from

$$q_{ts}(t) = U_{ts} A_{ts} [T_1(t) - T_2(t)] , \quad (21)$$

where

$A_{ts}$ = thin slab heat transfer area ($m^2$)

$T_1, T_2$ = temperatures of the compartments separated by the slab (K).

Values of $U_{ts}$ ($J/m^2 \cdot s \cdot K$) are supplied as part of the code input data (one value for each vertical slab and two values for each horizontal slab). For horizontal slabs, two values of $U_{ts}$ are required because free-convection film coefficients depend on the direction, upward or downward, of heat flow through the slab.

*II.C.7. Heat-Load Decay Model*

Cooling of a component such as a pipe filled with hot stagnant fluid or a pump that has ceased operating is simulated through the use of a lumped-parameter heat transfer model. Most compartments in the secondary containment have a large thermal capacity because of the bounding concrete slabs. It is therefore assumed that the component temperature changes on a faster time scale than the compartment air temperature; i.e., the air temperature is assumed to remain fairly constant during the cooldown of the component. With this assumption, the component heat dissipation rate $Q_c(t)$ is governed by

$$\gamma_c \frac{dQ_c(t)}{dt} = -Q_c(t) , \quad (22)$$

where

$$Q_c(t_0) = Q_{co} \quad (23)$$

and $\gamma_c$ ($s^{-1}$), the thermal time constant of the component, is given by

$$\gamma_c = \frac{M_c C_{pc}}{U_c A_c} , \quad (24)$$

where

$M_c$ = mass of the component (kg)

$C_{pc}$ = specific heat of the component ($J/kg \cdot K$)

$U_c$ = overall heat transfer coefficient (J/m$^2$·s·K)

$A_c$ = component heat transfer area (m$^2$).

In Eq. (23), $t_0$ (s) is the time at which the cooldown process begins, and $Q_{co}$, which is supplied as input data, is the heat dissipation rate prior to cooldown. Solution of Eqs. (22) and (23) gives the exponential-decay approximation used in COTTAP to model heat dissipation of cooling components. The component time constant $\gamma_c$ is specified as input data except in the case of hot piping, where it is calculated by the code from the piping description data.

*II.C.8. Time-Dependent Compartment Model*

With the time-dependent compartment (TDC) model, environmental conditions within a compartment are specified as a function of time; i.e., temperature, pressure, and relative humidity versus time are supplied as tabular input data. This model is particularly useful for representing outside air conditions, including solar and thermal radiation effects. The influence of solar and long-wave atmospheric radiation on exterior buildup surfaces can be described by specifying the effective Sol-Air temperature[14] in the TDC instead of the actual outside air temperature. In secondary containment analysis, the TDC model is also useful for describing transient conditions within the primary reactor containment, which are generally known from the results of detailed licensing basis calculations.

**II.D. Numerical Solution Methods**

An energy balance and two mass balances are solved for each compartment to determine gas temperature, air mass, and water vapor mass. In addition, the one-dimensional heat conduction equation is solved for each slab. Before computing the numerical solution of the governing equations, partial differential equations describing heat flow through slabs are approximated by sets of ordinary differential equations (ODEs). This is accomplished through application of the method of lines (MOL). In the MOL, a finite difference approximation is applied only to the spatial derivative in Eq. (4), giving

$$\frac{dT_{si}}{dt} = \alpha_s T_{sxxi} \ , \tag{25}$$

where

$i = 1,2,3,\ldots,N$, the number of equally spaced grid points

$T_{si}$ = slab temperature at grid point $i$

$T_{sxxi}$ = finite difference approximation to the second-order spatial derivative at grid point $i$.

Following the approach used by Pirkle and Schiesser[15] in the MOL solution of parabolic equations, fourth-order central difference formulas are used to compute $T_{sxxi}$ at interior grid points:

$$T_{sxxi} = \frac{1}{12\Delta^2}(-T_{si-2} + 16T_{si-1} - 30T_{si} + 16T_{si+1} - T_{si+2}) + O(\Delta^4) \ , \tag{26}$$

where

$i = 3,4,\ldots,N-2$

$\Delta$ = spacing between grid points.

A six-point sloping difference formula is used to approximate $T_{sxxi}$ at $i = 2$ and $i = N-1$:

$$T_{sxx2} = \frac{1}{12\Delta^2}(10T_{s1} - 15T_{s2} - 4T_{s3} + 14T_{s4} - 6T_{s5} + T_{s6}) + O(\Delta^4) \tag{27}$$

and

$$T_{sxxN-1} = \frac{1}{12\Delta^2}(10T_{sN} - 15T_{sN-1} - 4T_{sN-2} + 14T_{sN-3} - 6T_{sN-4} + T_{sN-5}) + O(\Delta^4) \ . \tag{28}$$

For the end points, where the normal derivatives are specified through convective boundary conditions, the following finite difference approximations, recommended by Pirkle and Schiesser,[15] are used to compute $T_{sxxi}$:

$$T_{sxxi} = \frac{1}{12\Delta^2}\left(-\frac{415}{6}T_{s1} + 96T_{s2} - 36T_{s3} + \frac{32}{3}T_{s4} - \frac{3}{2}T_{s5} - 50\Delta T_{sx1}\right) + O(\Delta^4) \tag{29}$$

and

$$T_{sxxN} = \frac{1}{12\Delta^2}\left(-\frac{415}{6}T_{sN} + 96T_{sN-1} - 36T_{sN-2} + \frac{32}{3}T_{sN-3} - \frac{3}{2}T_{sN-4} + 50\Delta T_{sxN}\right) + O(\Delta^4) \ . \tag{30}$$

In Eqs. (29) and (30), the normal derivatives $T_{sx1}$ and $T_{sxN}$ are evaluated in accordance with Eqs. (5) and (6), the convective boundary conditions; i.e.,

$$T_{sx1} = -\frac{h_1}{k_s}(T_1 - T_{s1})$$

and

$$T_{sx2} = -\frac{h_2}{k_s}(T_{sN} - T_2) \ . \tag{31}$$

All governing equations are now expressed in terms of ODEs of the form

$$\frac{dy}{dt} = F(y,t) \quad \text{with } y(0) = y_0 \quad . \tag{32}$$

Solutions of Eq. (32) exhibit rapid initial adjustments in compartment air temperature caused by the relatively small thermal capacitance of the air contained within the compartment. Moreover, slab temperatures undergo rapid initial changes in narrow regions near the boundaries, resulting in the formation of spatial thermal boundary layers. In the numerical integration of Eq. (32), small time steps are required to simulate these initial transients. As the initial transient response decays, however, it is desirable to increase step sizes in order to reduce the computation time required to follow the slowly varying part of the solution. Equations, such as Eq. (32), which exhibit initial temporal boundary layer structures are termed stiff differential systems (see the discussion in Ref. 16), and because of stability limitations, they cannot be solved efficiently with explicit integration schemes. For this reason, an implicit scheme was selected for COTTAP.

Numerical integration of the governing Eq. (32) is carried out with the LSODES code,[17] which uses the implicit backward differentiation methods proposed by Gear for the solution of stiff systems. The LSODES code also employs sparse matrix inversion techniques in solving the implicit finite difference equations. With these numerical integration features, it is feasible to carry out the integration of the large differential systems that arise in the simulation of secondary containment transients. As an illustration of the problem dimension, simulation of the SSES-1 and -2 secondary containments under postaccident conditions required the solution of 20 101 coupled ODEs.

For these large-scale problems, reevaluation of code-calculated slab heat transfer coefficients at every time step leads to unacceptably long computation times. To alleviate this difficulty, the frequency of reevaluation (number of steps between reevaluation of coefficients) is a parameter supplied as input to the code. Sensitivity calculations on small-scale problems representative of postaccident secondary containment transients indicate that coefficients can be reevaluated as infrequently as once per ten steps without introducing significant errors in the results. The CPU time requirements were reduced by a factor of 4 when coefficients were reevaluated at every tenth time step.

### II.E. Code Limitations in Modeling Accident Scenarios

The following modeling limitations have been identified in the current version of the COTTAP code:

1. Fission product transport among compartments is not modeled.

2. Cooler modeling does not describe moisture removal under conditions where the cooling coil temperature is below the dew point of the inlet gas mixture.

3. Pipe break modeling is valid only for lines containing steam or saturated liquid; breaks involving the release of subcooled liquid cannot be described.

4. Compartment flooding events cannot be simulated because all liquid is assumed to exit through compartment floor drains.

## III. RESULTS OF SSES SECONDARY CONTAINMENT ANALYSIS FOR POSTACCIDENT CONDITIONS

This section gives representative results for a COTTAP simulation of the combined SSES-1 and -2 secondary containments under postaccident conditions. The thermal responses of the Units 1 and 2 secondary containments are coupled by heat transfer through common walls that separate the two structures. The SSES model consists of 105 compartments, 16 time-dependent compartments, 767 slabs, 38 thin slabs, and 505 heat loads. The simulation was carried out for 30 h and required 124 min of CPU time on an IBM 3090 computer. Note that most of the CPU time is required to simulate the rapidly varying part of the transient that occurs within the first few hours of the event. Thus, substantially longer simulation times do not significantly increase CPU time requirements.

For this analysis, it is assumed that a loss-of-coolant accident (LOCA) occurs in SSES-1 and a false LOCA signal (a spurious signal that indicates loss of reactor coolant and leads to ventilation system isolation and operation of ECCS injection pumps) is generated on SSES-2. Under postaccident conditions, ECCS injection pumps comprise the key equipment within the secondary containment structure. The ECCS consists of the residual heat removal (RHR), core spray, and high-pressure coolant injection (HPCI) systems. These systems receive electrical power from high-voltage buses contained within emergency switch gear and load center rooms. Figure 1 shows the calculated temperature response within a SSES-1 RHR pump room (each unit contains two RHR pump rooms and two core spray pump rooms). Initially, the air temperature increases rapidly because of the small thermal capacitance of the air within the compartment. As air temperature increases, a balance between compartment heat sources and losses to compartment air coolers and slabs begins to develop. At this time, air temperature starts to increase on the slow time scale governed by the slab thermal capacity and transport properties. An initial rapid temperature rise followed by a much slower temperature increase is characteristic of all compartment heatup transients. After 1 h of operation, this particular RHR pump switches from the injection mode of operation to the suppression pool cooling

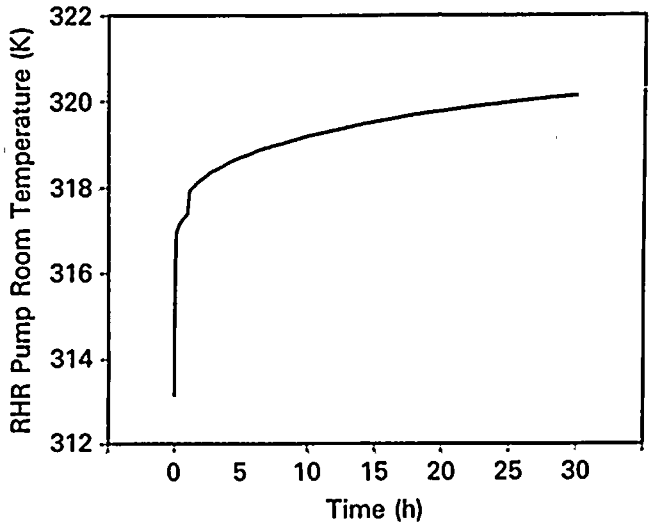


Fig. 1. Simulation of postaccident temperature response within SSES-1 RHR pump room for LOCA on SSES-1 and false LOCA on SSES-2.

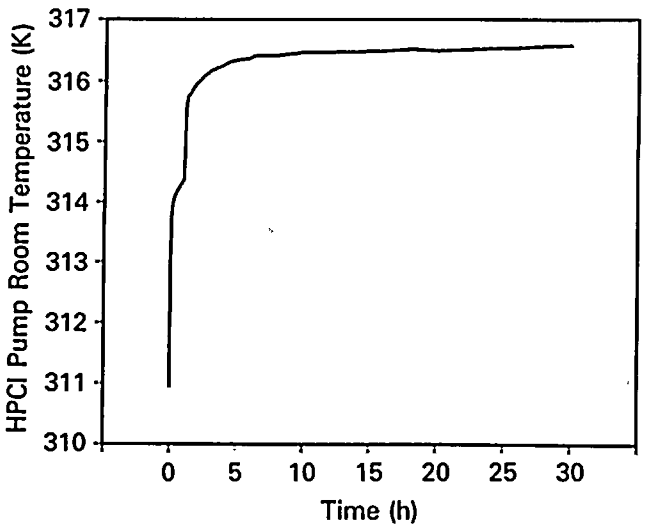


Fig. 3. Simulation of postaccident temperature response within SSES-1 HPCI pump room for LOCA in SSES-1 and false LOCA in SSES-2.

mode. As a result of increased compartment heat loads associated with the change in operating mode, the temperature again increases rapidly until a new balance between the heat-generation and heat-loss rates is attained.

The temperature response within a SSES-1 core spray pump room is shown in Fig. 2. Core spray operation begins at the start of the event and ceases 1 h later. Temperature decreases rapidly at this point because, once pump operation is terminated, no significant heat loads remain in the compartment. Figure 3 illustrates the temperature response of the SSES-1 HPCI system, which also begins operation at the start of the accident. In this case, however, compartment temperature continues to increase when the system ceases operation at 1 h into the transient. This occurs because piping heat loads within this compartment are substantial. When HPCI pump operation stops, an associated room cooling unit also ceases operation. Upon shutdown of the cooling unit, slowly decaying piping heat loads rapidly increase compartment temperature until a balance between heat generation and heat losses to compartment slabs is approached. Figure 4 gives the temperature within a SSES-1 load center room that

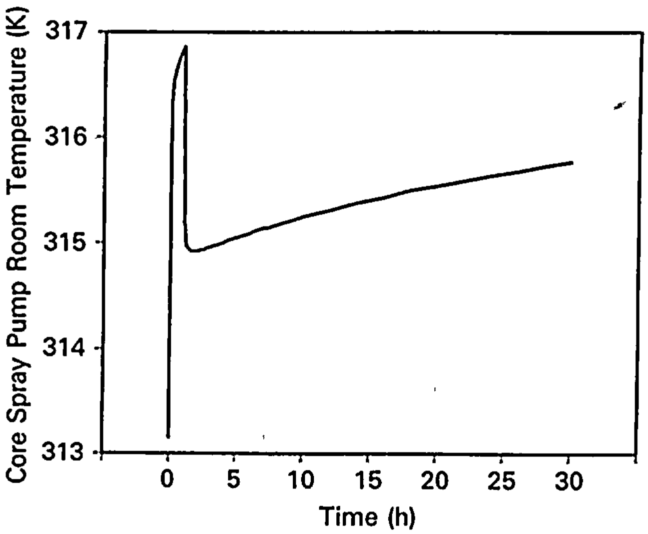


Fig. 2. Simulation of postaccident temperature response within SSES-1 core spray pump room for LOCA in SSES-1 and false LOCA in SSES-2.

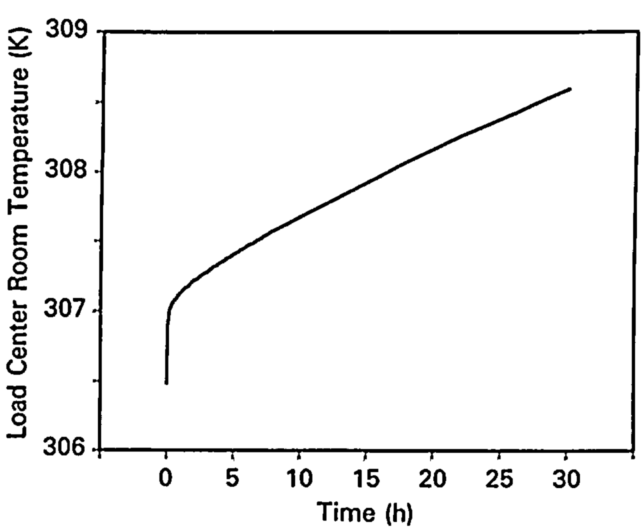


Fig. 4. Simulation of postaccident temperature response within SSES-1 load center room for LOCA in SSES-1 and false LOCA in SSES-2.

supplies electrical power to emergency equipment. In this compartment, heat loads remain essentially constant throughout the transient.

From the results of this analysis, it is determined that under postaccident conditions, some of the equipment within the secondary containment would be exposed to temperatures that exceed their qualification values. Consequently, components were reassessed for operation at higher temperatures, and in some instances equipment was relocated to compartments with less severe environmental conditions. Furthermore, a procedure was developed to instruct plant operators to shed nonessential electrical loads within 24 h after an accident in order to moderate the temperature responses within secondary containment compartments.

## IV. EVALUATION OF CODE ACCURACY

As part of the verification process for the COTTAP code, calculational results were compared with those obtained with the CONTAIN (Ref. 2) program, which has been verified through comparison with experimental data.[18,19] Although the CONTAIN code does not accommodate a direct heat input (such as from operating mechanical or electrical equipment) to a compartment, useful problems can nevertheless be formulated in order to investigate the modeling and computational accuracy of COTTAP. Two such problems were formulated for code verification. The first problem tests the COTTAP compartment mass and energy balance calculations and the slab heat transfer simulation. This problem consists of a single compartment that has a 1000-$m^3$ volume and contains air at 300 K and 101 325-Pa initial temperature and pressure. Concrete slabs, which range in thickness from 0.1 to 1 m, form the walls of the compartment. All slabs have a uniform, initial temperature of 300 K. To add heat to the compartment, the air in contact with the outer surface of one slab (the slab that is 0.1 m thick) is suddenly increased to 400 K at $t = 0$. In addition, at 50 s into the transient, air with a temperature of 500 K is injected into the compartment at a 0.26 kg/s flow rate. Outer surface temperature rise and air injection conditions were selected to effect significant, but not excessive, temperature and pressure response.

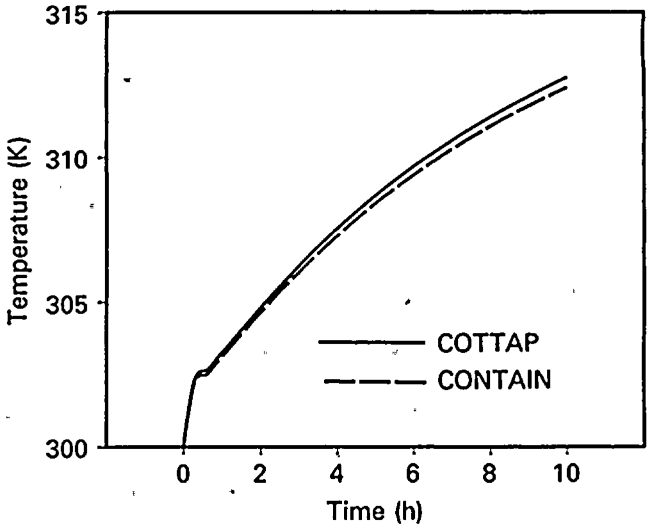


Fig. 5. Comparison of COTTAP and CONTAIN compartment temperature simulations for test problem 1.

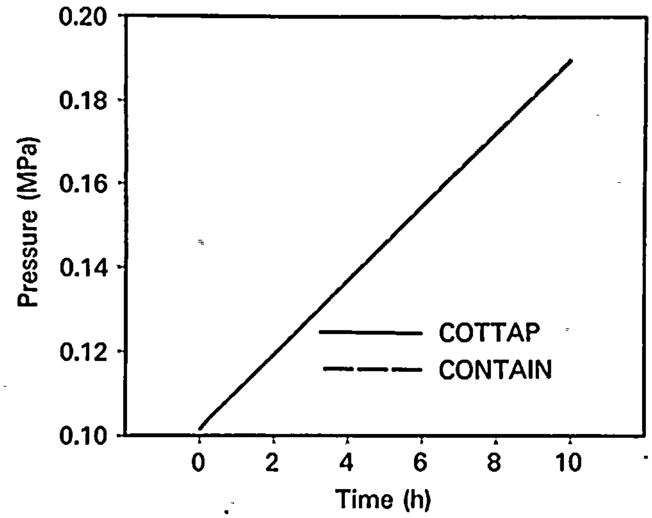


Fig. 6. Comparison of COTTAP and CONTAIN compartment pressure simulations for test problem 1.

Figures 5 and 6 present a comparison of the COTTAP and CONTAIN calculation results for the first test problem. The temperature and pressure simulations both show excellent agreement; note that the pressure response curves given in Fig. 6 completely overlap. In Fig. 5, the initial temperature increase, which is due to injection of hot air into the compartment, begins to level off at ~0.5 h. Heat addition by means of conduction through the externally heated slab then begins to occur, causing a further but less rapid increase in temperature.

The second test problem considered for code verification involves modeling of compartment temperature and pressure behavior under conditions where high-energy steam is injected into the compartment. In this problem, condensation effects strongly influence the rate of temperature and pressure increase. Compartment physical description data are the same as that for test problem 1. In this case, however, the only heat source is the steam entering the compartment at a 0.20 kg/s flow rate and a $2.7756 \times 10^6$ J/kg enthalpy. This flow rate and enthalpy are characteristic of a small steam leak within a secondary containment compartment. Figures 7 and 8 show a comparison of the

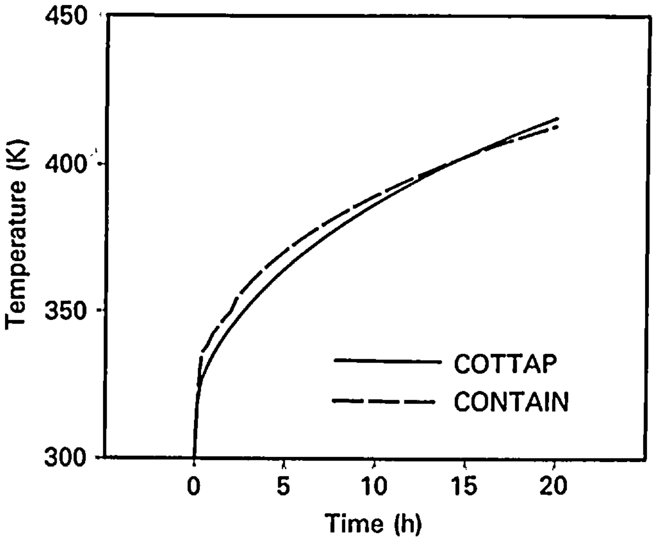


Fig. 7. Comparison of COTTAP and CONTAIN compartment temperature simulations for test problem 2.

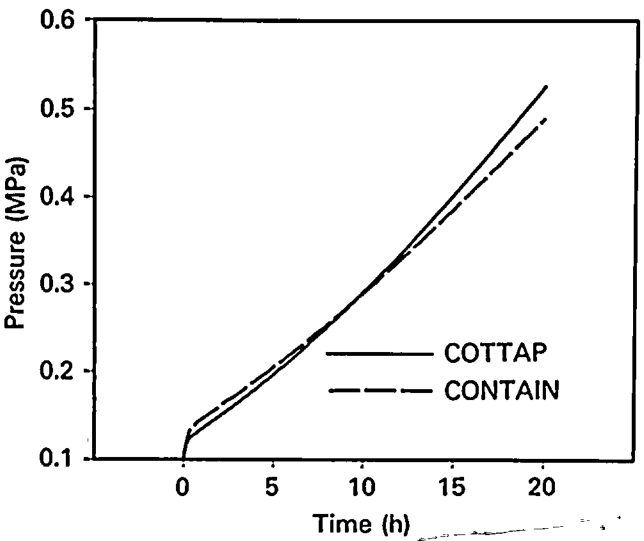


Fig. 8. Comparison of COTTAP and CONTAIN compartment pressure simulations for test problem 2.

COTTAP and CONTAIN simulation results. The results show good agreement even though the codes employ considerably different approaches in the calculation of condensation rates on slab surfaces. The COTTAP code uses the experimentally determined Uchida[12] condensation coefficient, while CONTAIN carries out a detailed computation of the thermal resistances associated with the gas boundary layer and the condensate film.

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