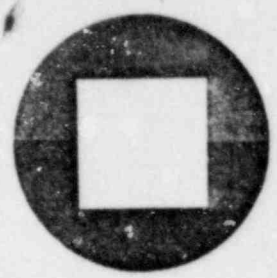
Offshore Power Systems



ATTACHMENT 1

THE CLASIX COMPUTER PROGRAM

for the

ANALYSIS OF REACTOR PLANT CONTAINMENT RESPONSE

to

HYDROGEN RELEASE AND DEFLAGRATION

OPS REPORT NO. 36A31

OCTOBER, 1981

PST-NE-359

Offshore Power Systems

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October 27, 1981

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Subject: OPS CLASIX Topical Report, No. OPS-07A35 (Proprietary), No. OPS-36A31 (Non-Proprietary)

Gentlemen:

Enclosed are proprietary and non-proprietary versions of the CLASIX Topical Report as well as other documents relevant to your use of this Topical Report and submission of it to the Nuclear Regulatory Commission. The complete list of enclosures is tabulated at the end of this letter. The draft letter of application for withholding of proprietary information has been prepared and the number of copies of the Topical Report has been transmitted assuming that TVA will submit the report to the Nuclear Regulatory Commission and that Duke and AEP will reference that submittal and likewise request withholding on their dockets.

As per our proposal, additional modifications to CLASIX are underway. These modifications include changes to model sumps and recirculation flow, incorporation of a variable burn fraction for propogating burns, addition of a spray heat transfer correlation, and changes to reduce the run time. These modifications will add additional realism to the program and improve

its efficiency but are not expected to have any major impact on current results or conclusions. These modifications are discussed in Tasks 1.2.1.1, 1.2.2, 1.2.3.1, 1.2.3.2 and 1.3.1.1 of our proposal. When these modifications are complete, an addendum or revision to the Topical Report will be necessary. The addendum or revision will include a description of the new features as well as additional verification relative to these modifications.

Sincerely,

Kenneth C. Perry

Kenneth C. Perry, Manager
Safety & Systems Analysis

/aw

Enclosures:

(1) Draft letter application for withholding of proprietary information.

(2) Letter from Westinghouse to the NRC authorizing the use of the proprietary information.

(3) Affidavit.

(4) Copies of report OPS-07A35 (Proprietary):
TVA (for transmittal to NRC) - 5 copies
TVA - 3 copies
Duke- 3 copies
AEP - 3 copies

(5) Copies of report OPS-36A32 (Non-Proprietary):
TVA (for transmittal to NRC) - 1 copy
TVA - 1 copy
Duke- 1 copy
AEP - 1 copy

(6) Index of Responses to NRC Question 6.

THE CLASIX COMPUTER PROGRAM

FOR THE

ANALYSIS OF REACTOR PLANT CONTAINMENT RESPONSE

TO

HYDROGEN RELEASE AND DEFLAGRATION

by

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ABSTRACT

The CLASIX computer program is based on a multi-compartment model of an ice condenser containment. The purpose of the program is to predict the temperature and pressure response of the containment to a degraded core transient during which hydrogen is released to the containment and then burned. The program has been used extensively in licensing activities by the utilities. Extensive verification of the program demonstrates that the program provides realistic, but conservative, predictions of the temperatures and pressures resulting from a hydrogen deflagration.

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I. BACKGROUND AND INTRODUCTION

During the incident at Three Mile Island (TMI) in March 1979, hydrogen, generated by the zirconium-water reaction in the degraded core, was released to the containment atmosphere. A spike in the containment pressure some hours into the transient is evidence that the hydrogen concentration in at least part of the containment reached combustible limits and was ignited. As an applicant for a Manufacturing License for Floating Nuclear Plants (FNP), Offshore Power Systems (OPS) was interested in the implications of the TMI incident on the integrity of the FNP containment. Consequently OPS began the development of an analytical capability to investigate the response of the FNP containment to a TMI type incident. The result of this development is the CLASIX* computer program.

A significant feature of the subject transient is the introduction of an additional gas which then results in a chemical reaction. Thus, to adequately analyze the transient, an inventory of the masses of the individual constituents of the containment atmosphere must be maintained. No existing program for reactor plant safety analysis had such a capability. It was concluded that it would be more difficult, require more resources and, most important, take more calendar time to modify an existing program than to develop a new program specifically designed for the TMI type transient.

The CLASIX computer program, in various stages of development, has been used to support the licensing activities of four ice condenser containment reactor plant designs. Analytical results produced by CLASIX were instrumental in the Tennessee Valley Authority receiving an operating license for the Sequoyah Plant in 1980. Similar analytical results generated for the McGuire Plant of Duke Power Company were utilized in obtaining a full power license in 1981. American Electric Power Service Company has used CLASIX

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*Since this type of transient would be in the category of a Class 9 accident, the Roman numeral IX was substituted for the Arabic 9 and shortened to CLASIX for the name of the program.

results in resolving TMI issues for the Cook Plants. OPS has also used CLASIX results in licensing activities relative to the Manufacturing License for the FNP.

To minimize development time, the analytical model was tailored to specifically represent the ice condenser containment. However, the model has sufficient versatility to be applicable to a variety of containment configurations. The analytical methods, of course, are general and applicable to this type transient regardless of the containment.

II. ANALYTICAL MODEL

The analytical model of CLASIX can represent the containment with up to seven compartments or control volumes interconnected with a fixed set of flow paths. An eighth volume is included to represent a discharge volume, such as the atmosphere of another vessel, to which the containment may be vented. A schematic of the analytical model is shown in Figure 1. Volume 1 in the figure generally represents the entire lower compartment of the ice condenser containment. However, the lower compartment can be subdivided to include Volumes 5, 6 and 7 as shown in the figure. Volume 5 represents the equipment and instrument volumes off the main volume of the lower compartment. Volumes 6 and 7 represent segregated volumes associated with the pressurizer and steam generator enclosure volumes, respectively. The lower compartment is vented to the ice condenser inlet plenum via the lower inlet doors which function the same as check valves to permit only unidirectional flow. Volume 2 generally represents the ice condenser inlet plenum or the volume between the lower inlet doors and the bottom of the ice filled portion of the ice baskets. As the ice melts during the transient, [ ]* the inlet plenum increases *a,c in volume. Volume 3 represents the volume between the top of the ice in the ice baskets and the top deck doors or basically the outlet plenum. [ ] a,c [ ]

Within the ice filled portions of the ice baskets there is some net free gas volume. As part of the input to the program, this volume must be specified. [ ] a,c

The upper compartment of the containment is represented by Volume 4 and consists of the balance of the containment net free volume. Volume 8 is the vent volume or discharge volume of the containment. This volume is unique only because of the connecting flow path which will be discussed below.

In addition to the rather conventional flow paths shown in the figure, there are special flow paths that can be specified as connecting any two volumes and for which the head/flow correlation may be specified. These flow paths are utilized to represent fan flow.

III. MAJOR ASSUMPTIONS

Discussed here are the major assumptions utilized in the program. Other assumptions are stated explicitly in the analytical development and some are implicit in the way that the equations are written.

The only non-condensible gases assumed to be of sufficient concentration to be considered in the program are oxygen, nitrogen and hydrogen. These gases are assumed to be perfect gases with constant specific heats.

The water vapor properties are taken from the ASME steam tables within the limits of the tables and may be either saturated or superheated. Above the 1500 F upper limit of the steam tables, the steam is assumed to be a perfect gas.

In each compartment, or control volume, all gases are assumed to be instantaneously perfectly mixed.

Except for the condition where hydrogen is burned as generated, the combustion of the hydrogen is assumed to occur at a uniform, constant rate over the period of combustion.

Superheated liquid entering the compartment either as breakflow or spray water is assumed to instantaneously vaporize sufficient water to achieve thermodynamic equilibrium corresponding to the total pressure of the compartment. The vapor and its associated energy are added to the inventory of the compartment atmosphere. For the breakflow, the liquid portion is assumed to fall immediately to the floor to be collected by the sumps and drains. For the sprays, the liquid portion must fall through the atmosphere over some period of time as discussed later.

IV. PROGRAM DESCRIPTION

Following is a general discussion of the program, what the program is designed to do and how it performs its function. Development of equations to carry out the numerics is left to a later section.

As shown in Figure 1 and discussed above, the ice condenser containment is represented by a number of volumes interconnected with a fixed set of flow paths. Any of the volumes may be eliminated by setting the volume to zero and any of the flow paths may be eliminated by setting the flow area to zero. In each of the active volumes, an inventory is maintained of the masses of the constituent gases and of the total internal energy of the gases. Based on the assumption of perfect mixing, the atmosphere of the compartment will have one temperature. From the assumption of perfect gases and/or the steam tables, the partial pressure of the individual gases and, consequently, the total pressure in the compartment can be determined.

Each of the active flow paths shown in Figure 1 can be represented by a flow area and a dimensionless loss coefficient. In flow paths 1, 2 and 3, the flow areas can be controlled by representation of a door which can reduce the reverse flow to zero or some small value. In all flow paths, the critical pressure ratio for transition to critical or choked flow is assumed to be a constant. This pressure ratio is monitored to assure use of the appropriate flow correlation. Special flow paths may also be designated for interconnection of active volumes. For these special flow paths, the head/flow correlation is externally specified in tabular form and the flow paths may be restricted to operate only over a portion of the transient. The primary intent of these special flow paths is to represent fan forced flow.

As indicated previously, flow path number 8 is a special case. This flow path has a simulation of a rupture disc. No flow can occur until the upper compartment pressure exceeds a given value. Once the rupture disc pressure set point is exceeded, flow calculations for this flow path are initiated.

A length, or slug, of water and a submergence depth may be specified to represent discharge under water with the connecting pipe partially filled with water. This slug of water, if it exists, must be accelerated and discharged before gas flow can be initiated. Consistent with the underwater capability, no reverse gas flow through this flow path is permitted.

Hydrogen, nitrogen, water and heat may be added to selected compartments at externally specified rates. Only the heat rates may have negative values which may be used to simulate fan coolers and other heat sinks. Hydrogen and nitrogen additions must be accompanied by corresponding temperatures as a measure of the heat energy in the gas. Water additions must be accompanied by an enthalpy. The enthalpy of the water is compared to the saturated liquid and vapor enthalpies corresponding to the total pressure in the compartment. According to a prior assumption, the liquid and vapor portions and their associated energy are added to the drains and atmosphere, respectively.

Sprays may also be added to selected compartments by specifying the flow rate, heat transfer coefficient and temperature as a function of time. The spray drop size exiting the spray nozzles and the rate of fall of the spray are assumed to be constant for a given spray. Depending upon the instantaneous transient conditions, some of the spray entering a compartment may instantaneously vaporize. The liquid portion falls through the atmosphere. As the spray droplets fall, there is heat transfer between the atmosphere and the water. Depending upon the specific conditions, condensation, vaporization or simple temperature changes may occur during the period of time the spray drop is falling.

Passive heat sinks are available in all compartments. These are modeled as one dimensional heat transfer heat sinks which may be multilayered with film coefficients of heat transfer between layers. Several film coefficient correlations for the internally exposed surface are available in the program or the coefficient may be externally specified in tabular form as a function of either time or the temperature difference between the heat sink surface and the compartment atmosphere.

The ice condenser is represented [ ] a,c

[ ]

The ignition and rate of combustion of hydrogen are controlled by externally specified criteria. The criteria which must be specified are listed in Table 1. The first criterion is the volume fraction of hydrogen at which ignition is assumed to be permissible. Tests indicate that when ignition occurs at concentrations less than about 10 volume percent of hydrogen, not all of the hydrogen present will be consumed. The second parameter as listed in the table is the percent of hydrogen present which is to be consumed. Experimental results also demonstrate that below some minimum oxygen concentration, hydrogen will not ignite regardless of its concentration. Thus, even though the first criterion is satisfied, the third must also be satisfied before ignition will actually take place. The next parameter is the oxygen concentration at which an existing flame will be extinguished. Available data indicate that combustion will proceed until all of the oxygen is exhausted. The program monitors the oxygen content of the compartment and should the oxygen be depleted below the stated value for the fourth parameter, combustion is stopped.

The deflagration of hydrogen in the physical world proceeds as a flame front which has a velocity of a few feet per second. Based on the dimensions of the compartment, the flame speed and the assumed location of the ignition, the burn time of a compartment can be calculated. This is the fifth parameter required for combustion calculations. As the flame front proceeds, it will pass through openings to adjoining compartments. If the hydrogen concentration is sufficiently high and the required amount of oxygen is present, the flame will propagate into this adjoining compartment. The hydrogen concentration required for propagation is the sixth parameter in the table and the time required for the flame to propagate

from the ignition source to the adjoining compartment is the propagation delay time.

During the course of the analysis, the program will, upon appropriate command, write an exhaustive file of all pertinent parameters so that the transient can be restarted from this point with modified input. This restart feature permits the examination of the results from a given set of input, modification of the input and continuation the transient.

A simplified flow diagram of the CLASIX computer program is shown in Figure 2. The input to the program may be a complete set of input to initiate a new transient or it may be a restart file with some modified input. In either event, a complete input edit is generated. Upon completion of the input edit, a finite difference integration loop is entered which continues until one of the program stops is encountered. If a new transient is being initiated, an output edit of initial conditions is generated. Otherwise, the frequency at which output is generated is controlled by the conditions specified in the input.

[ ] a,c

The first calculation is the volumetric rates of flow between the compartments. This calculation includes evaluation of the door position and area of flow for those paths having doors and the use of head/flow tables for the special flow paths. Using the volumetric flow rates and the conditions in the source volume, the rates of change of mass for each constituent and the rate of change of energy in both the source and sink volumes can be evaluated for each flow.

Heat is transferred to the surface of the passive heat sink by convective heat transfer and by radiation. As discussed briefly above, the film

coefficient of heat transfer may be derived from one of the built-in correlations or from tabular input. The radiant heat transfer rate is a function of the emmissivity of the containment atmosphere.

The spray flow rate, temperature and film coefficient of heat transfer are linearly interpolated from the input tables. Heat and mass transfer rates are calculated for the spray over the period of its fall or until the drops evaporate.

The heat addition rate from the input tables are added to or subtracted from the atmosphere. The hydrogen and nitrogen mass addition rates must be positive and are added, with their associated enthalpies, to the atmosphere. The break flow, which also must be positive, is expanded against the total pressure of the atmosphere with the vapor and its associated energy being added to the atmosphere with the balance being added to the sumps and drains.

If ice exists in the ice condenser, the rate of heat transfer to the ice will be a function of the flow rate and the constituents of the flow. As the steam condenses during its passage through the ice bed, the film coefficient is adjusted and the overall heat transfer rate to the ice evaluated.

The conditions in each compartment are compared with the specified criteria to determine if ignition should occur. Each flow path is also examined to determine if a flame front has arrived from an adjoining compartment and, if so, if ignition due to propagation should occur. If ignition occurs for either reason, the rates of removal of oxygen and hydrogen and the rates of addition of water vapor and energy are determined. The mass of hydrogen to be burned is determined and the clocks for each connected flow path are initialized for propagation delay times. The propagation delay times are measured from the time of ignition. All active flow paths shown in Figure 1 are assumed to propagate flame whether or not a door is present and closed. No propagation is assumed in the fan flow paths.

[ ]a,c

Once the time step, temperature and pressure have been evaluated, all other parameters can be updated. These parameters include such things as total pressure in each compartment, the clocks for propagation delay times, mass of ice in the ice condenser and wall internal temperatures.

V. ANALYTICAL DEVELOPMENT

This section develops the equations utilized in the CLASIX computer program. The development will generally follow the order in which the equations are used in the program as shown schematically in Figure 2.

A. Intercompartmental Flow Rates

The flow paths connecting the compartments in the analytical model are of two classes. The first class includes those for which the flow rate is calculated internally based on the differential pressure. This class of flow paths is further subdivided by those with doors and those without doors. Only flow paths 1, 2 and 3 have the capability of having doors. The second class includes flow paths for which the correspondence between differential pressure and flow rate is externally specified by tabular input. This class of flow paths may be restricted to operate only over a portion of the transient.

1. Door Analyses

There are three types of doors in the ice condenser containment. The lower inlet doors in flow path 1 of Figure 1 basically operate as check valves allowing flow in only one direction.The intermediate deck doors in flow path 2 open upward and once fully open may fail to shut. The top deck doors in flow path 3 are basically a flexible blankets that are assumed not to close once opened even part way.

[ ] a,c

[ ] a,c

(A-1)

(A-2)

For the lower inlet doors and the intermediate deck doors, an angle and an area may be specified such that once this angle is exceeded, the flow area of the door will never decrease below the area specified. This feature may be used to simulate failure of some of the intermediate deck doors to shut.

Because of the design of the top deck doors, additional features are required. One is a by-pass flow area to represent the curtained flow area associated with these doors. The second is that a minimum differential pressure is required to initiate opening because these doors are taped down. Finally, because of the construction of these doors, the flow area is assumed never to decrease regardless of the direction of flow and/or differential pressure.

[ ] a,c

[ ]a,c

[ ]a,c (A-3)

The minimum area, A', would be A_t for the top deck doors but may be zero or some other value for the other doors depending upon the history of the door and the conditions specified for non-closure discussed above.

2. Flow Equations

Each of the flow paths shown in Figure 1 is represented by an area and a flow loss coefficient. In the subsonic flow region, the flow relation is represented by

$$H = kV^2/2g \qquad (A-4)$$

where H = differential head
k = loss coefficient
V = velocity
g = gravitational constant

In terms of a differential pressure,

$$P = kV^2/2g\rho \qquad (A-5)$$

and $FR = VA$ (A-6)

where ρ = density

FR = volumetric flow rate

Combining these three equations and using an average density

$$FR_i = A_i \left\{ \frac{2g}{K_i} [2(P_j - P_k)/(\rho_j + \rho_k)] \right\}^{0.5} \quad \text{(A-7)}$$

where $(\,)_i$ = flow path i

$(\,)_j$ = source volume

$(\,)_k$ = sink volume

The transition to sonic flow is assumed to occur at a pressure ratio of 0.5 for all flow paths regardless of the relative concentrations of the constituent gases. In the sonic flow region, the flow is a function only of the upstream pressure so that to a first approximation

$$FR_i = k_{s_i} P_j \quad \text{(A-8)}$$

where k_{s_i} = sonic flow constant

Assuming that the flow is continuous at the point of transition

$$k_{s_i} P_j = A_i \left\{ \frac{2g}{K_i} [2(P_j - P_k)/(\rho_j + \rho_k)] \right\}^{0.5} \qquad @\ P_k = 0.5 P_j$$

or $$k_{s_i} = \frac{A_i}{P_j} \left\{ \frac{2g}{K_i} [2(P_j - P_k)/(\rho_j + \rho_k)] \right\}^{0.5} \quad \text{(A-9)}$$

Based on the volumetric flow rate and the assumption of perfect mixing in each compartment, the mass and energy flow rates can be determined. Thus

$$\dot{m}_{n_j} = -\dot{m}_{n_k} = -FR_i \left(m_{n_j} / \bar{V}_j\right) \qquad \text{(A-10)}$$

where $\dot{m}$ = mass flow rate

m = mass

$\bar{V}_j$ = volume of j^{th} compartment

$( )_{n_j}$ = n^{th} constituent in the j^{th} volume

$( )_{n_k}$ = n^{th} constituent in the k^{th} volume

The associated rate of energy transfer is

$$\dot{U}_j = -\dot{U}_k = -\sum_n \dot{m}_{n_j} h_{n_j} \qquad \text{(A-11)}$$

where $\dot{U}$ = energy transfer rate

h = enthalpy

As discussed above, flow path 8 in Figure 1 is unique. Although this flow path uses the same basic equations for gas flow developed above, some modifications are required. In this flow path, a rupture disc prevents flow until the differential pressure exceeds the rupture pressure. In addition, this flow path may have a slug of water in the pipe at the exit and discharge under water. [ ]a,c

[ ]a,c

[ ]a,c (A-12)

[ ]a,c (A-13)

(A-14)

(A-15)

Once the slug has been expelled, equations (A-7) to (A-11) inclusive become valid with the substitution

[ ]a,c (A-16)

This set of equations adequately describes the intercompartmental flow.

3. Fan Flow

The fan or pumped flow is based on tabular input of volumetric flow as a function of the differential pressure between the connected compartments. During the period of operation of the fan the volumetric flow is determined by linear interpolation of the tables. Using the fan flow rate, equations (A-10) and (A-11) can be used to determine the mass and energy rates.

B. Passive Heat Sink Heat Transfer Rates

Passive heat sinks are represented by a slab or one dimensional, rectilinear heat transfer. The heat sink may have multiple layers of different materials with resistances to heat transfer between layers in the form of film coefficients of heat transfer. The surface exposed to the compartment may have heat transfer by both convection and radiation. The opposite surface may be adiabatic or transfer heat by a film coefficient to a constant temperature heat sink.

1. Film Coefficient of Heat Transfer

The film coefficient of heat transfer between the compartment atmosphere and the exposed surface of the heat sink may be either externally specified or derived from one of the internally programed correlations. The externally specified film coefficient may be a function of either time or the differential temperature between the wall surface and the atmosphere. This table is linearly interpolated to find the film coefficient.

The primary correlation for the film coefficient is the widely used correlation of Tagami in Reference 1. The general form of this correlation is

$$H_T = \begin{cases} C_T \, (t/t_p)^{\frac{1}{2}} & 0 \leq t \leq t_p \\ H_S + (C_T - H_S)\, e^{-0.05(t-t_p)} & t > t_p \end{cases} \qquad \text{(B-1)}$$

where H_T = Tagami heat transfer coefficient

t = time in seconds

t_p = time of peak pressure from blowdown in seconds

C_T = material dependent coefficient having the dimensions Btu/hr-ft^2-F

H_S = stagnant film coefficient

[ ] a,c

[ ] a,c (B-2)

In these equations, all constants, and consequently the film coefficient, have the dimensions

Btu/hr-ft^2-F (B-3)

The material dependent coefficient is given by

[ ] a,c (B-4)

The material coefficients of interest are

[ ] a,c (B-5)

[ ] a,c

[ ] a,c (B-6)

(B-7)

2. Radiant heat Transfer

[ ] a,c

[ ] The emissivity of the water vapor is a function of its partial pressure, the effective beam length of the radiation and the ambient temperature. The water vapor emissivity correlations are derived from References 3, 4 and 5 and are linearly interpolated in the program. The emissivity of the wall surface must be specified as part of the input. The rate of radiant heat transfer is

[ ] (B-8)

[ ] a,c

3. Internal Heat Transfer

The analytical model of the passive heat sinks represents all heat sinks as one dimensional, rectilinear heat transfer in multiple layers. Between layers, a film coefficient may be specified to represent surface effects, paint and/or gaps between the surfaces. The surface opposite the surface exposed to the compartment ambient may be adiabatic or may have a constant temperature heat sink.

For conventional conductive heat transfer within a layer, there must be at least three temperature nodes in the layer. The distance between temperature nodes, assuming a node at each surface, is

$$\Delta x = TH/(NN-1) \qquad \text{(B-9)}$$

where

Δx = distance between temperature nodes
NN = number of temperature nodes in the layer
TH = thickness of the layer.

For an internal temperature node, the rate of heat transfer into the node is

$$Q_{in} = CO(TW_{J-1} - TW_J)/\Delta x \qquad \text{(B-10)}$$

where

Q_{in} = heat transfer rate per unit area
CO = conductivity of material
TW = wall node temperature
J = node of interest
J-1 = next nearest node toward the compartment

The heat transfer rate out of the node is

$$Q_{out} = CO(TW_J - TW_{J+1})/\Delta x \qquad \text{(B-11)}$$

where

J+1 = next nearest node away from the compartment
Q_{out} = heat transfer rate per unit area

The heat stored in the internal node is

$$Q_s = (\rho c)\Delta x(TW_J^N - TW_J)/Dt \qquad \text{(B-12)}$$

where

$( )^N$ = new temperature
Q_s = heat stored
ρc = heat capacity of material
Dt = differential time step

From conservation of energy

$$Q_{in} = Q_{out} + Q_s \qquad \text{(B-13)}$$

Combining equations (B-9) to (B-13) inclusive

$$TW_J^N = \frac{(CO)Dt}{(\rho c)} \left(\frac{NN-1}{TH}\right)^2 (TW_{J-1} + TW_{J+1} - 2TW_J) + TW_J \qquad \text{(B-14)}$$

This is the equation used by the program to evaluate internal temperatures once a stable time step has been determined. The surface node of this type of wall representation is associated with

only one half the thickness of an internal node. Thus, if Q_c is the convective heat transfer into a surface, and

$$Q_s = (\rho c)(\Delta x/2)(TW_J^N - TW_J)/Dt \qquad (B\text{-}15)$$

then using equation (B-13)

$$Q_c = (\rho c)(\Delta x/2)(TW_J^N - TW_J)/Dt + CO(TW_J - TW_{J+1})/\Delta x \qquad (B\text{-}16)$$

or

$$TW_J^N = [Q_c - CO(TW_J - TW_{J+1})(NN-1)/TH] \cdot \left(\frac{\rho c}{Dt}\frac{TH}{2(NN-1)}\right)^{-1} + TW_J \qquad (B\text{-}17)$$

Wall layers with less than three temperature nodes are special cases. [ ] a,c

[

] * (B-18) *a,c

[

] (B-19)

[ ] a,c

(B-20)

[ ] a,c

[ ] a,c

(B-21)

(B-22)

(B-23)

[ ] a,c

C. Heat Transfer to the Ice

The rate of heat transfer to the ice in the ice condenser is based on the film coefficient of heat transfer correlation developed from the ice condenser tests at the Waltz Mill test facility (Reference 6). These correlations include the effects of the relative concentrations of air and steam. [ ] a,c

[

]a,c

[

]a,c
(C-1)

(C-2)

(C-3)

(C-4)

(C-5)

(C-6)

(C-7)

[

]a,c

[ ] a,c

[ ] a,c

(C-8)

[ ] a,c

[ ] a,c

(C-9)

(C-10)

(C-11)

(C-12)

[ ] a,c (C-13)

(C-14)

(C-15)

(C-16)

(C-17)

(C-18)

[ ] a,c

[ ] a,c

[ ] * (C-19) *a,c

(C-20)

[ ] a,c

[ ] a,c
(C-21)

[ ] a,c

[ ] a,c

(C-22)

(C-23)

[ ]a,c

[ ]* (C-24) *a,c

[ ]a,c

[ ]a,c (C-25)

[ ]a,c

[ ]* (C-26) *a,c

[ ]a,c

[ ]a,c (C-27)

[ ]a,c

(C-28)

[ ]a,c

[ ]a,c
(C-29)

[ ]a,c

[ ]a,c
(C-30)

[ ]a,c

D. Hydrogen Ignition and Combustion

Hydrogen entering the containment from an input table may be introduced as a non-condensible added to the ambient atmosphere or it may be burned as it is introduced. The latter is a special case that has two assumptions that must be carefully considered in utilizing this option. The first assumption is that there is always adequate oxygen for complete combustion of the hydrogen. The second is that there is no hydrogen initially present or flowing in from another compartment. Attempting to use this option when these assumptions are not valid will provide invalid results.

If the option to add the hydrogen to the compartment atmosphere is selected, the criteria for ignition in each compartment are examined at each time step of the finite integration. For ignition to occur, both the required volume fraction of hydrogen and the required volume fraction of oxygen must be satisfied. Based on the perfect gas law, the ratio of the partial pressure to the total pressure is the same as the volume fraction. The partial pressure fraction is used in the program.

As discussed previously, at the time of ignition in a compartment, internal timers are started for each connected and active flow path shown in Figure 1. It is assumed that propagation will proceed whether doors are present or not. No propagation is permitted through fan flow paths. If the propagation delay time has expired in a flow path, the conditions in the connected compartment are examined to determine if ignition occurs. Both the volume fraction of oxygen for ignition and the volume fraction of hydrogen for propagation must be satisfied.

In each compartment where ignition occurs, the pounds of hydrogen to be burned is determined [ ]^{a,c}

[ ]^{a,c} (D-1)

[ ]a,c

[ ]* (D-2) *a,c

[ ]a,c

[ ]a,c (D-3)

[ ]a,c

[ ]

[ ]

[ ]

[ ] a,c (D-4)

E. Containment Spray

It is assumed that the spray flow enters the compartment with a uniform drop diameter and that the individual drops fall at a constant uniform velocity over the specified fall time. The spray flow rate, temperature and film coefficient of heat transfer are linearly interpolated from input tables which are a function of time.

In a conventional finite difference integration treatment of the spray, the mass of spray entering the compartment during a given time step must be tracked throughout its fall time. For each increment of spray flow, its mass, temperature and, because of a variable time step, the length of time since generation must be maintained. The order of magnitude of the number of time steps to complete the fall is 10^3. Thus, for each spray, several thousand memory locations and many calculations would be required. To simplify the treatment of the spray,

[ ] a,c

[ ] a,c (E-1)

[ ] a,c

[ ] a,c (E-2)

[ ] a,c

(E-3)

(E-4)

[ ] a,c

[ ] a,c

(E-5)

[ ] a,c

[ ] a,c

(E-6)

(E-7)

(E-8)

[ ] a,c (E-9) (E-10) (E-11)

[ ] a,c

[ ] a,c (E-12) (E-13) (E-14) (E-15)

[ ] a,c

(E-16)

This equation is valid for heat transfer in either direction provided that there is no vaporization during its period of application.

If vaporization is occurring, [ ] a,c

[ ] a,c

(E-17)

[ ] a,c

[ ] a,c

(E-18)

(E-19)

(E-20)

[ ] a,c

[ ] a,c

(E-21)

In the spray analysis any increase in drop diameter due to condensation is not considered. This would require prior knowledge of what the effects of heat removal from the atmosphere would have. If the

conditions in the atmosphere were near or at saturated conditions, probably most, but not necessarily all, of the heat removal would result in condensation. At high superheat conditions, probably only a small fraction, if any, would result in condensation. In the region of interest in the program, sprays may be heated from 80F to saturation at 50 psia or 280F for a change of 200F. If all of this heat were used to condense steam, the diameter of the drop would increase about 6 percent and the area about 16 percent. Even these limiting conditions of change would not have a significant effect on the analytical results.

Denoting the conditions of the spray entering the compartment with the subscript zero, the net spray flow completing the fall to the floor of the compartment is

[ ] a,c (E-22)

The net energy removed from the compartment atmosphere by the spray is

[ ] a,c (E-23)

and the mass rate of addition to the atmosphere is

[ ] a,c (E-24)

These equations in various combinations completely describe the spray/atmosphere interaction.

The implications of the assumption that the spray heat transfer occurs in a different time domain than the other equations is discussed in Section VIII and Appendix D. The assumption is shown to provide conservatively high temperatures and pressures in the containment.

F. Addition Tables

Heat, hydrogen, nitrogen and water may be added to the compartment atmosphere. All tables are entered as functions of time and are

linearly interpolated. Only the heat addition may have negative values to simulate heat removal.

The hydrogen and nitrogen tables must include temperature so that the associated enthalpy may be calculated and added to the compartment energy inventory.

Rather than temperature, the water addition tables must include the energy addition rate corresponding to the enthalpy of the water. The specific enthalpy of the water is compared to the saturation enthalpies corresponding to the total pressure in the compartment. If the specific enthalpy of the flow is greater than the saturated vapor enthalpy, the entire mass and energy are added to the atmosphere inventories. If the specific enthalpy is less than the saturated liquid enthalpy, the entire mass and energy are relegated to the sumps and drains with no effect on the atmosphere. If the specific enthalpy is between the saturation enthalpies, the flow is treated the same as the spray but with a zero fall time.

G. Energy Balance

Based on the preceding discussion, the rates of change of masses and energy in each compartment can be determined. Concurrent with these calculations, the amount of change in temperature or pressure which would reverse the process can also be calculated. For example, in calculating the flow between two compartments, a differential pressure is determined. If the upstream pressure were to decrease by more than this differential, the direction of flow would reverse. Similarly, an increase in the downstream pressure by more than the differential would also cause flow reversal. The minimum magnitudes for both increases and decreases in pressure which would cause flow reversal for each compartment are retained in memory and used in evaluating a stable time step.

The maximum time step is specified as input. The initial value for the time step to be used in the calculation is determined from

[ ] a,c (G-1)

Using this initial value of the time step and the rates of change previously calculated, the total masses of each constituent and the total internal energy in each compartment can be evaluated. Based on these totals a unique pressure and temperature can be determined. There are basically three regions of interest. Saturated, superheated or above the steam tables. The conditions of pressure and temperature at the beginning of the time step are used as the first guess of the conditions at the end of the time step.

[ ] a,c (G-2) (G-3) (G-4)

[ ]a,c

[ ]a,c
(G-5)
(G-6)
(G-7)

[ ] a,c
[ ]a,c
(G-8)
(G-9)

[ ] a,c
[ ]a,c
(G-10)

[ ]a,c

[ ]a,c
(G-11)

[ ]a,c

[ ]a,c
(G-12)

[ ]a,c

[ ] a,c

[ ] a,c

[ ] a,c

[ ] a,c

(G-13)

[ ] a,c

[a,c (G-14)

(G-15)

(G-16)

(G-17)]

[ ] a,c

[ ] *(G-18) * a,c

[ ] a,c

[ ] * (G-19) * a,c

In well behaved transients the reduction in time step will not be activated for monotonically increasing or decreasing portions of the transient. At a change in sign in the first derivative of pressure with respect to time, there could be a brief reduction in the time step. In regions of instability where a steady state or diverging oscillation would occur, the minimum time step is used continuously. In the regions of interest where instabilities occured, the maximum pressure oscillation experienced was to the order of [ ]* psi peak to peak and * a,c
the corresponding temperature oscillation was [ ]* F using the minimum * a,c

time step given by equation (G-19). Note that the externally specified time step may be less than the minimum value given by equation (G-19). In this event, the externally specified time step will always be used.

After the pressure and temperature evaluations have been completed, a number of parameters must be updated. Among these is the mass of hydrogen yet to be burned in a compartment where deflagration is taking place. [ ]a,c

[ ]a,c (G-20)

However, if the volume fraction of oxygen drops below the volume fraction of oxygen required to support combustion, the burn rate and mass of hydrogen to be burned are set to zero to simulate extinguishing the burn.

Since the time step is known, the clocks measuring the propagation delay time can be updated. Also, the rate of heat transfer in the ice condenser can be converted to a mass of ice melted and a change in heat transfer area. Finally, the internal heat transfer equations in the passive heat sinks are used to update the nodal temperatures.

With the updated values, the calculations can proceed to the next time step and iterate to the completion of the transient.

VI. INPUT DESCRIPTION

Contrary to general usage, this section is not intended to be an input manual but, as the title indicates, a description of the necessary input. The primary purposes of this discussion are to indicate the level of detail of the input and the degree of flexibility of the program, and to emphasize some of the assumptions inherent in the development of the program.

The program has the capability of continuing a transient from an intermediate time in the transient, provided the restart file has been written and saved from a previous execution of the program. If the present execution is a restart, any input parameter can be changed that is not a function of the history of the preceding calculations. For example, the area of a flow path is affected by the door position and cannot be changed but the flow loss coefficient can be altered. Changing initial conditions or tabular input for times preceding the restart time will have no effect. However, changing values in the table at subsequent times will have an effect.

Whether or not the present execution is a restart, restart files may be written at future specified times and just prior to a given computer execution elapsed time.

The heat of combustion and the perfect gas constants are provided with default values which may be overwritten by input. The perfect gas constants include the specific heats at constant volume and constant pressure, and the gas constant for the perfect gas law.

The maximum time step may be specified as a function of the transient time. The rate at which output is generated may also be controlled as a function of the transient time. The output is discussed later.

For each active compartment, the initial conditions must be specified and are not necessarily steady state conditions. The net free volume, temperature, the contents by constituent and burn control parameters for each compartment must be specified. The burn control parameters include volume fraction of hydrogen and volume fraction of oxygen for ignition, the volume fraction of hydrogen for propagation, the volume fraction of oxygen below which the flame is extinguished and the fraction of the hydrogen to be burned.

For each of the flow paths numbered 1 to 10 inclusive in Figure 1, the flow area, flow loss coefficient and the propagation delay time are required. Areas must be zero for flow paths connecting two inactive compartments or an active compartment to an inactive one. A door may be represented in any or all flow paths designated 1, 2 and 3 in Figure 1. For each door, the maximum angle of opening, the differential pressure required to achieve this opening and the corresponding flow area are required. For flow paths 1 and 2, a special angle and opening may be specified so that if this angle is once achieved, the flow area will never be less than the area specified regardless of flow conditions. In flow path 3, a bypass flow area and a minimum differential pressure to initiate opening may be specified. In flow path number 8, an initial length of a slug of water, depth of submergence, exit loss coefficient, disc rupture pressure and the density of the water may be specified.

The ice condenser is fully represented by specifying a mass of ice with its corresponding area of heat transfer, density, heat of fusion, flow loss coefficient and net free volume.

Fans are represented by designating a suction node and a discharge node, time of activation, time of deactivation, a fan flow multiplier and a fan head/flow table number. The fan head/flow table is simply a list of differential heads with corresponding volumetric flow rates to represent the head/flow curve. The fan flow multiplier is simply a multiplication factor on the flow derived from the table and can be used to represent multiple parallel fans or a flow split between compartments.

Based on assumptions in the development, a single fall time and a single drop size are used for each spray. The input tables of flow rate, temperature and film coefficient as functions of time, supply all the remaining necessary information for the spray.

Heat, nitrogen, hydrogen and water addition tables are discussed in the development of analytical equations. Each addition table is a function of time with temperature also supplied for the nitrogen and hydrogen tables and enthalpy supplied with the water tables.

Each wall or passive heat sink is specified by a compartment number, surface area, initial uniform temperature, exterior heat sink temperature and the heat transfer correlation to be used. If the Tagami correlation is selected, the time of peak pressure and total energy as well as a multiplying coefficient must be specified. If radiant heat transfer is desired, a surface emissivity and effective beam length are required. If an externally specified film coefficient is to be used, the film coefficient as a function of time or differential temperature must also be specified. Each passive heat sink may have up to 7 layers of material. For each layer, the number of temperature nodes, thickness, conductivity, heat capacity and exit film coefficient of heat transfer must be specified.

Regardless of whether the transient is newly started or started from a restart, a complete input edit of all input parameters is written to the output.

VII. OUTPUT

In addition to the input edit discussed above, the program generates output at frequencies controlled by the input. The short-form output is a single line of output listing the temperature and pressure in each compartment. At the same time as the short-form is written, the time and all conditions of temperature, partial pressures and constituent masses in each compartment are written to a tape which can be saved and used to generate plots of the transient. Because of the sharp peaks in pressure experienced during a burn, the pressure is scanned during each burn and the maximum pressure in the burn compartment and the time it occured are retained in memory. This information is written to a separate tape every time plot information is written.

At the specified interval for long form output, two separate tapes are written. On one tape the detailed conditions in each volume and flow path are written. Also included is information about doors, flow paths, the ice condenser and the surface temperature and heat rate to each wall. Each long form output to this tape consists of a single page. To the second tape are written all of the details of the passive heat sinks, including the temperature at every node in every wall. This output may consist of numerous pages each time it is written and depends on the number of passive heat sinks and the number of nodes in each heat sink.

The final form of output is the restart file which is also controlled by the input.

VIII. VERIFICATION

Verification of a computer program can be performed in a number of ways. The four methods of verification most frequently used are 1) comparison of calculated results with the calculated results of other accepted computer programs, 2) comparison of calculated results with test measured results, 3) comparison of calculated results with the results of external calculations performed using the given program methodology, and 4) sensitivity studies involving various parameters used in the program. Each of these methods has been employed in the verification of the CLASIX computer program.

For the first part of the verification analyses, CLASIX calculated results have been compared with the calculated results of the Transient Mass Distribution (TMD), Reference 6, and COCOCLASS9, Reference 7, computer programs. Both of these programs are design programs developed by Westinghouse Electric Corporation. TMD has been accepted by the Nuclear Regulatory Commission (NRC). Results of COCOCLASS9 analyses have been presented to the NRC Staff in support of dry containment plant licensing and COCO, Reference 8, the base program from which COCOCLASS9 was developed, has been accepted by the NRC.

The TMD program was developed for analyses of ice condenser containment response during the initial few seconds following a design basis loss of coolant accident (LOCA). Because this period is characterized by rapid pressure transients, a detailed spatial analysis is necessary and TMD contains a multi-compartment analytical model. Furthermore, since containment safeguards do not function during this period, neither the containment sprays nor the air return fans are included in the TMD analytical model. For similar reasons neither nitrogen, hydrogen, nor fission product energy addition is included in the model. Finally, since no significant heat transfer to the containment walls is expected to occur during this brief period, passive heat sinks are not included in the TMD analytical model. Therefore comparison of CLASIX calculated results to TMD calculated results is limited to multi-compartment pressure and temperature responses to high

enthalpy water mass and energy addition. This comparison provides verification of CLASIX pressure and temperature response calculations, flow path calculations, and aspects of the CLASIX ice condenser model.

Calculated results from the CLASIX program were compared to TMD calculated results for a series of cases as described in Appendix A. These comparisons show very good agreement between CLASIX and TMD calculations with CLASIX calculated values being generally conservative relative to TMD calculated values.

The COCO program was developed for analyses of dry containment response to a design basis LOCA. Since the program was developed to analyze the entire design basis post LOCA transient, the COCO analytical model has the capability to simulate containment safeguards operation and heat transfer to passive heat sinks as well as high enthalpy water mass and energy addition. Because a dry containment consists primarily of a large open region surrounding the reactor coolant system, the COCO analytical model provides only a single volume representation of the containment.

The COCOCLASS9 program is an extension of the COCO program. COCOCLASS9 has all the features of COCO and also has the capability to simulate events related to degraded core accidents such as hydrogen burn phenomena. Although comparisons of CLASIX calculated results to COCOCLASS9 calculated results are limited to single compartment pressure and temperature response to high enthalpy water and/or hydrogen mass and energy additions, they can include simulation of hydrogen burns, heat transfer to containment sprays and/or heat transfer to passive heat sinks. However, since the COCOCLASS9 spray model does not allow evaporation and the CLASIX spray model does, the two spray models cannot be compared effectively. The comparisons of CLASIX calculated results to COCOCLASS9 calculated results provide verification of the CLASIX pressure and temperature response to mass and energy additions, burn model and model for heat transfer to passive heat sinks.

Calculated results from the CLASIX program were compared to COCOCLASS9 results for a series cases as described in Appendix B. These cases provided comparisons of single compartment pressure and temperature response to high

enthalpy water and hydrogen mass and energy additions and included hydrogen burn simulation. These comparisons show excellent agreement between CLASIX and COCOCLASS9 calculated results.

For the second part of the verification analyses, CLASIX calculated results have been compared with test measured results from recent hydrogen burn tests performed at both the Fenwal test facility, References 9 and 10, and at the Lawrence Livermore National Laboratory, Reference 11. The tests, designed to study the capabilities of diesel glow plug ignitors, provide data for verification of the CLASIX burn model, the CLASIX models for hydrogen and high enthalpy water mass and energy addition to the containment, and some aspects of the CLASIX models for heat transfer to passive heat sinks and sprays. Details of the comparisons of CLASIX calculated results with test measured results are given in Appendix C. The results of these comparisons indicate CLASIX conservatively overpredicts the pressure and temperature response to a burn over a wide range of conditions. A large portion of the conservatism has been shown to be the result of using constant values for constituent gas specific heats in the CLASIX analytical model.

In addition to the comparisons with other programs and with test measurements, CLASIX calculated results have been compared with the results of external calculations using the CLASIX methodology. These comparisons, performed throughout the development of the program, test various aspects of the CLASIX computations including conservation of mass and energy, heat removal by sprays, operation of fans, heat transfer to passive heat sinks, and interpolation and integration of tabular input data. All externally calculated results agreed with CLASIX printed output within calculated roundoff error. Samples of these comparison results are given in Table 2.

Finally, numerous sensitivity studies were performed during the CLASIX development. Early CLASIX analyses for ice condenser containments, Reference 12, included sensitivity studies for all spray parameters, for the air return fan flow rate, for the ice condenser initial ice mass and drain temperature, and for hydrogen burn parameters. Recently a number of sensitivity studies were performed as part of the comparison to test

measured results given in Appendix C. These studies include evaluation of the sensitivity of calculated results to various parameters associated with the passive heat sinks, to the containment atmosphere constituent gas specific heats, and to the calculational time step. The results of all sensitivity studies demonstrate that there is no unusual dependence on any tested parameter.

In summary, four methods were used in the verification of the CLASIX computer program. Each method provides a level of confidence in one or more aspects of the CLASIX calculations. Comparisons of CLASIX calculated results with TMD calculated results provide confidence in the CLASIX calculation of multi-compartment pressure and temperature response to mass and energy addition, flow path calculations and ice condenser model. Comparisons of CLASIX calculated results with COCOCLASS9 calculated results provide additional confidence in the CLASIX calculation of pressure and temperature response to mass and energy addition. These comparisons also provide confidence in the CLASIX models for hydrogen burn calculations and heat transfer to passive heat sinks. Comparisons of CLASIX calculated results to test measured results demonstrate conservatism in the CLASIX burn model and provide confidence in the CLASIX models for heat transfer to passive heat sinks and containment sprays. Sensitivity studies and comparisons of CLASIX calculated results with the results of external calculations using the CLASIX methodology provide added confidence in all aspects of the CLASIX calculational model.

The only significant aspect of the program which has not been examined in detail is the analytical model of flow path 8. However, this flow path is not germain to the design analysis of the hydrogen mitigation systems for ice condenser plants.

In addition to the verification of analytical techniques, two assumptions were also intensively investigated. The first of these assumptions was that the heat transfer coefficient correlation[ ]* was applicable to the high temperature gases generated by a burn in the lower compartment. As discussed in the Analytical Development section of this report, the

*a,c

correlations provide film coefficient values [ ]* depending on specific conditions. To evaluate the impact of the correlation on the analytical results, a typical transient for the Sequoyah plant was selected. In the region investigated, burns occurred in both the lower compartment and the ice condenser outlet plenum. [ ]a,c *a,c

[ ]a,c These results indicate that there is no major effect on the analytical results or conclusions from using the ice condenser heat transfer correlations from the Waltz Mills tests.

The second assumption that was investigated was the assumption that the spray heat transfer could operate in a separate time domain. A comparison of the CLASIX representation with a conventional finite difference approach is presented in Appendix D. The assumption of a separate time domain for the spray is shown to be conservative by predicting slightly higher temperatures and pressures in the containment.

Based on the preceding discussion, it is concluded that the CLASIX program, exclusive of the model of flow path 8, is adequately verified and qualified for the type of design analysis for which it is intended and, particularly, within the range of validity of the assumptions utilized in its development. For these analyses, CLASIX produces conservatively high predictions of temperatures and pressures within the containment. Containments designed to withstand the pressures and temperatures predicted by CLASIX will be adequate to withstand the pressures and temperatures produced by actual transients.

IX. CONCLUSION

Based on the above, CLASIX is shown to be a viable tool for the evaluation of the pressure and temperature response of an ice condenser containment to a hydrogen deflagration. Extensive use of the program for a number of plants and extensive sensitivity studies have shown no anomalies in the results. Comparisons with test data and other methods of analysis provide ample assurance that the temperatures and pressures predicted by CLASIX are conservatively high and that a containment designed to withstand the conditions predicted by CLASIX will have a significant margin of safety.

X. REFERENCES

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6. "Ice Condenser Containment Pressure Transient Analysis Methods", WCAP-8077 (Proprietary Class 2), March 1973, WCAP-8078 (Proprietary Class 3), March 1973.

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9. Appendix V of the Tennessee Valley Authority Sequoyah Nuclear Plant Core Degradation Program, Volume 2, "Report on the Safety Evaluation of the Interim Distributed Ignition System", December 15, 1980 (NRC Docket No. 50-327).

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12. Appendix U of the Tennessee Valley Authority Sequoyah Nuclear Plant Core Degradation Program, Volume 2, "Report on the Safety Evaluation of the Interim Distributed Ignition System", December 15, 1980 (NRC Docket No. 50-327).

TABLE 1

BURN CONTROL PARAMETERS

1. $^{V}/_{O}$ H_2 IGNITION
2. % H_2 CONSUMED
3. $^{V}/_{O}$ O_2 IGNITION
4. $^{V}/_{O}$ O_2 SUPPORT COMBUSTION
5. BURN TIME
6. $^{V}/_{O}$ H_2 PROPAGATION
7. PROPAGATION DELAY TIME

TABLE 2

CLASIX vs External Calculations

Typical Comparisons

Parameter	Externally Calculated Value	CLASIX Calculated Value	
Hydrogen Addition Rate (lbm/sec) interpolated from input table values	[		a,c
Temperature of Hydrogen Gas (F) added interpolated from input table values			
Total Hydrogen added (lbm)			
Fan flow rate (cfs)			
Spray heat removal rate no evaporation (Btu/sec)			
Spray heat removal rate with evaporation (Btu/sec)			
Ice Condenser Lower Plenum Volume (ft^3)			
Ice Melt (lbm)		]	

All differences in results are within roundoff error.

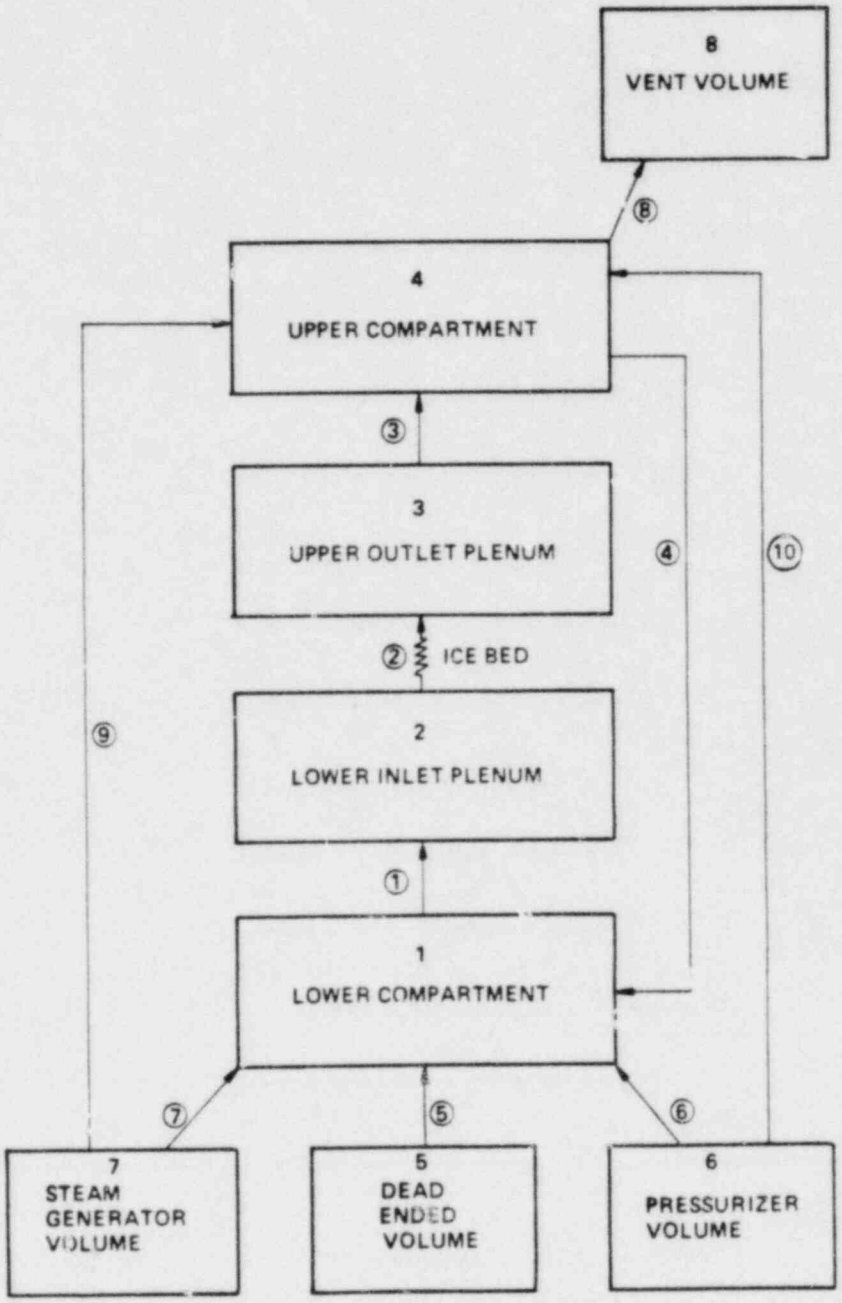


Figure 1

CLASIX MODEL OF THE ICE CONDENSER CONTAINMENT

[

a,c]

Figure 2

FLOW DIAGRAM

[ ]a,c

Figure 2

(CONTINUED)

APPENDIX A

Comparison of CLASIX Results with TMD Results

INTRODUCTION

The Transient Mass Distribution (TMD) program, Reference A-1, was developed to analyze the short term phase of the transient from a loss of coolant accident (LOCA) in an ice condenser containment and has been accepted by the NRC as a design tool, Reference A-2. A comparison of CLASIX calculated results to TMD calculated results is presented in this Appendix.

MODELING

The TMD program was developed for analyses of ice condenser containment response during the initial few seconds following a design basis LOCA. Because this period is characterized by rapid pressure transients, a detailed spatial analysis is necessary and TMD contains a multicompartment analytical model. Furthermore, since containment safeguards do not function during this period, neither the containment sprays nor the air return fans are included in the TMD analytical model. For similar reasons neither nitrogen, hydrogen, nor fission product energy addition is included in the model. Finally, since no significant heat transfer to the containment walls is expected to occur during this brief period, passive heat sinks are not included in the TMD analytical model. Therefore comparison of CLASIX calculated results to TMD calculated results is limited to multi-compartment pressure and temperature responses to high enthalpy water mass and energy addition. This comparison provides verification of CLASIX pressure and temperature response calculations, flow path calculations, and aspects of the CLASIX ice condenser model.

The TMD and CLASIX analytical models were selected to be as similar as possible. Both containment models include a lower compartment, ice condenser upper compartment and dead ended volume. Schematic diagrams of these models are given in Figures A-1 and A-2.

The CLASIX ice condenser is divided into two parts, the lower and upper plenums. The ice condenser model in TMD is divided into five sections except in the case with a saturated blowdown and ice present in the ice condenser. For this transient a three compartment ice condenser model with ice present in only one compartment was utilized. Although the ice condenser was modeled for all cases, some comparisons were performed by not including ice in the ice condenser.

Three sets of doors are modeled. These are the lower inlet doors which are located between the lower compartment and the inlet plenum, the intermediate deck doors which are located between the ice baskets and the upper plenum, and the top deck doors (blankets) which are located between the upper plenum and upper compartment.

The physical parameters used in this verification analysis are typical of an ice condenser containment. Tables A-1 and A-2 contain the TMD input and flow path parameters. A summary of the CLASIX input is given in Tables A-3 and A-4.

RESULTS

Four comparison runs were made covering the anticipated range of the blowdown energy from saturation to superheat conditions. Direct comparisons were made between the temperatures and pressures resulting from the TMD and CLASIX calculations. Indirectly, these comparisons provide verification of CLASIX flow path calculations.

The first case investigated had a saturated blowdown in a containment without ice in the ice condenser. The lower compartment and upper compartment pressures are shown in Figures A-3 and A-4. The corresponding temperatures are given in Figure A-5. As shown in these plots, the CLASIX calculated values for both temperature and pressure are generally conservative by being higher relative to the TMD calculated values over most of the transient. CLASIX is expected to be conservative relative to TMD

because of the difference in the treatment of the flashing of the breakflow as it enters the containment. [ ] a,c

[ ]

The second case is very similar to the first case but has a superheated blowdown. Figure A-6 shows the TMD and CLASIX calculated pressures in the upper compartment. In this case, lower compartment pressures are nearly identical to the upper compartment pressures and therefore are not included. The temperature plots for this case are given in Figure A-7. Close agreement exists between TMD and CLASIX calculated results.

The next phase of the verification duplicates the first two cases and includes ice in the ice condenser section. Figures A-8, and A-9 are the plots for the saturated blowdown case. The plots for the superheated blowdown case are given in Figures A-10, and A-11. For both cases CLASIX and TMD calculated pressures agree within [ ]* psi. In addition, the calculated temperatures agree closely with CLASIX values being slightly more conservative in the lower compartment but slightly non-conservative in the upper compartment. *a,c

An oscillation can be observed in the CLASIX temperature plot for the lower compartment in the saturated blowdown case with ice present (Figure A-9). Similar results were seen in an earlier comparison analysis in Reference A-3, and are known to be caused by convergence criteria and at the interface between saturated and superheated conditions. The current

version of CLASIX has a tighter convergence than the previous version so that most of the current plots are smoother than those found in Reference A-3. However, as can be observed from these results, there is no cumulative error leading to divergence of results. Other studies with tighter convergence criteria reduced the magnitude of the oscillation but had no effect on the general results and conclusions. For reasonable computer time, however, the convergence criteria in CLASIX were not modified.

CONCLUSION

The comparison of CLASIX calculated results to TMD calculated results has shown that the two programs are in excellent agreement with CLASIX being generally conservative over a range of conditions. The few differences that occur are explained by the differences in the analytical assumptions associated with the two programs. Therefore, a high level of confidence can be placed on the CLASIX analytical predictions for multi-compartment pressure and temperature response calculations, flow path calculations and ice condenser calculations.

REFERENCES

A-1 "Ice Condenser Containment Pressure Transient Analysis Methods", WCAP-8077 (Proprietary Class 2), March 1973, WCAP-8078 (Proprietary Class 3), March 1973.

A-2 NRC letter from D.B. Vassalo, NRC Chief Engineer, Light Water Reactor Project Branch to Westinghouse Nuclear Safety Manager, Ramano Salvatori, December 18, 1973.

A-3 Appendix V of the Tennessee Valley Authority Sequoyah Nuclear Plant Core Degradation Program, Volume 2, "Report on the Safety Evaluation of the Interim Distributed Ignition System", December 15, 1980 (NRC Docket No. 50-327).

TABLE A-1

TMD INPUT PARAMETERS

ELEMENT NUMBER	DESCRIPTIVE LOCATION	VOLUME (FT3)	CONDENSATE FILM LENGTH (FT)	ICE MASS (LB)	ICE HEAT TRANSFER AREA (FT2)	INITIAL STEAM PRESSURE (PSIA)	INITIAL AIR PRESSURE (PSIA)	INITIAL TEMPERATURE (F)
[								]a,c

TABLE A-2

TMD FLOW PATH PARAMETERS

ELEMENT	FLOW TO ELEMENT	FLOW PATH LENGTH (FT)	FLOW AREA (FT2)	LOSS COEFFICIENT (K)
[				a,c]

TABLE A-3

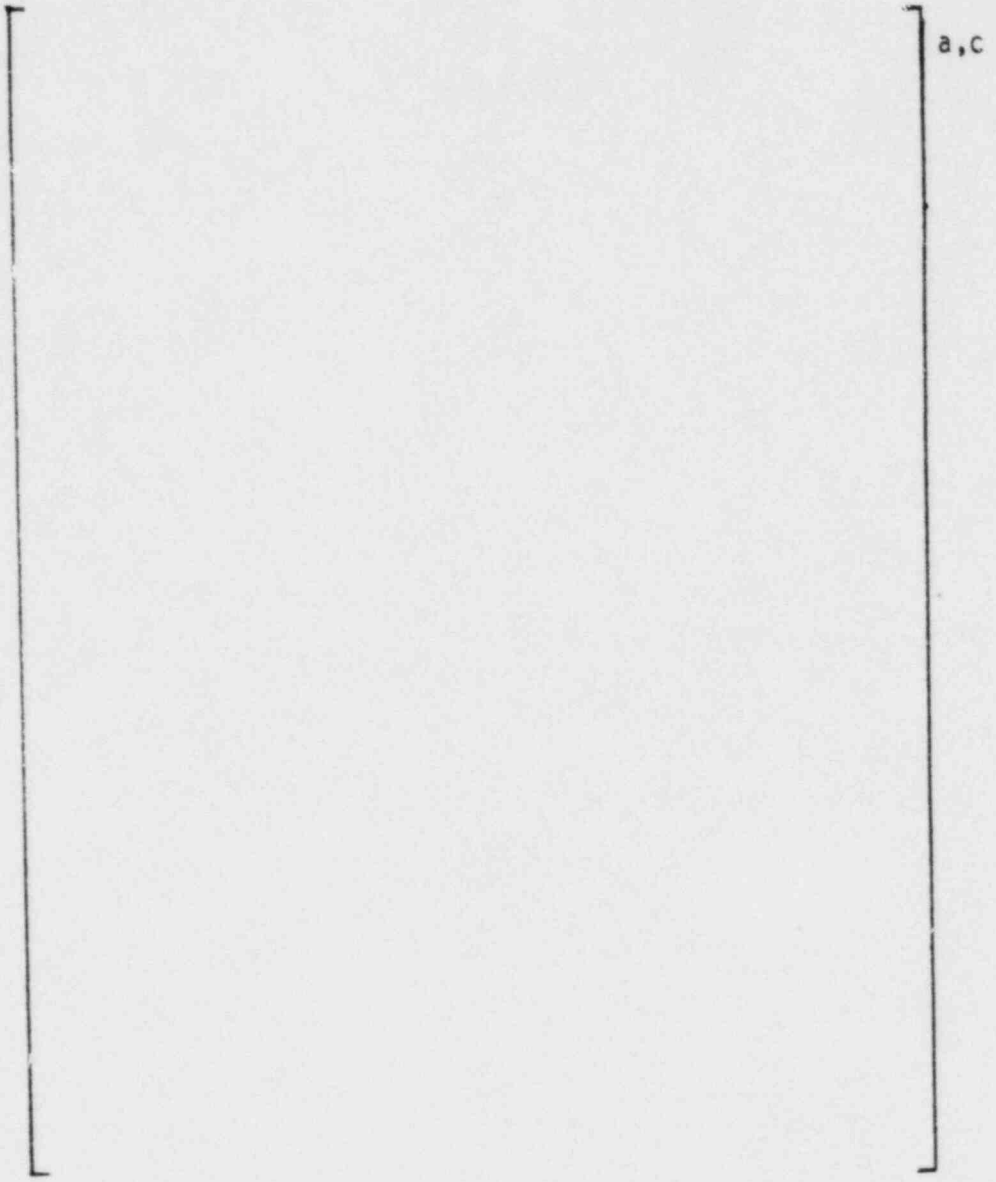
CLASIX INPUT PARAMETERS

ELEMENT NUMBER	DESCRIPTIVE LOCATION	VOLUME (FT3)	ICE MASS (LB)	ICE HEAT TRANSFER AREA (FT2)	INITIAL STEAM PRESSURE (PSIA)	INITIAL AIR PRESSURE (PSIA)	INITIAL TEMPERATURE (F)
[							] a,c

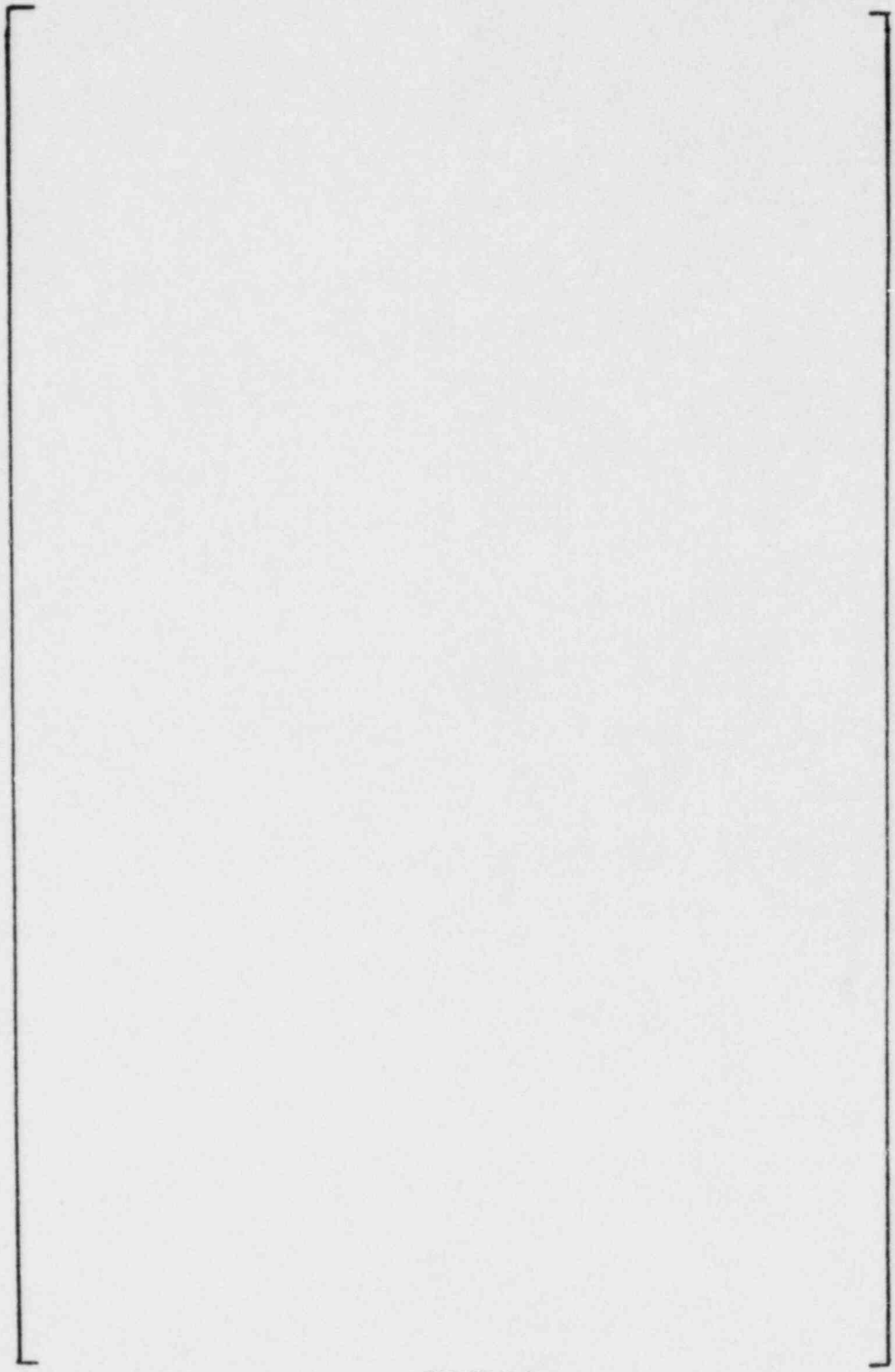
TABLE A-4

CLASIX FLOW PATH PARAMETERS

ELEMENT	FLOW TO ELEMENT	FLOW AREA (FT2)	LOSS COEFFICIENT (K)
[			a,c]



CLASIX MODEL OF THE ICE CONDENSER CONTAINMENT



a,c

FIGURE A-2
TMD MODEL OF THE ICE CONDENSER CONTAINMENT

[a,c

[ ]

CLASIX TMD COMPARISON
10,000 LBM/SEC BLOWDOWN
500 BTU/LBM
NO ICE

FIGURE A-3

[ ]a,c

CLASIX TMD COMPARISON
10,000 LBM/SEC BLOWDOWN
500 BTU/LBM
NO ICE

FIGURE A-4

[

a,c]

CLAS X TMD COMPARISON
10,000 LBM/SEC BLOWDOWN
500 BTU/LBM
NO ICE

FIGURE A-5

[ ]a,c

CLASIX TMD COMPARISON
10,000 LBM/SEC BLOWDOWN
1205 BTU/LBM
NO ICE

FIGURE A-6

[ ] a,c

CLASIX TMD COMPARISON
10,000 LBM/SEC BLOWDOWN
1205 BTU/LBM
NO ICE

FIGURE A-7

CLASIX TMD COMPARISON
10,000 LBM/SEC BLOWDOWN
500 BTU/LBM
WITH ICE

FIGURE A-8

[ ]a,c

CLASIX TMD COMPARISON
10,000 LBM/SEC BLOWDOWN
500 BTU/LBM
WITH ICE

FIGURE A-9

[ ] a,c

CLASIX TMD COMPARISON
10,000 LBM/SEC BLOWDOWN
1205 BTU/LBM
WITH ICE

FIGURE A-10

[ ]a,c

CLASIX TMD COMPARISON
10,000 LBM/SEC BLOWDOWN
1205 BTU/LBM
WITH ICE

FIGURE A-11

APPENDIX B

Comparison of CLASIX Results with COCOCLASS9 Results

COCO (Reference B-1), the base program for COCOCLASS9 (Reference B-2), was developed by Westinghouse Electric Corporation for the analyses of entire design basis post loss of coolant accident (LOCA) transients in dry containments. COCO has been accepted by the Nuclear Regulatory Commission (NRC) as a design program for this purpose. The COCOCLASS9 Program is an extension of the COCO program. COCOCLASS9 has all the features of COCO and also has the capability to simulate events related to degraded core accidents. Results from COCOCLASS9 have been presented to the NRC in support of dry containment plant licensing.

The CLASIX and COCOCLASS9 analytical models have the capability to simulate high enthalpy water addition, hydrogen mass and energy additions, hydrogen burning and heat transfer to passive heat sinks and containment sprays. However, the two spray models cannot be compared effectively because the COCOCLASS9 spray model does not allow evaporation and the CLASIX spray model does. In addition, since COCO was developed for analyses of dry containments, its analytical model provides only a single volume representation of the containment. Therefore, comparisons of CLASIX calculated results to COCOCLASS9 calculated results are limited to single compartment pressure and temperature responses.

Six comparison cases were run using the same basic transient. Hydrogen was added at a constant rate over a limited portion of the transient. After the hydrogen addition had stopped, a burn was initiated at a specified time and with a specified burn rate. Three cases were run with a saturated blowdown during the entire transient and then all three were repeated with a superheated blowdown.

Case 1 is the basic transient with a saturated blowdown. This case does not include heat transfer to passive heat sinks. Case 2 and Case 3 are the basic transient with a saturated blowdown and include heat transfer to passive heat sinks. In Case 2 there is convective heat transfer with a constant wall surface film coefficient and no radiant heat transfer. In

Case 3 the Tagami heat transfer correlation is used and radiant heat transfer is included. Cases 4, 5 and 6 are respectively identical to Cases 1, 2 and 3 except they have a superheated blowdown. Input parameters for these cases are summarized in Tables B-1 and B-2. The initial conditions and passive heat sink parameters are typical of ice condenser containments.

The calculated pressures and temperatures as functions of time are presented in Figures B-1 through B-12. As can be seen from these figures, CLASIX and COCOCLASS9 produced almost identical analytical results for all cases considered. Neither program consistently produced lower results than the other. The calculated pressure and temperature differences were respectively less than [ ]* percent and [ ]* percent. *a,c

The comparison of CLASIX and COCOCLASS9 indicates negligible differences between the analytical results of the two programs. This provides a high level of confidence in the CLASIX modeling of the blowdown, hydrogen addition, hydrogen burning and heat transfer to passive heat sinks. Since CLASIX and COCOCLASS9 have different time step and convergence criteria, the comparison also indicates that these criteria in CLASIX are adequate.

References

B-1 Bordelon, F.M., and Murphy, E.T., "Containment Pressure Analysis Code (COCO)", WCAP-8327 (Proprietary Class 2), July 1974, WCAP-8326 (Proprietary Class 3) July, 1974.

B-2 "Zion Probabilistic Safety Study", Module 4, Section 4, 1981 (NRC Docket Nos. 50-295 and 50-304).

TABLE B-1

General Input Parameters for CLASIX and COCOCLASS9 Comparison Cases

Parameter	Value
Volume (ft^3)	1.2×10^6
Initial temperature (F)	100
Initial air pressure (psia)	.28
Initial steam pressure (psia)	14.71
H_2O mass addition rate (lbm/sec)	200
H_2O energy addition (Btu/lbm)	
saturated	500
superheated	1205
H_2 addition rate (lbm/sec)	10
H_2 addition temperature (F)	1500
H_2 addition initiated (sec)	30
H_2 addition terminated (sec)	90
Burn initiated (sec)	100
Burn rate (lbm/sec)	30

TABLE B-2

Passive Heat Sink Input Parameters

for CLASIX and COCOCLASS9 Comparison Cases

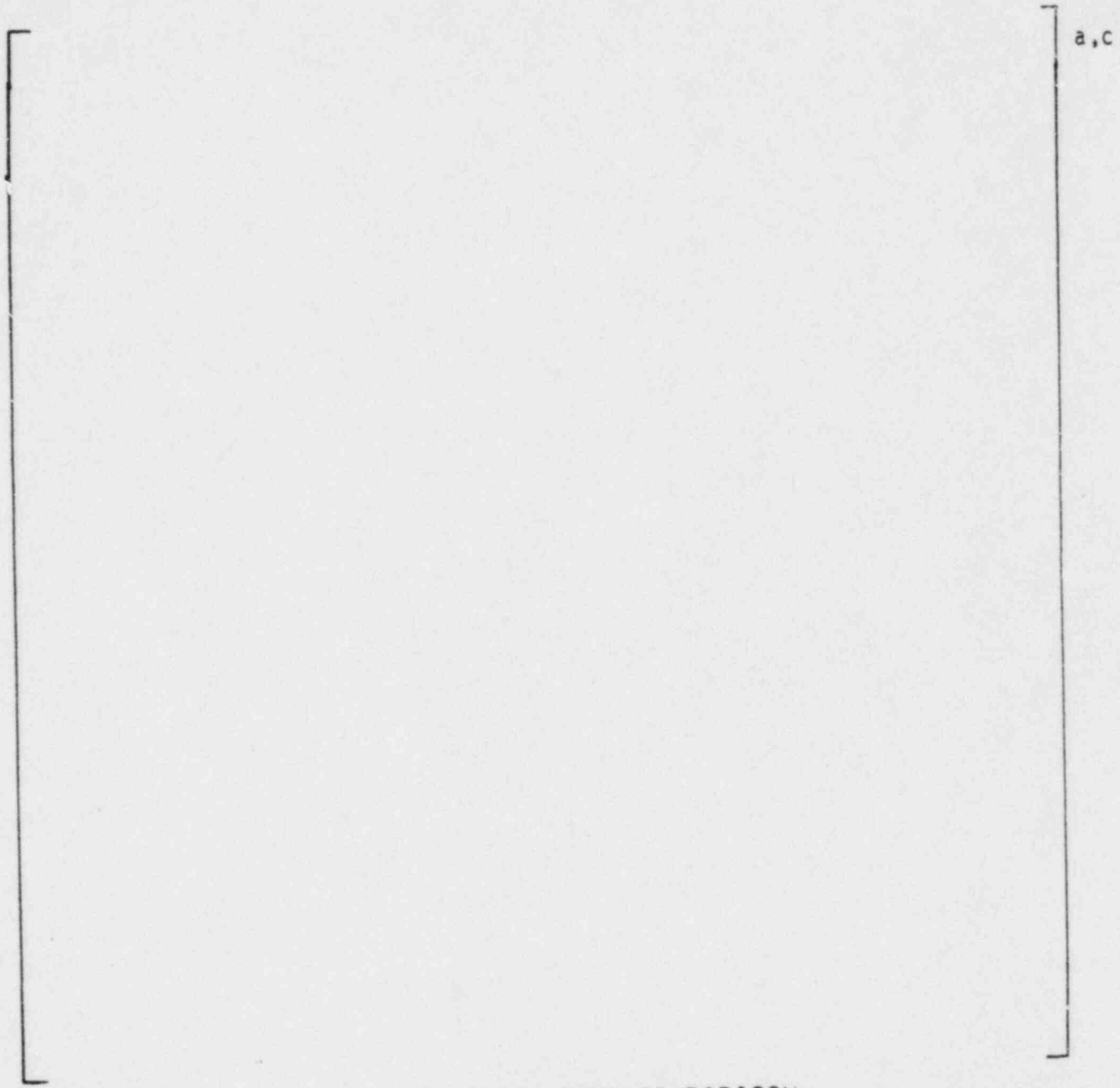
	Wall #1	Wall #2
Surface area (ft^2)	2×10^4	3×10^5
Initial temperature (F)	100	100
Emissivity*	0.4	0.9
Radiant heat transfer beam length (ft)*	100	100
Layer 1 - Material	Stainless Steel	Paint
Thickness (ft)	0.06	0.001
Number of nodes	30	2
Thermal conductivity (Btu/hr ft F)	26.0	0.08
Heat capacity (Btu/ft^3 F)	56.4	28.4
Exit heat transfer coefficient ($Btu/hr\ f^2$ F)	0.0	1×10^4
Layer 2 - Material		Concrete
Thickness (ft)		1
Number of nodes		12
Thermal conductivity (Btu/hr ft F)		0.8
Heat capacity (Btu/ft^3 F)		28.8
Exit heat transfer coefficient ($Btu/hr\ f^2$ F)		1×10^8
Layer 3 - Material		Concrete
Thickness (ft)		2
Number of nodes		12
Thermal conductivity (Btu/hr ft F)		0.8
Heat capacity (Btu/ft^3 F)		28.8
Exit heat transfer coefficient ($Btu/hr\ f^2$ F)		0.0

*Used in Cases 3 and 6.

[ ] a,c

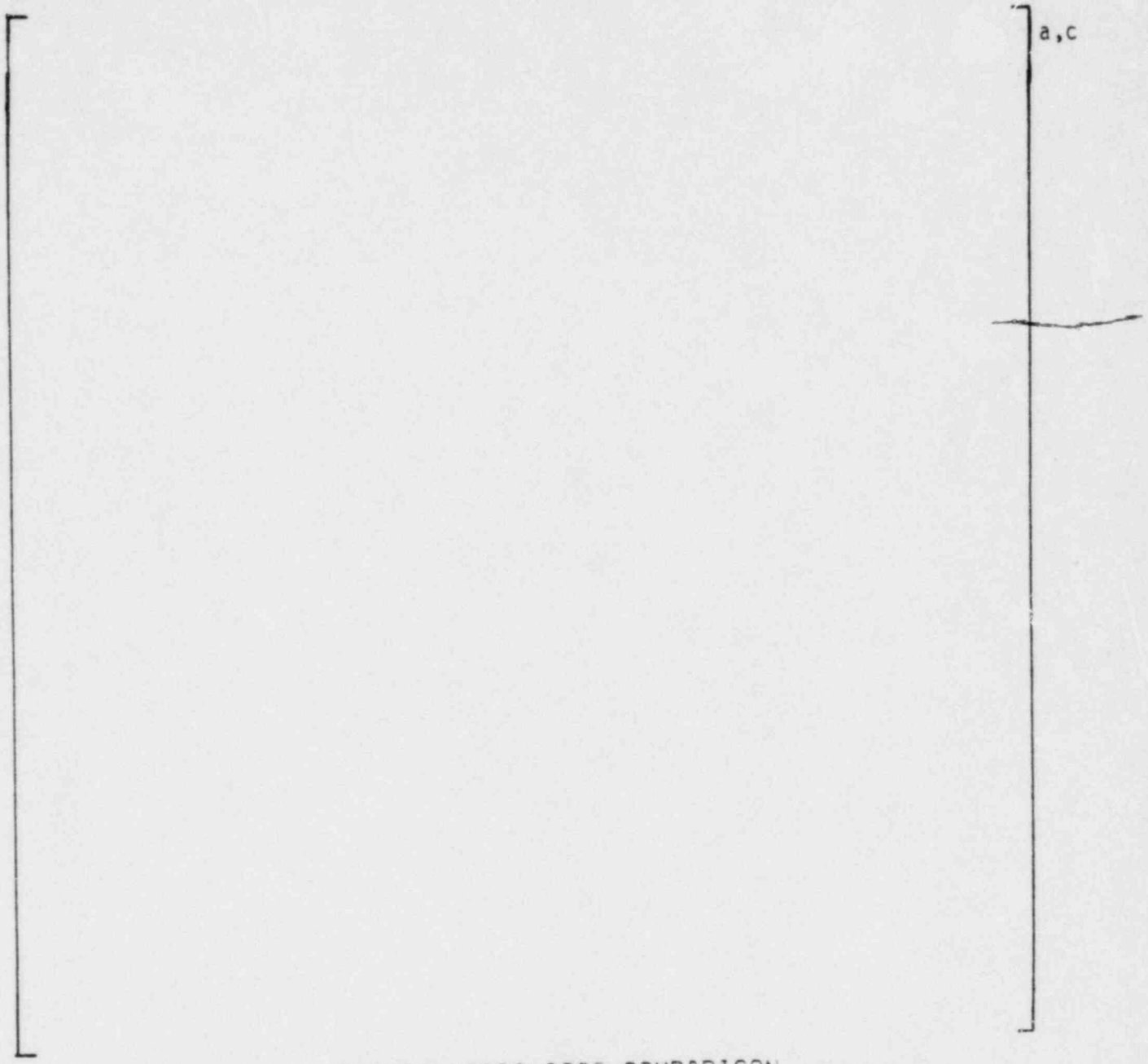
CLASIX COCOCLASS9 COMPARISON
CASE 1
500 BTU/LBM BLOWDOWN
NO HEAT SINKS

FIGURE B-1



CLASIX COCOCLASS9 COMPARISON
CASE 1
500 BTU/LBM BLOWDOWN
NO HEAT SINKS

FIGURE B-2



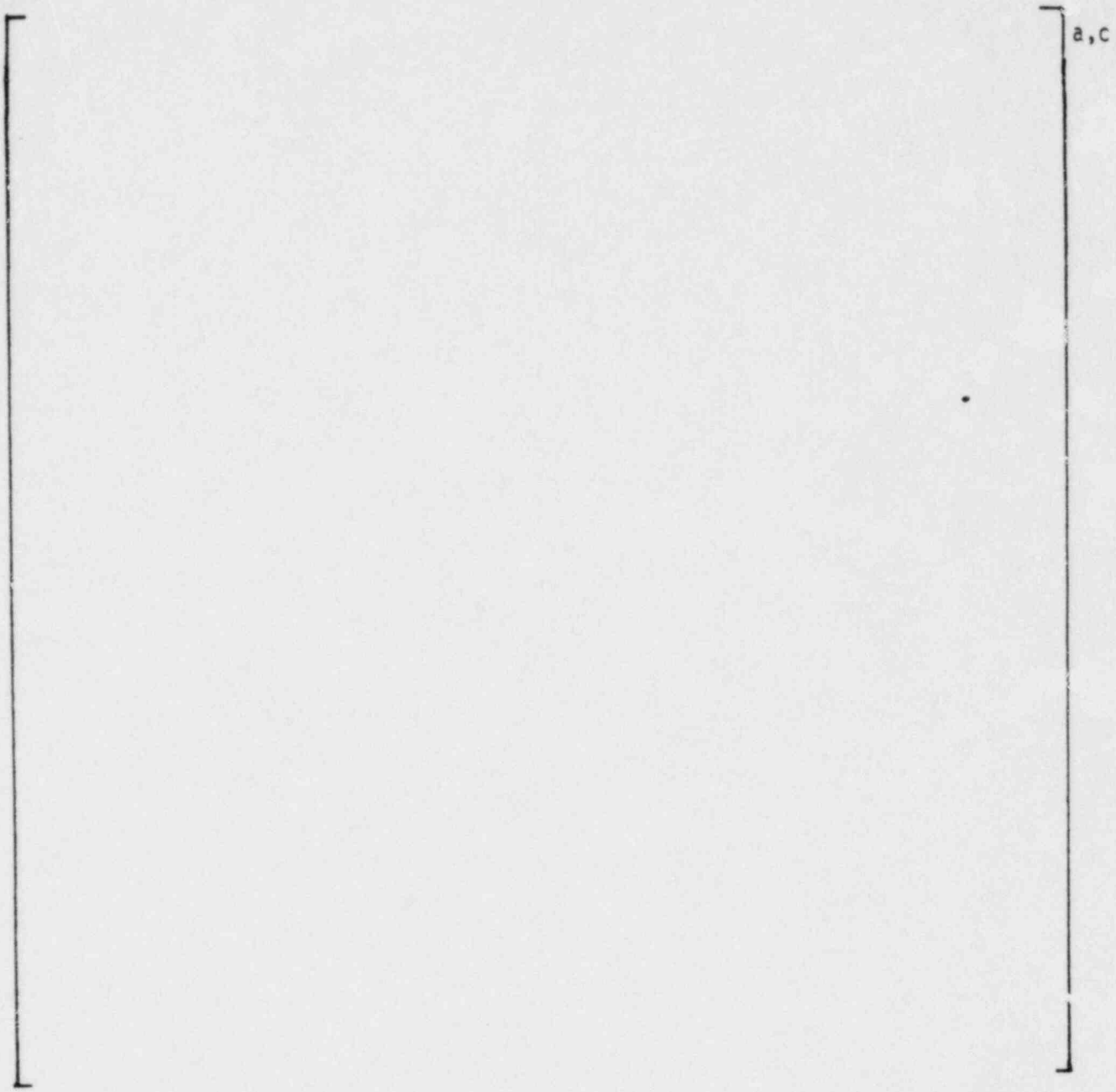
CLASIX COCOCLASS9 COMPARISON
CASE 2
500 BTU/LBM BLOWDOWN
WALLS WITHOUT RADIANT HEAT TRANSFER

FIGURE B-3

[ ]a,c

CLASIX COCOCLASS9 COMPARISON
CASE 2
500 BTU/LBM BLOWDOWN
WALLS WITHOUT RADIANT HEAT TRANSFER

FIGURE B-4



CLASIX COCOCLASS9 COMPARISON
CASE 3
500 BTU/LBM BLOWDOWN
WALLS WITH RADIANT HEAT TRANSFER

FIGURE B-5

[ ]a,c

CLASIX COCOCLASS9 COMPARISON
CASE 3
500 BTU/LBM BLOWDOWN
WALLS WITH RADIANT HEAT TRANSFER

FIGURE B-6

[ ]a,c

CLASIX COCOCLASS9 COMPARISON
CASE 4
1205 BTU/LBM BLOWDOWN
NO HEAT SINKS

FIGURE B-7

[

a,c]

CLASIX COCOCLASS9 COMPARISON
CASE 4
1205 BTU/LBM BLOWDOWN
NO HEAT SINKS

FIGURE B-8

[ ]a,c

CLASIX COCOCLASS9 COMPARISON
CASE 5
1205 BTU/LBM BLOWDOWN
WALLS WITHOUT RADIANT HEAT TRANSFER

FIGURE B-9

[ ]a,c

CLASIX COCOCLASS9 COMPARISON
CASE 5
1205 BTU/LBM BLOWDOWN
WALLS WITHOUT RADIANT HEAT TRANSFER

FIGURE B-10

[ ]a,c

CLASIX COCOCLASS9 COMPARISON
CASE 6
1205 BTU/LBM BLOWDOWN
WALLS WITH RADIANT HEAT TRANSFER

FIGURE B-11

[ ]a,c

CLASIX COCOCLASS9 COMPARISON
CASE 6
1205 BTU/LBM BLOWDOWN
WALLS WITH RADIANT HEAT TRANSFER

FIGURE B-12

APPENDIX C

Comparison of CLASIX Results with Test Measured Results

Introduction

Comparisons between CLASIX calculated results and test measured results from two series of thermal ignitor experimental tests are presented in this appendix. The two test series were conducted by Fenwal Incorporated, Ashland, Massachusetts, References C-1 and C-2, and Lawrence Livermore National Laboratory (LLNL), Livermore, California, Reference C-3. The purpose of these tests was to determine the reliability and capability of thermal ignitors to initiate deflagration under various environmental conditions typical of the reactor containment during accidents.

The various test conditions are divided into four divisions in this appendix: dry, steam, spray and transient. The dry cases consist of air and hydrogen mixtures, and have no additions to the vessel after the glow plug is activated. Steam cases are those cases in which steam was added initially at various concentrations. These steam cases also have no additions to the vessel after the glow plug is activated. The spray cases have a steady water spray in the vessel throughout the period in which the glow plug is active. The transient cases are those in which a constant flow of hydrogen and steam is added to the vessel during the period in which the glow plug is active. The dry and steam tests were performed by both Fenwal and LLNL. The remaining two divisions were conducted by Fenwal. Representative tests from each of these four divisions were selected for use in the CLASIX verification analysis. The test results were compared to CLASIX calculated results to verify the CLASIX burn model, the CLASIX models for hydrogen and high enthalpy water mass and energy additions, and some aspects of the CLASIX models for heat transfer to passive heat sinks and sprays.

General CLASIX Input

For both the Fenwal and the LLNL test comparisons, the free volume inside the vessel was treated as a single element. For this simple model, CLASIX input consists of the initial conditions, burn parameters, and passive heat sink data. All of these input parameters except the heat sink data and the net free gas volumes are case dependent and will be discussed in the next section.

Passive heat sink data are summarized in Table C-1 for the Fenwal vessel and Table C-2 for the LLNL vessel. These include the wall surface area, the initial wall temperature, the emissivity, the radiant heat transfer beam length, and individual layer data. For the Fenwal vessel, the wall surface area was calculated from the known volume and vessel geometry. For the LLNL vessel, the wall surface area was obtained from LLNL. The initial wall temperature is case dependent and equal to the initial gas temperature. Individual layer data input to CLASIX includes the thickness, the number of nodes, the thermal conductivity, the heat capacity, and the exit heat transfer coefficient. The layer thicknesses are determined by the vessel specifications, the thermal conductivity and heat capacity are material dependent parameters, and the layer exit heat transfer coefficients are functions of the materials in adjacent layers. Where possible, passive heat sink parameters are the standard values used in ice condenser containment analyses. The remaining values are based on standard textbook values. A schematic of the Fenwal and LLNL test vessels are shown in Figures C-1 and C-2, respectively.

Case Specific CLASIX Input

The CLASIX initial conditions include the initial gas temperature, initial total pressure, and initial partial pressure or volume fraction for the gas constituents. All of these values were obtained directly from the test reports. Oxygen and nitrogen partial pressures were calculated using the standard air fractions of 0.209 for oxygen and 0.79 for nitrogen.

The burn parameters include the hydrogen volume fraction for ignition, the hydrogen fraction burned, the minimum oxygen volume fraction required for ignition, the minimum oxygen volume fraction required to support combustion, and the burn time. The hydrogen parameters are case dependent and, except for the burn fraction for the Fenwal tests, are taken directly from the test report. The oxygen parameters are standard values that have been used in ice condenser containment hydrogen transient analyses.

For the Fenwal tests, the burn fraction is calculated from the test data by taking the difference between the pre-burn and post-burn hydrogen concentrations. The pre-burn concentration can be determined from the partial pressure of hydrogen initially added to the test vessel or from the pre-burn gas analysis. The post-burn concentration can be determined from the post-burn gas analysis or from an evaluation of oxygen depletion. The oxygen depletion is the difference between pre-burn and post-burn oxygen concentrations. The pre-burn oxygen concentration can be determined from the initial partial pressure of air in the test vessel or from the pre-burn gas analysis. The post-burn oxygen concentration is available only from post-burn gas analysis. If the reported data are consistent, all methods of calculating the burn fraction should give the same result.

Uncertainties of Some Data

In many of the Fenwal test gas analyses, both pre-burn and post-burn, the total volume fractions of gas constituents did not add up to 1.0. In addition, in cases from all phases of the tests, the pre-burn gas analysis indicated significantly different gas concentrations than expected based on the partial pressure of gas added to the vessel.

A review of the LLNL test data indicated that the data reported in Table 2 of Reference C-3 does not always illustrate the actual burning of hydrogen as reflected in the pressure traces. A good illustration is represented in LLNL test number 39. The recorded burn time for the test is five seconds. A better representation of the burn time, as obtained from page A6 of Reference C-3, was estimated to be 3.75 seconds. Also, some pressure plots provided do not give a clear indication of the nature of the

burn. Some plots are of a jagged nature as opposed to the generally smooth and rounded plots. This might indicate localized burning instead of one large burn, as modeled by CLASIX.

Additionally, there is some uncertainty in the LLNL data reported for hydrogen burn fraction. After the burn has apparently ended, a small fan is operated to remix the gases before a sample is taken. This remixing of the gases can result in additional burning because of the exposure of more hydrogen to the still hot glow plug. A small pressure increase was noted on several tests when the fan was activated. Also, on one of the anomalous tests (Test #34), a small pressure rise of one psi was noted when the circulation fan was activated. The gas analysis from this test indicated 30 percent of the original hydrogen was consumed although no burn was indicated.

Dry Tests

There are three dry cases included in Phase I of the Fenwal testing program. All three cases were selected for inclusion in the CLASIX verification analyses. One of these was a 12 percent by volume (v/o) hydrogen test, and the other two were 8 v/o hydrogen tests. The CLASIX initial conditions and burn parameters for these cases are summarized in Table C-3. For the 12 v/o hydrogen case, the hydrogen burn fraction was assumed to be 1.0 based on the recorded post-burn gas analysis data and the generally accepted very large body of existing test results which indicate complete or nearly complete combustion for this hydrogen concentration in dry air. The burn fractions for the two 8 v/o hydrogen cases were calculated by three methods mentioned above. The three methods are: 1) assume the pre-burn hydrogen concentration indicated by the partial pressure and the post-burn hydrogen concentration as shown by the gas analysis are correct; 2) assume the gas analysis is correct for both the pre and post-burn hydrogen concentrations; and 3) assume pre-burn hydrogen concentration from the partial pressure is correct and calculate the post burn hydrogen concentration by determining the total amount of oxygen used during the burn, and then finding the amount of hydrogen required to completely burn that amount. The pre-burn oxygen concentration was obtained from the

partial pressure and the post burn oxygen concentration was obtained from the gas analysis. The burn fractions calculated by each of these methods were used in the CLASIX analyses and compared to the test results.

Three dry cases were selected from the Livermore tests for inclusion in CLASIX verification analyses. These cases have initial hydrogen concentrations ranging from 8.0 v/o to 15.1 v/o. The CLASIX initial conditions and burn parameters for these cases are summarized in Table C-4.

The results of a comparison of CLASIX predicted values to the Fenwal and Livermore measured values for dry cases are summarized in Tables C-5 and C-6, respectively. The CLASIX calculated temperatures are significantly higher than the test results. This variation is attributed to the slow response time of the thermocouples used in the tests, and for this reason, no temperature comparisons are made.

In Case 1, the Fenwal 12 v/o hydrogen case, the CLASIX calculated peak pressure is [ ]* psia, and the pressure rise during the burn is [ ]* psi compared to 53.0 psi for the test. In Case 2, a Fenwal 8 v/o hydrogen case, the calculated pressure rise was [ ]* psi and [ ]* psi for each respective burn fraction of [ ]* and [ ]*. The calculated pressure rise for the smaller burn fraction is lower than the measured test result. Comparing this test to other similar tests, a burn fraction of [ ]* is considered to be too low underestimating the true amount of hydrogen burned. The calculated pressure rise for the larger burn fraction is higher than the measured test result. For Case 3, the final Fenwal case of this series, the calculated pressure rise ranged from [ ]* to [ ]* psi. All of the estimates of the completeness of this burn resulted in a higher calculated pressure rise than the 3.0 psi recorded for the test. For all three Livermore test cases, the calculated peak pressure and pressure rise were higher than corresponding values recorded in the test.

*a,c

*a,c

*a,c

*a,c

*a,c

In addition to specific test comparisons, Figure 5 of the erratum to Reference C-3 shows a comparison between the Livermore dry cases and an adiabatic pressure rise calculated using the CECS code. The calculations by the code were made by using conditions which represent the dry LLNL tests.

A similar adiabatic pressure rise was calculated for a few of the dry tests using the CLASIX computer code. In all cases, CLASIX predicted higher results than both the LLNL tests and the CECS program, see Figure C-3. The higher pressure rise calculated by CLASIX is attributed to the specific heat assumptions in the CLASIX program. The point representing "Special CLASIX" will be explained later.

Steam Tests

The Fenwal steam tests consist of 12 v/o, 10 v/o, and 8 v/o initial hydrogen concentrations, and ranged from 9.5 to 27.0 percent steam. In Phase I of the Fenwal report, six 12 v/o, two 10 v/o, and three 8 v/o hydrogen tests are reported. Five of these hydrogen tests were chosen for CLASIX verfication analyses. Initial conditions and burn parameters for these cases are summarized in Table C-7. A burn fraction of 1.0 was assumed for the 12 v/o and 10 v/o hydrogen cases since no hydrogen was recorded in the postburn gas analysis and generally accepted results from other tests indicate complete combustion at these concentrations. For the 8 v/o hydrogen cases, as in the Fenwal 8 v/o hydrogen dry cases, three methods were used to calculate the burn fraction.

Livermore test cases include environmental vessel conditions of approximately 30 and 40 percent steam by volume. They varied in initial conditions and ranged from 7.1 to 14.9 percent initial hydrogen. Four of these cases were selected for CLASIX verification analyses. Initial conditions and burn parameters for these cases are summarized in Table C-8. All case dependent properties were obtained from Table 2 of Reference C-3.

Comparisons of CLASIX calculated results to test measured results for the Fenwal 12 v/o and 10 v/o hydrogen test cases are similar. The CLASIX calculated pressure rises were all considerably higher than the acutal test results. The results of these three tests are summarized in Table C-9. One example of the CLASIX conservatism is illustrated in Case 7, a 12 v/o hydrogen test. The pressure rise calculated by CLASIX is [ ]* psi, where the test pressure rise was reported to be 72.0 psi. This represents a [ ] percent conservatism factor associated with the CLASIX results.

*a,c

a,c

Comparison of CLASIX results to test results for the Fenwal 8 v/o hydrogen tests are more complex. With the initial input, CLASIX results were lower than the measured test results. The two cases in this comparison are summarized in Table C-9. The long burn times in both of these cases indicate that the deflagration was not representable by a single uniform burn as modeled by CLASIX. A review of the test pressure trace, Figure C-4, indicates that Case 10, the first of the 8 v/o hydrogen cases represented, actually has three distinct regions which can be identified with three sets of burn parameters. Since the CLASIX model assumed one distinct burn, results of this case were not valid and the case was remodeled. The results of the CLASIX calculations with the revised model are presented in Figure C-4. The pressure in the vessel increased [ ]* psi during the first burn of [ ]* seconds. The second portion of the burn was a slow continuous burn which continued for [ ]* seconds, and resulted in a pressure rise of [ ]* psi. The pressure then began a smooth climb to [ ]* psia after which it tapered off. During the burns, 80 percent of the hydrogen was consumed which agrees with the test report. This representation of the burn agrees very closely with the actual pressure trace. Detailed information was not available for Case 11, the other Fenwal 8 v/o hydrogen case considered. However, since this case is similar in type to Case 10 above, it is likely that it consists of a non-uniform burn over the relatively long burn time of nine seconds. As shown for Case 10, a non uniform burn would not produce results comparable to the uniform burn modeled in CLASIX.

*a,c

*a,c

*a,c

*a,c

The results from comparisons of CLASIX calculations to measured results from the Livermore steam cases were generally conservative and similar to the previous comparisons with test results. The results of the four representative cases are summarized in Table C-10. Cases 12 and 13 show CLASIX to have a higher pressure rise by as much as [ ]* percent. Case 14 has a calculated pressure rise of [ ]* psi compared to the measured value of 9.5 psi. As mentioned previously, this case had a recorded burn time different than that indicated by the pressure plot. When the new burn time of 3.75 seconds was input to CLASIX, the pressure rise increased to [ ]a,c psi. This result is summarized with Case 14 on Table C-10. The more accurate representation of the actual burn time results in a conservatism

*a,c

*a,c

more consistent with the previous results. Case 15 resulted in a calculated peak pressure lower than the measured result. For Case 15, the pressure plots provided do not give a clear indication of the nature of the burn. This case has a long burn time and high steam concentration, and is likely to consist of a non uniform burn similar to Case 10, an 8 v/o hydrogen Fenwal steam case.

Sensitivity Study

To provide confidence in the wall parameters used in the CLASIX model and to determine the relative importance of various CLASIX parameters, a sensitivity study was conducted. The test case used for this study was Case 7, Fenwall test 6. Various sets of parameters were changed to determine their overall impact on the calculated pressure and temperature. The following parameters were investigated:

a) Specific heat of gas constituents (C_p and C_v)
b) Heat transfer rate
   i) modifying coefficient
   ii) removing wall (adiabatic burn)
c) Emissivity
d) Beam length
e) Thermal conductivity
f) Heat capacity
g) Exit film coefficient
h) Time step

Of the above parameters, only the adiabatic burn case and the specific heat parameters had significant effect. The adiabatic burn was achieved by removing the wall from the CLASIX input and resulted in a [ ]* psi increase *a,c in the pressure rise. The specific heat values that have been used in the CLASIX program are constant room temperature values. In reality, specific heat values are temperature dependent quantities. To determine the significance of the temperature dependence of the constituent gas specific heats, these quantities were evaluated at a temperature midway between the maximum and minimum temperatures calculated by CLASIX in Case 7. Case 7

was then rerun with the new specific heat values input to CLASIX. This process was repeated for several other temperatures over the range of temperatures calculated in Case 7. The results of these analyses, summarized in Table C-11, indicate the temperature dependence of the constituent gas specific heats has a significant effect on the CLASIX calculated pressure rise.

Since the specific heat was determined to have an important effect on the pressure rise, a special single volume version of CLASIX was created which includes a calculation of the specific heats at each time step. Case 7 was rerun with this special version. Results of this run show a lower value for the pressure rise than calculated earlier by CLASIX, but still higher than the measured test result. Table C-12 summarizes a few additional cases that have been presented earlier in this appendix and have been rerun with the special version of CLASIX. The results of these cases are similar to those for Case 7. The point on Figure C-3, labeled "Special CLASIX", was obtained by using this special version of CLASIX along with removing the wall parameters. This point shows a comparison between CLASIX and the special version of CLASIX, and also represents the conservatism associated with each one.

Fenwal Spray Tests

A series of tests, one transient and three static, were run to determine the effect of sprays upon ignitor performance. One of the static tests, test #2-3-1 of Reference C-1, was chosen for the CLASIX verification analysis.

CLASIX input parameters for this case are summarized in Table C-13. The burn fraction was calculated by using the pre-burn hydrogen concentration indicated by the partial pressure and the post-burn hydrogen concentration as shown by the gas analysis. The spray water temperature and flow rate were specified in Reference C-1. The remaining spray parameters were based on values used in ice condenser containment analyses.

For this test, the CLASIX calculated peak pressure is [ ]* psia, and the pressure rise during the burn is [ ]* psi. The test measured pressure rise was reported to be 50.0 psi. The CLASIX result is higher than the test measured result indicating that the CLASIX model for this spray case is calculating a conservative pressure rise due to the hydrogen burn. *a,c *a,c

Fenwal Transient Tests

A series of tests were conducted in Phase II of the Fenwal test study to determine the characteristics of the burning which occurs when hydrogen is introduced into a test vessel at a constant rate and when both hydrogen and steam are simultaneously introduced into the test vessel at a constant rate. One of the transient tests was simulated using CLASIX. The pressure plot for this test was obtained from Reference C-1 where the test is numbered 2-2-2 and is included here in Figure C-5. CLASIX input parameters for this case are summarized in Table C-14.

The CLASIX simulation of this case was divided into a series of ten intervals. The burn parameters were adjusted in each timeinterval until an approximate fit was achieved. The CLASIX pressure history is plotted in Figure C-5. The CLASIX analysis was stopped at 595 seconds (9.917 minutes) because no burns are apparent after that time. The first of eight burns in the CLASIX simulation occurs at [ ]* seconds with a pressure rise of [ ]* psi. A slow burn consisting of 40 percent of the remaining hydrogen follows. The pressure then drops rapidly to [ ]* psi where it slowly rises due to the pressure increase resulting from the incoming hydrogen and steam. The second major burn occurs at [ ]* seconds resulting in a pressure rise of [ ]* psi, and is followed by another slow burn of 40 percent of the remaining hydrogen. The maximum total pressure of [ ]* psia occurred at the fifth peak. This burn also had the highest pressure rise with a value of [ ]* psi. After the last burn, a slow burn occurred resulting in [ ]* percent of the available hydrogen being burned and was followed by a rapid pressure drop. Following this drop, no more burns occur and the slight pressure increase is due to the continued addition of hydrogen and steam. *a,c *a,c *a,c *a,c *a,c *a,c

The CLASIX simulation of Case 2-2-2 is in close agreement with the test measured results. The pressure increases due to each burn are very similar. The CLASIX pressure curve is shifted slightly upward resulting in higher maximum pressures. The fifth peak, for example, actually resulted in a maximum measured pressure of 26.7 psia as compared to the CLASIX calculated value of [ ]* psia. The gas sample taken after the transient was terminated indicated a final hydrogen concentration of 23.9 percent. Adding the mass of hydrogen injected during the 305 seconds that CLASIX did not model, yields a final hydrogen concentration of [ ]* percent in the CLASIX analysis. Since the burn parameters were not defined for each burn in the transient, a direct comparison cannot be made between the measured test results and the CLASIX calculated results. However, the CLASIX calculated pressure results indicate that CLASIX has the ability to model a transient similar to Case 2-2-2 above. *a,c *a,c

Conclusion

For all tests which were representable by a single uniform hydrogen burn, CLASIX predicted conservative values for the peak pressure. This provides a high degree of confidence in the CLASIX burn model and the CLASIX models for heat transfer to passive heat sinks and sprays. A high degree of conservatism has been shown to be the result of using constant room temperature values for constituent gas specific heats in the CLASIX analytical model.

References

C-1 Appendix N of the Tennessee Valley Authority, Sequoyah Nuclear Plant Core Degradation Program, Volume 2, "Report on the Safety Evaluation of the Interim Distributed Ignition System", December 15, 1980 (NRC Docket No. 50-327).

C-2 Tennessee Valley Authority, "Research Program on Hydrogen Combustion and Control Quarterly Progress Report", March 16, 1981 (NRC Docket No. 50-327).

C-3 Lowry, William, "Preliminary Results of Thermal Igniter Experiments in H_2-Air-Steam Environments", from "Proceedings of the Workshop on the Impact of Hydrogen on Water Reactor Safety", edited by Marshall Berman, Sandia Laboratories, August 1981 (NUREG/CR-2017).

TABLE C-1

FENWAL TEST COMPARISON CLASIX INPUT

PASSIVE HEAT SINK DATA

Wall surface area (ft^2)	126.64
Initial wall temperature (F)	*
Emissivity	0.2
Radiant heat transfer beam length (ft)	4.23
Layer 1 - Stainless Steel	
Thickness (ft)	0.0104
Number of nodes	6
Thermal conductivity (BTU/hr ft F)	9.87
Heat capacity (BTU/ft^3 F)	59.2
Exit heat transfer coefficient ($BTU/hr\ ft^2$ F)	10^8
Layer 2 - Carbon Steel	
Thickness (ft)	0.0521
Number of nodes	31
Thermal conductivity (BTU/hr ft F)	27.3
Heat capacity (BTU/ft^3 F)	59.2
Exit heat transfer coefficient ($BTU/hr\ ft^2$ F)	10
Layer 3 - Insulation	
Thickness (ft)	0.25
Number of nodes	3
Thermal conductivity (BTU/hr ft F)	0.025
Heat capacity (BTU/ft^3 F)	2.0
Exit heat transfer coefficient ($BTU/hr\ ft^2$ F)	0.0

* Case dependent parameter equal to the initial gas temperature.

TABLE C-2

LIVERMORE TEST COMPARISON CLASIX INPUT

PASSIVE HEAT SINK DATA

Wall surface area (ft^2)	26.2
Initial wall temperature (F)	*
Emissivity	0.7
Radiant heat transfer beam length (ft)	1.11
Layer 1 - Carbon Steel	
Thickness (ft)	0.015625
Number of nodes	12
Thermal conductivity (BTU/hr ft F)	27.3
Heat capacity (BTU/ft^3 F)	59.2
Exit heat transfer coefficient (BTU/hr ft^2 F)	10.0
Layer 2 - Insulation	
Thickness (ft)	0.291667
Number of nodes	3
Thermal conductivity (BTU/hr ft F)	0.025
Heat capacity (BTU/ft^3 F)	2.0
Exit heat transfer coefficient (BTU/hr ft^2 F)	0.0

* Case dependent parameter equal to the initial gas temperature.

TABLE C-3

FENWAL TEST COMPARISON CLASIX INPUT

DRY TESTS

	Case 1	Case 2	Case 3
Initial Conditions			
Actual test number	1	1	3
Temperature (^{o}F)	180	180	180
Total pressure (psia)	18.24	17.45	18.86
O_2 partial pressure (psi)	3.357	3.357	3.628
N_2 partial pressure (psi)	12.69	12.69	13.713
H_2 partial pressure (psi)	2.191	1.396	1.510
H_2O partial pressure (psi)	0.0	0.0	0.0
Burn Parameters			
Hydrogen V/F for ignition	0.12	0.08	0.08
Hydrogen fraction burned*	1.0	[	] a,c
Minimum oxygen V/F for ignition	0.05	0.05	0.05
Minimum oxygen V/F to support combustion	0.0	0.0	0.0
Burn time (seconds)	0.5	4.0	4.7

* When multiple burn fractions are given, the fractions listed are estimates of the actual burn fraction.

TABLE C-4

LLNL TEST COMPARISON CLASIX INPUT

DRY TESTS

	Case 4	Case 5	Case 6
Initial Conditions			
Actual test number	17	21	24
Temperature (^{o}F)	81	54	82
Total pressure (psia)	15.9	16.5	17.2
O_2 partial pressure (psi)	2.957	2.904	2.958
N_2 partial pressure (psi)	11.53	11.75	11.51
H_2 partial pressure (psi)	1.272	1.716	2.597
H_2O partial pressure (psi)	0.0	0.0	0.0
Burn Parameters			
Hydrogen V/F for ignition	0.08	0.104	0.151
Hydrogen fraction burned	0.55	1.0	1.0
Minimum oxygen V/F for ignition	0.05	0.05	0.05
Minimum oxygen V/F to support combustion	0.0	0.0	0.0
Burn time (seconds)	5.0	0.5	0.3

TABLE C-5

FENWAL TEST COMPARISON

CLASIX RESULTS SUMMARY - DRY TESTS

	Case 1	Case 2*	Case 3*
Actual test number	1	2	3
CLASIX Results			
Peak pressure (psia)	[		] a,c
Pressure rise (psi)			
FENWAL pressure rise (psi)	53.0	33.0	3.0

*Multiple results are due to the multiple burn fraction estimates and correspond to the hydrogen fraction burned in Table C-3.

TABLE C-6

LLNL TEST COMPARISON

CLASIX RESULTS SUMMARY - DRY TESTS

	Case 4	Case 5	Case 6
Actual test number	17	21	24
CLASIX Results			
Peak pressure (psia)	[		] a,c
Pressure rise (psi)			
LLNL pressure rise (psi)	3.5	45.0	87.0

TABLE C-7

FENWAL TEST COMPARISON CLASIX INPUT

STEAM TESTS

	Case 7	Case 8	Case 9	Case 10	Case 11
Initial Conditions					
Actual test number	6	13	10	5	14
Temperature (^{o}F)	176	350	146	138	350
Total pressure (psia)	26.64	26.58	21.11	20.75	26.44
O_2 partial pressure (psi)	3.592	4.590	3.402	3.419	4.563
N_2 partial pressure (psi)	13.578	17.349	12.858	12.926	17.246
H_2 partial pressure (psi)	3.199	3.193	2.108	1.661	2.116
H_2O partial pressure (psi)	6.27	1.450	2.746	2.740	2.510
Burn Parameters					
Hydrogen V/F for ignition	0.12	0.12	0.10	0.08	0.08
Hydrogen fraction burned*	1.0	1.0	1.0	[	] a,c
Minimum oxygen V/F for ignition	0.05	0.05	0.05	0.05	0.05
Minimum oxygen V/F to support combusion	0.0	0.0	0.0	0.0	0.0
Burn time (seconds)	0.656	0.406	0.875	18.25	9.0

*When multiple burn fractions are given, the fractions listed are estimates of the actual burn fraction. Only the highest and lowest values are included in this table.

TABLE C-8

LLNL TEST COMPARISON CLASIX INPUT

STEAM TESTS

	Case 12	Case 13	Case 14	Case 15
Initial Conditions				
Actual test number	29	35	39	37
Temperature (^{o}F)	190	181	198	180
Total pressure (psia)	26.5	29.7	30.2	25.7
O_2 partial pressure (psi)	2.957	3.763	3.098	3.184
N_2 partial pressure (psi)	11.18	14.22	11.71	12.04
H_2 partial pressure (psi)	3.948	2.257	3.02	2.596
H_2O partial pressure (psi)	8.400	9.445	12.35	7.864
Burn Parameters				
Hydrogen V/F for ignition	0.148	0.076	0.10	0.101
Hydrogen fraction burned	1.0	0.46	0.57	0.96
Minimum oxygen V/F for ignition	0.5	0.5	0.5	0.5
Minimum oxygen V/F to support combusion	0.0	0.0	0.0	0.0
Burn time (seconds)	1.0	4.0	5.0/3.75*	4.5

*Two different burn times were chosen for this case to determine its importance.

TABLE C-9

FENWAL TEST COMPARISON

CLASIX RESULTS SUMMARY - STEAM TESTS

	Case 7	Case 8	Case 9	Case 10*	Case 11*
Actual test number	6	13	10	5	14
CLASIX Results					
Peak pressure (psia)	[				] a,c
Pressure rise (psi)					
FENWAL pressure rise (psi)	72.0	60.0	53.7	22.6	30.0

*Multiple results are due to the multiple burn fraction estimates and correspond to the hydrogen fraction burned in Table C-7.

+See text for an explanation of results.

TABLE C-10

LLNL TEST COMPARISON

CLASIX RESULTS SUMMARY - STEAM TESTS

	Case 12	Case 13	Case 14*	Case 15
Actual test number	29	35	39	37
CLASIX Results				
Peak pressure (psia)	[			]a,c
Pressure rise (psi)				
LLNL pressure rise (psi)	50.0	2.5	9.5	22.0

*The results on the right side of Case 14 indicate the faster burn time of 3.75 seconds.

+See text for an explanation of results.

TABLE C-11

SENSITIVITY STUDY

EFFECT OF SPECIFIC HEATS

TEMPERATURE AT WHICH Cp and Cv WERE CALCULATED	CLASIX CALCULATED PRESSURE RISE (psi)
[	] a,c

*The base case is Case 7, Fenwal test #6. Initial conditions and burn parameters are given in Table C-7. The reported pressure rise for this test is 72.0 psi.

TABLE C-12

SENSITIVITY STUDY

EFFECT OF SPECIFIC HEATS - SPECIAL CLASIX*

	Case 7	Case 8	Case 5+
Actual test number	FENWAL 6	FENWAL 13	LLNL 21
CLASIX Results			
Special CLASIX peak pressure (psi)	[		] a,c
CLASIX pressure rise (psi)			
Special CLASIX pressure rise (psi)			
Actual test pressure rise (psi)	72.0	60.0	45.0

*Special CLASIX is a version that calculates specific heats of each gas constitutent at each time step.

+An adiabatic CLASIX result of this case is plotted on Figure C-3 for comparison.

TABLE C-13

FENWAL TEST COMPARISON CLASIX INPUT

SPRAY TEST

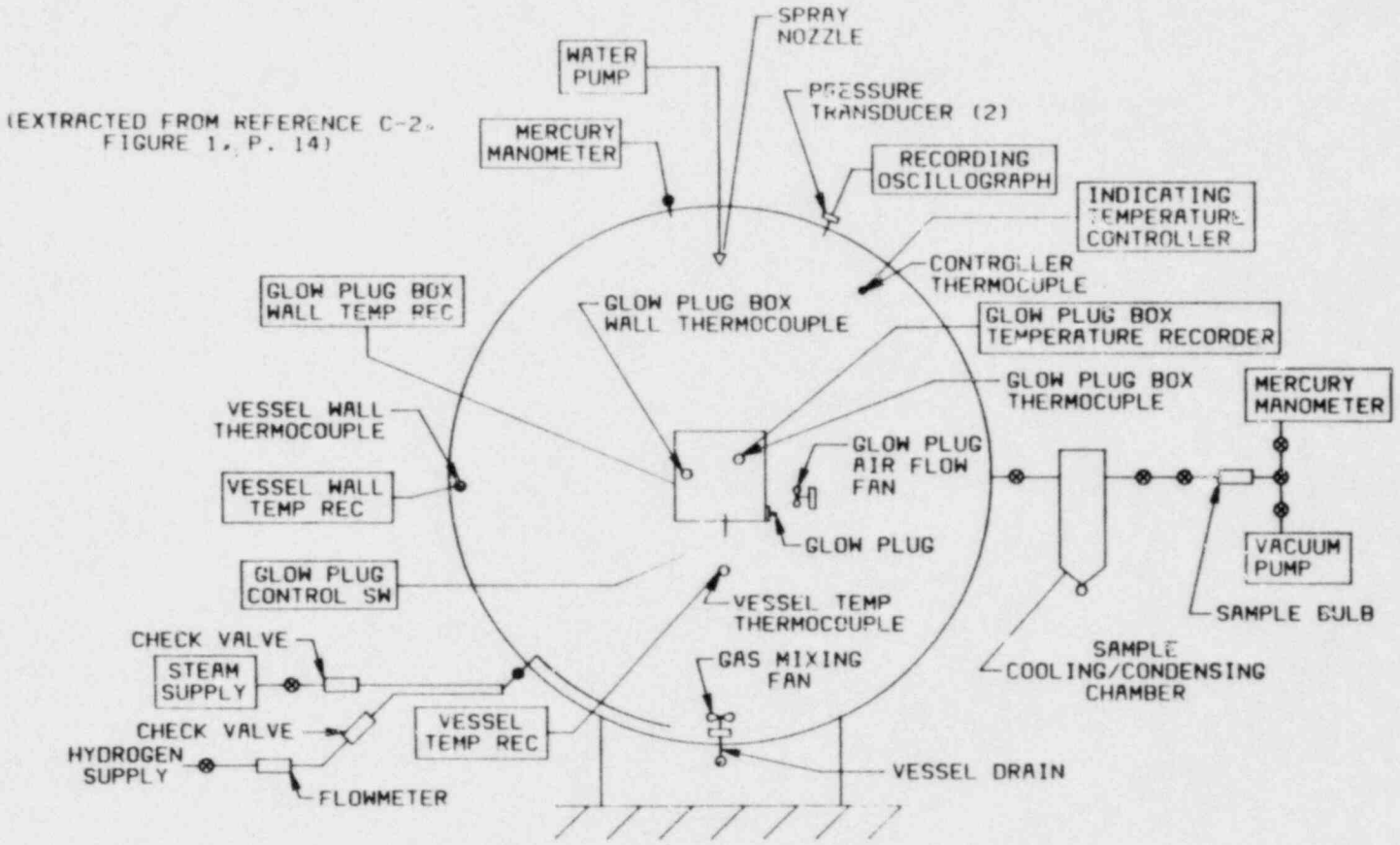
	Case 16
Initial Conditions	
Actual test number	2-3-1
Temperature (F)	82.0
Total pressure (psia)	16.31
O_2 partial pressure (psi)	3.07
N_2 partial pressure (psi)	11.61
H_2 partial pressure (psi)	1.63
H_2O partial pressure (psi)	0.0
Burn Parameters	
Hydrogen V/F for ignition	0.10
Hydrogen fraction burned	0.92
Minimum oxygen V/F for ignition	0.05
Minimum oxygen V/F to support combusion	0.0
Burn time (seconds)	0.65
Spray Parameters	
Drop diameter (μ)	700.0
Drop fall time (sec)	1.06
Temperature (F)	50.0
Flow rate (gpm)	1.9
Drop film coefficient (Btu/hr ft^2 F)	20.0

TABLE C-14

FENWAL TEST COMPARISON CLASIX INPUT

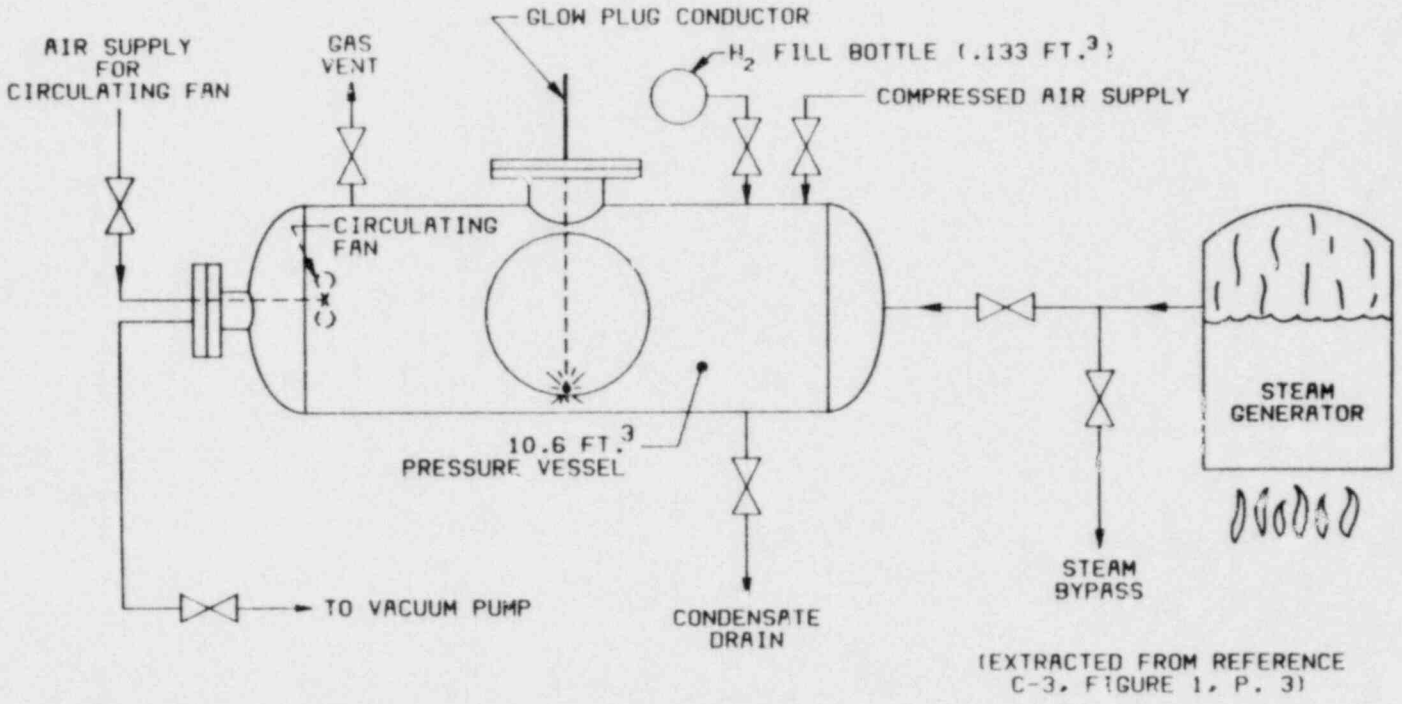
TRANSIENT TEST

Initial Conditions	Case 17
Actual test number	2-2-2
Temperature (F)	160.0
Total pressure (psia)	14.7
O_2 partial pressure (psi)	3.087
N_2 partial pressure (psi)	11.613
H_2 partial pressure (psi)	0.0
H_2O partial pressure (psi)	0.0
Additions	
Hydrogen addition rate (lbm/sec)	3.487×10^{-4}
Hydrogen temperature (F)	68.0
Steam addition rate (lbm/sec)	0.0005
Steam energy (Btu/lbm)	1176.0



FENWAL H_2 IGNITER TEST SCHEMATIC

FIGURE C-1



(EXTRACTED FROM REFERENCE C-3, FIGURE 1, P. 3)

LLNL H_2 IGNITER TEST SCHEMATIC

FIGURE C-2

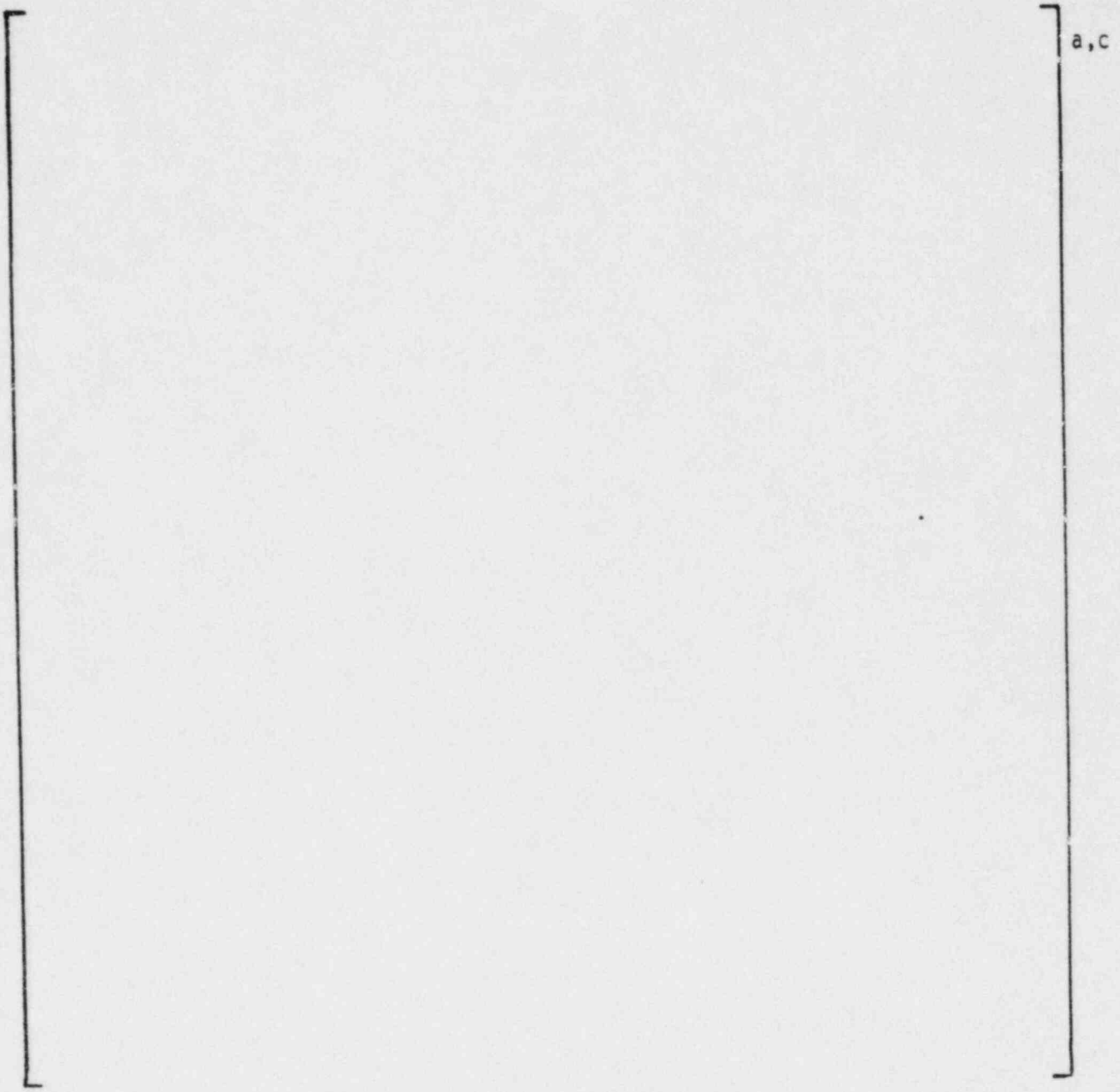
PRESSURE RISE AS A FUNCTION OF H_2 CONCENTRATION

FIGURE C-3

[ ]a,c

CASE 10 COMPARISON

FIGURE C-4



CASE 2-2-2 TRANSIENT COMPARISON

FIGURE C-5

APPENDIX D

Evaluation of Separate Spray Time Domain and Heat Transfer Assumptions

The purpose of this appendix is to evaluate the effect of the spray operating in a time domain that is different from that in which all other calculations operate.

In conventional analyses, a small mass of spray enters the compartment each time step of the finite difference integration. As the transient progresses, the number of spray masses increases and each mass reacts with the compartment atmosphere until it completes its fall or until it completely vaporizes. In CLASIX, the compartment ambient conditions are frozen until the small amount of spray completes its fall. As far as the spray is concerned, it sees a steady state ambient condition. To evaluate the differences of these two assumptions, a special subroutine for a single volume model in CLASIX was prepared and the results using the two subroutines were compared.

Since only the heat removed by the spray is being compared, the CLASIX model was chosen to be relatively simple. The model contains one compartment with a single spray system. Initial conditions for this CLASIX model are given in Table D-1. The time step was kept at a constant value to allow direct comparisons. The spray was turned on immediately and allowed to run the entire transient. The heat addition to the system was input as a ramp function of time increasing linearly until a peak value was reached. The heat addition rate then decreased linearly until a zero value was again achieved. No further heat was added after this. Numerical values for the heat addition are given in Table D-2.

The finite difference method divides the single compartment spray into one thousand elements and calculates the heat removed by the spray at an instant in time for each element. For the next time step, the elements move down one place with the last element discarded and the first element set at the spray's initial conditions. Drop temperature, drop diameter, and mass are recorded for each element.

The rate of heat removed from an element can be calculated by two methods.

$$\dot{Q} = hA\Delta T = hA(T_C - T_D) \qquad (D\text{-}1)$$

$$\dot{Q} = m C_p \frac{\Delta T}{\Delta t} = m C_p \frac{(T_D' - T_D)}{\Delta t} \qquad (D\text{-}2)$$

h = drop film coefficient
A = total surface area of the drops in an element
m = total mass of the drops in an element
C_p = specific heat of the drops
Δt = differential time
T_C = compartment temperature
T_D = drop temperature
T_D' = updated drop temperature after the differential time

The drop film coefficient (h), the specific heat of the drops (C_p), and the time step (Δt) are all constants whose values are given in Table D-3. The compartment temperature (T_C) is input directly to the subroutine from the CLASIX program.

The surface area and mass of the drops in each element can be expressed as functions of the drop diameter.

$$A = n4\pi\left(\frac{D}{2}\right)^2 \qquad \frac{A}{A_o} = \left(\frac{D}{D_o}\right)^2 \qquad A = A_o\left(\frac{D}{D_o}\right)^2 \qquad (D\text{-}3)$$

$$m = n\rho\frac{4}{3}\pi\left(\frac{D}{2}\right)^3 \qquad \frac{m}{m_o} = \left(\frac{D}{D_o}\right)^3 \qquad m = m_o\left(\frac{D}{D_o}\right)^3 \qquad (D\text{-}4)$$

$$\frac{A_o}{m_o} = \frac{n4\pi\left(\frac{D_o}{2}\right)^2}{n\rho\frac{4}{3}\pi\frac{D_o}{2}^3} = \frac{6}{D_o}$$

D = drop diameter

n = the number of drops in each element

ρ = drop density which is a constant

$( )_o$ = initial conditions

Substituting (D-3) and (D-4) into (D-1) and (D-2) and setting (D-1) equal to (D-2) enables the updated drop temperature to be calculated.

$$h A_o \left(\frac{D}{D_o}\right)^2 (T_C - T_D) = m_o \left(\frac{D}{D_o}\right)^3 C_p \left(\frac{T'_D - T_D}{\Delta t}\right)$$

$$T'_D = \frac{6 \Delta t\, h}{C_p \rho} \left(\frac{1}{D}\right) (T_C - T_D) + T_D \qquad \text{(D-5)}$$

At this point a determination of whether or not saturation conditions within the drop are met must be performed. The compartment pressure, which is input from the main CLASIX program to the subroutine, is used to find a corresponding saturation temperature (T_{SAT}) from the steam tables. If the updated drop temperature is lower than the saturation temperature, saturation conditions are not present and the heat removed from each element is calculated.

$$Q = m C_p (T'_D - T_D) \qquad \text{(D-6)}$$

When the updated drop temperature becomes higher than the saturation temperature (T_{SAT}), saturation conditions occur and an excess of heat (Q_{EX}) for each element is calculated.

$$Q_{EX} = m C_p (T'_D - T_{SAT}) \qquad \text{(D-7)}$$

The mass of spray vaporized (Δm) is then calculated.

$$\Delta m = Q_{EX} / h_{fg} \qquad \text{(D-8)}$$

h_{fg} = latent heat of vaporization of the spray

This enables the heat removed by each element to be found.

$$Q = -\Delta m\, h_f \tag{D-9}$$

h_f = specific enthalpy of the liquid spray

The mass of each element and the drop diameter must then be updated.

$$m' = m - \Delta m \tag{D-10}$$

$$D' = D_o \sqrt[3]{\frac{m}{m_o}} \tag{D-11}$$

The values of heat removed by each individual element are then summed to give the total heat removed by the spray (Q_{SUM}) for each time step.

$$Q_{SUM} = \sum_{i}^{1000} Q_i \tag{D-12}$$

The amount of spray mass vaporized during each time step is calculated similarly.

$$m_{SUM} = \sum_{i}^{1000} m_i \tag{D-13}$$

The total heat removed (Q_{SUM}) and the total mass vaporized (m_{SUM}) for each time step must then be converted into heat and vaporization rates which are returned by the subroutine to the CLASIX program.

$$\dot{Q} = Q_{SUM}/\Delta t \tag{D-14}$$

$$\dot{m} = m_{SUM}/\Delta t \tag{D-15}$$

The temperature and pressure of the compartments are then calculated by CLASIX.

The integrated heat removed by the spray is calculated directly from a heat balance at any particular instant in time. The following method of calculating the integrated spray heat removal can apply when either the spray subroutine or the finite difference method subroutine is used with CLASIX.

$$\int \dot{Q}_S dT = Q_{SS} + \int \dot{Q}_A dT - Q_T \qquad \text{(D-16)}$$

Q_{SS} = initial heat of the system

$\int \dot{Q}_A dT$ = integrated heat added to the system

Q_T = total heat of the system

$\int \dot{Q}_S dT$ = integrated heat removed by the spray

Q_{SS}, which is the initial heat of the system, is found at the start of the transient. The $\int \dot{Q}_A dT$ term is the integrated heat added to the system and is calculated using the ramp function of heat addition. Q_T is the total heat of the system at a given time found in the CLASIX results. $\int \dot{Q}_S dT$ is the integrated heat removed by the spray at a particular time.

RESULTS

The containment temperature and pressure responses calculated by CLASIX using the spray subroutine with a separate time domain and the conventional finite difference method subroutine are given in Figures D-1 and D-2. As expected, the CLASIX results using the spray subroutine predict higher temperatures and pressures because the CLASIX spray subroutine removes less heat than the finite difference method subroutine. Since the same ramp function of heat addition was used with both subroutines, the shape of the containment pressure and temperature response plots agree closely.

The containment temperature response, Figure D-1, shows the CLASIX results using both subroutines reaching peak values almost simultaneously at [ ]* seconds. The results using the CLASIX spray subroutine show a peak temperature of [ ]*°F while the the finite difference method subroutine shows a peak temperature of [ ]*°F. As the two transients continue the temperatures decrease and approach [ ]*°F with the finite difference method subroutine approaching this value sooner. *a,c *a,c *a,c *a,c

The containment pressure response, Figure D-2, is similar to the containment temperature response. The peak values are [ ]* psia for the CLASIX spray subroutine and [ ]* psia for the finite difference method subroutine. These peak values occur at [ ]* seconds after the start of the transient. As the two transients continue, the pressures decrease and approach [ ]* psia with the finite difference method subroutine approaching this value sooner. *a,c *a,c *a,c *a,c

The difference between the integrated spray heat removed using the CLASIX spray subroutine and the finite difference method subroutine is found in Figure D-3. As anticipated, the difference is greater in the region where there is heat addition. The maximum difference occurs at [ ] a,c seconds with the finite difference method subroutine removing [ ] a,c Btu more heat with the spray than the CLASIX spray subroutine. As the transient progresses, this difference decreases and approaches a zero value.

CONCLUSION

The comparison of the results using the CLASIX spray subroutine and the finite difference method subroutine show excellent agreement with the CLASIX subroutine always predicting conservatively high containment pressure and temperature responses. This was anticipated because the CLASIX subroutine removes less heat than the finite difference method subroutine. Therefore, the CLASIX calculations of the containment pressures and temperatures using the spray subroutine are valid and conservative.

TABLE D-1

CLASIX PARAMETERS

Volume of Compartment:	1,000,000 Ft^3
Initial Temperature of Compartment:	$100^{\circ}F$
Initial Nitrogen Partial Pressure:	11.61 PSIA
Initial Oxygen Partial Pressure:	3.07 PSIA
Initial Steam Partial Pressure:	0.30 PSIA
Time Step:	0.01 Seconds

TABLE D-2

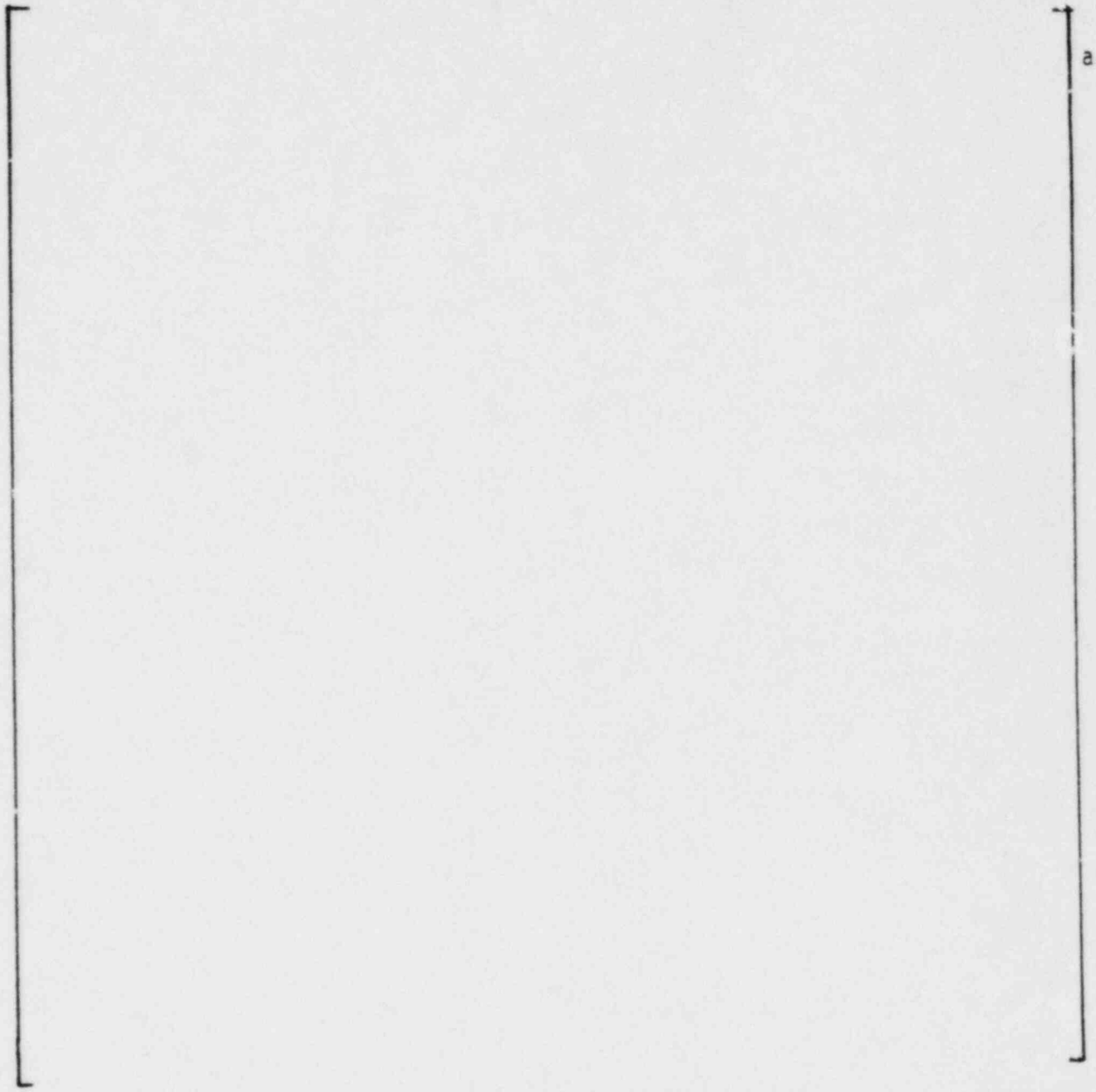
HEAT ADDITION TABLE

TIME (SECONDS)	HEAT RATE (BTU/SEC)
0.0	0.01
50.0	1,000,000
100.0	0.01

TABLE D-3

SPRAY PARAMETERS

Initial Spray Flow Rate:	1000. LB/SEC
Initial Spray Temperature:	$100^{\circ}F$
Initial Drop Diameter:	0.0276 Inches
Drop Fall Time:	10.0 Seconds
Drop Film Coefficient:	20.0 $BTU/HR\text{-}Ft^2\text{-}^{\circ}F$
Drop Density:	62.4 LB/Ft^3
Drop Specific Heat:	1.0 $BTU/LB\ ^{\circ}F$



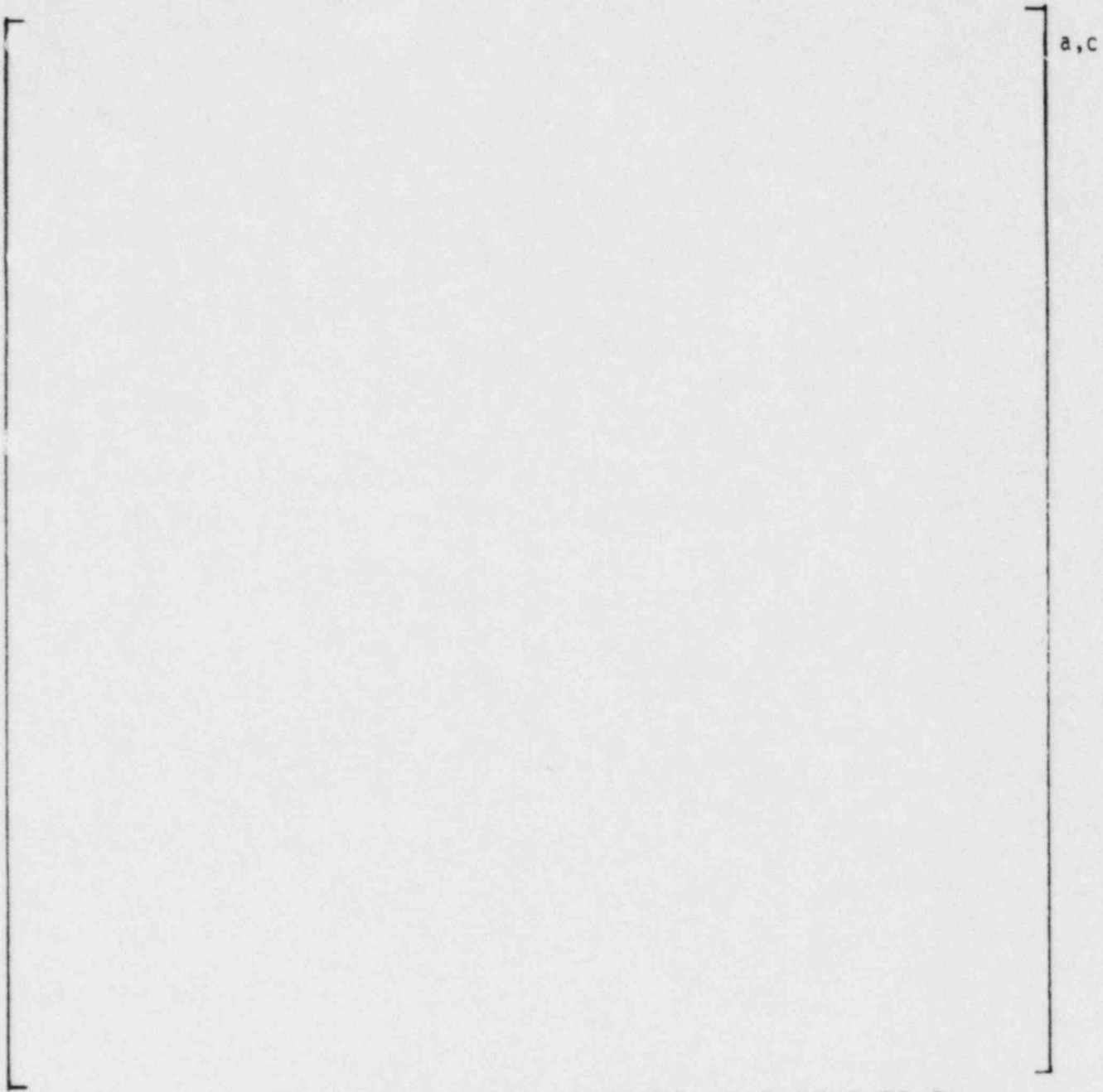
CLASIX SPRAY/FINITE DIFFERENCE METHOD
TEMPERATURE COMPARISON

FIGURE D-1

[ ]a,c

CLASIX SPRAY/FINITE DIFFERENCE METHOD
PRESSURE COMPARISON

FIGURE D-2



DIFFERENCE OF INTEGRATED HEAT REMOVED BY SPRAY USING THE CLASIX SPRAY AND FINITE DIFFERENCE METHOD

FIGURE D-3