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**BEACON/MOD2A:
A COMPUTER PROGRAM FOR SUBCOMPARTMENT ANALYSIS
OF
NUCLEAR REACTOR CONTAINMENT --
A USER'S MANUAL**

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March 1979

EG&G Idaho, Inc.

IDAHO NATIONAL ENGINEERING LABORATORY

DEPARTMENT OF ENERGY

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INTERIM REPORT

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BEACON/MOD2A:

A COMPUTER PROGRAM FOR SUBCOMPARTMENT ANALYSIS OF
NUCLEAR REACTOR CONTAINMENT --

A USER'S MANUAL

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ABSTRACT

The BEACON code is a Best Estimate Advanced Containment code which is being developed by EG&G, Idaho, Inc., at the Idaho National Engineering Laboratory. The program is designed to perform a best estimate analysis of the flow of a mixture of air, water, and steam in a nuclear reactor containment system under loss-of-coolant accident conditions. The code can simulate two-component, two-phase fluid flow in complex geometries using a combination of two-dimensional, one-dimensional, and lumped-parameter representations for the various parts of the system. The current version of BEACON, which is designated BEACON/MOD2A, contains mass and heat transfer models for wall film and for wall conduction. It is suitable for the evaluation of short term transients in PWR dry containment systems. This manual describes the models employed in BEACON/MOD2A and specifies code implementation requirements. It provides application information for input data preparation and for output data interpretation.

SUMMARY

This document is a user's manual for the BEACON/MOD2A computer code. It describes the code and provides instructions for its use. This manual contains analytical model descriptions, code input instructions, output and code programming details, examples of code application and mathematical derivations. Program structure details are also presented.

BEACON is a Best Estimate Advanced Containment analysis code used to predict environmental conditions within a PWR dry containment system, following a postulated loss-of-coolant accident. It provides lumped-parameter, one-dimensional and two-dimensional flow modeling capability for the solution of two-component two-phase fluid problems. It is a modular code containing nearly 200 subroutines and utilizing dynamic storage allocation of variables.

The basic solution procedure used in BEACON is based on the K-FIX code developed by Los Alamos Scientific Laboratory (LASL). BEACON, like K-FIX, is a two-component, two-phase fluids code which permits unequal velocities and unequal temperatures between the phases. Many models and options have been developed and added to increase the versatility of the code. The single region computing mesh scheme has been modified to permit lumped-parameter, one-dimensional, and two-dimensional coupling and interconnecting. This feature allows the modeling of complete, multi-compartment containment systems. The capability to model interior walls and obstacles within a compartment has been added. Mass, momentum, and energy sources can be introduced anywhere in the system. Interphasic heat, mass, and momentum transfer models have been added. The equation-of-state modules developed by Brookhaven National Laboratory (BNL) for real steam and water properties have been modified and extended to meet the code requirements.

Six categories of BEACON input data may be used to describe a containment problem. These input categories are basic data, Eulerian region data, lumped-parameter data, source cell data, coupling data, and heat structure data. The input information must be submitted in card image form in accordance with instructions provided in the program application section of this manual. Instructions are also included for obtaining printed output, plots, and restart tapes.

Results of seven sample problems solved with BEACON/MOD2A show that the code is useful for containment analysis. These sample problems demonstrate the use of various flow modeling techniques and the use of new heat transfer models. The code does not have BWR containment models and it would be extremely expensive to use this version for long-term transient analysis. It is recommended for the evaluation of short-term transients in PWR dry containment systems.

Information on the BEACON code structure, overlay arrangement, and dynamic storage allocation is provided. All subroutines are categorized and briefly described. Code implementation requirements and job control statements are also provided for those who must install, run, and maintain the BEACON code. Lastly, appendices present BEACON flow numerical methods and equations, user information on the BEACON postprocessing plot file program, and flow charts of major subroutines.

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I. INTRODUCTION

BEACON is an advanced, best estimate computer code designed to predict conditions within a nuclear reactor containment system during a postulated loss-of-coolant accident (LOCA). This code is currently under development by EG&G, Idaho, Inc., at the Idaho National Engineering Laboratory (INEL). The current version of the code, incorporating all of the developments to date, is designated BEACON/MOD2A and is suitable for analysis of short term transient behavior of PWR dry containment systems including heat conduction to surrounding walls.

BEACON represents an advancement over other containment system analysis codes by incorporating more sophisticated modeling features. In addition to providing lumped-parameter homogeneous flow modeling, as in present codes, BEACON provides Eulerian (one-dimensional and two-dimensional), nonhomogeneous and nonequilibrium flow modeling capabilities. These additional capabilities allow a more accurate formulation of many important containment analysis problems than is possible with other codes. Table I shows a brief comparison of the characteristics of two existing containment codes and BEACON. Previously developed containment codes have used the lumped-parameter approach wherein only a single set of average properties is used to describe the flow field in a large volume. BEACON maintains this capability and adds the ability to look at the details of a two-component, two-phase flow field in one or two dimensions under nonhomogenous, nonequilibrium conditions (unequal velocities, unequal temperature between the two phases). This allows for the analysis of problems such as the calculation of the jet impact forces of a fluid leaving a pipe break, the motion of a large pressure wave across a compartment, the variation in flow properties as air is displaced from a compartment by steam and water, the water entrainment or deentrainment by a high speed vapor flow, the flow of a flashing liquid, and many other complex nonequilibrium problems found in containment system analyses.

TABLE I

COMPARISON OF CONTAINMENT ANALYSIS CODES

<u>FEATURE</u>	<u>CONTEMPT-LT</u> ⁽¹⁾	<u>CONTEMPT4</u> ⁽²⁾	<u>BEACON/MOD2A</u>
1. Containment Applications	Dry, suppression pool	Dry, multi-compartment, ice condenser	Dry, multi-compartment
2. Compartment Model	Lumped parameter	Lumped parameter	Lumped-parameter, Eulerian mesh
3. Flow Model	Two-phase, homogeneous between phases	Two-Phase, homogeneous between phases	Two-phase, two-dimensional, unequal velocity between phases
4. Thermodynamic Model	Equilibrium between phases	Equilibrium between phases	Nonequilibrium between phases

The long range objective for BEACON is a general analysis capability for all types of containment systems and related subsystems, for both short term and long term transients. BEACON/MOD2A, with its present flow dynamics and thermodynamics modeling, and with the recently added wall film and heat conduction modeling, is suitable for short term transient analysis and PWR dry containment systems. Future versions of BEACON will contain other models including spray systems, heat exchangers, fans, ice condensers, and BWR suppression systems.

This manual presents program and model descriptions, application information, sample problems, and program structure information for the BEACON/MOD2A code. A general overview of the program features is given. Detailed model descriptions are presented, giving, where necessary, purpose and intended use, method of solution, restrictions, and available options. For the code user detailed input and output descriptions are provided. Sample problems are included to assist the code user and to illustrate the various modeling features of the code. The BEACON code is a highly modular and structured program with dynamic storage allocation features.

II. PROGRAM DESCRIPTION

The BEACON/MOD2A code is a highly flexible, versatile and user-oriented program which may be used for a wide range of containment system problem applications. The code can be used, for example, to model complete containment systems, to perform isolated or separate effects component studies, or to examine in detail complex nonhomogeneous, nonequilibrium flow behavior. The major modeling features, user conveniences, and programming features of the BEACON/MOD2A code are summarized in Table II. The general sequence of computations for the BEACON/MOD2A code is illustrated in Figure 1. At the start of program execution, all input data is read, processed, and checked for errors. Input may be in the form of cards or cards and a restart tape in the case where conditions are set from previously computed results. After initial conditions have been set and there are no input errors, control is transferred to the time advancement computations. The time advancement computations consist of calculations for heat structures, wall film, Eulerian fluid regions, lumped-parameter regions, and output. Additional calculations include the timestep calculations and the control logic for the overall time advancement of a given problem. The major computational set is the Eulerian fluid calculations which are performed for every problem and for every timestep. Within the Eulerian calculations are several modeling options which may be exercised by user input. Also optional are the heat structure, wall film, and lumped-parameter calculations. Output is obtained at periodic intervals determined by user input. When the problem transient stop time is reached, the next case is read or the program execution is terminated as applicable.

The timesteps in BEACON are generally governed by the Eulerian fluid computations which limit the maximum allowable timestep due to material velocity restrictions (Courant restricted flow). BEACON does allow larger timesteps to be taken for the heat structure and lumped-parameter calculations.

TABLE II

BEACON/MOD2A PROGRAM FEATURES

Category and Feature	Function
<u>Eulerian Region Modeling</u>	Models one- and two-dimensional regions
. Numerical Technique	Computes two-component and two-phase, nonhomogeneous and non-equilibrium flow
. Coordinate Systems	Models Cartesian, cylindrical, and spherical geometries
. Variable Mesh Spacing	Permits variable spacing between computational nodes
. Boundary Modeling	Specifies inflow, outflow, and constant-pressure boundaries, slip or no-slip rigid boundaries
. Obstacle Cells	Forms interior walls, ducts, and subcompartments
. Partial Flow Modeling	Models the effects of obstructions smaller than computational cell size
. Mass, Momentum, and Energy Sources	Models time-dependent steam, liquid, or mixture breaks, leaks, etc.
<u>Mixed-Dimensional, Multi-Region Modeling</u>	
. One-Dimensional Flow Model	Models one-dimensional pipes and ducts, allows coupling of one-dimensional models of different cross sectional flow areas
. Lumped-Parameter Models	Model regions that are much larger than Eulerian regions
. Coupling Methods	Couples Eulerian regions explicitly, couples one-dimensional regions to lumped-parameter regions explicitly

TABLE II (Cont'd)

<u>Category and Feature</u>	<u>Function</u>
<u>Wall Film and Heat Structure Modeling</u>	Models heat and mass transfer to surrounding walls and physical structures
. Wall Film	Models formation and motion of liquid film on walls
. Heat Structures	Solves one-dimensional transient conduction equation numerically
<u>Thermodynamic Models</u>	
. Interphasic Exchange Functions	Models heat, mass, and momentum transfer between phases
. Equation-of-State	Computes air, steam, and water thermodynamic properties
<u>Program User Features</u>	
. Input	Utilizes INEL INP input system; free-field, mixed format, card number identifiers
. Output	Obtains print listings and time-frame plots
. Tape Restart	Restart problem from previously computed results
. Postprocessor Plot File Program	Obtains time-history plots of BEACON results
<u>Program Design Features</u>	
. Top-Down Program Design	Structure and modularity enhances use and development of BEACON code
. Dynamic Storage Allocation	Allocates memory according to size of problem.

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Fig. 1 Sequence of computations of BEACON/MOD2A code.

The philosophy used in the BEACON code development has been to utilize applicable methods and computer subcodes available in the nuclear industry whenever possible, and to develop new methods only when other sources are not available. The basic Eulerian flow solution procedure selected for BEACON is based on the K-FIX two-dimensional, two-phase numerical method developed by the Los Alamos Scientific Laboratory^[3]. The K-FIX numerical method solves the six field equations of the two plans using a coupled, explicit-implicit Eulerian finite-difference computational procedure. The two-phases are coupled by interphasic mass, momentum, and energy exchange functions. The degree of coupling determines the general characteristics of the flow, whether homogeneous or nonhomogeneous, equilibrium or nonequilibrium.

The basic K-FIX numerical method has been extensively enhanced at the INEL to meet BEACON code requirements. Modifications were made to allow two-component gas mixtures of air and vapor. Specified flow boundaries and obstacle cell modeling have been generalized. Mass, momentum, and energy sources have been added and generalized so that they may be introduced anywhere in the system, including lumped-parameter regions. The most recent modeling improvements to the K-FIX numerical method include variable mesh spacing and partial flow cell modeling.

Other models and options have been developed at INEL to meet containment system modeling requirements. A major feature of BEACON is the mixed-dimensional, multi-region coupling, a network solution method for solving interconnected one-dimensional, two-dimensional, and lumped-parameter regions. This capability allows the modeling of complete, multicompartment containment systems. The BEACON lumped-parameter model is compatible with the nonhomogeneous, nonequilibrium fluid computations of the Eulerian regions. The coupling of one-dimensional regions of different cross sectional flow areas is also permitted.

BEACON/MOD2A can also account for heat and mass transfer to surrounding walls. The wall film and heat structure modeling considers the calculation of heat transfer to or from the boundary structures, the resulting condensation or evaporation of fluid, the formation and motion of a liquid film on the wall and internal structures, the addition of liquid to the film from impact deentrainment, and the wall temperature distributions. Heat conduction to walls may optionally be computed without wall film modeling. In line with the philosophy of using available methods, the wall heat conduction subcode used in the CONTEMPT codes is also used in BEACON.

Thermodynamic modeling in BEACON includes models for the interphasic exchange functions, an optional equation-of-state based on real steam and water properties, and heat and mass correlations for wall film and heat structure surfaces. Changes have also been made in BEACON/MOD2A to improve the original K-FIX perfect gas and incompressible liquid equation-of-state models.

BEACON also utilizes the INEL INP input processing system which facilitates data input for the user. Units conversion to SI units is also provided, and subsequent computer calculations and output are in SI units. Output consists of print listings and time-frame plots. Other user-convenient features of BEACON include tape restart and postprocessed time-history plots.

This last area of discussion concerns the design and programming aspects of the BEACON code. In developing BEACON, the principles of top-down program design are applied. As a result, the BEACON code is highly modular, structured, and well organized. These attributes facilitate code development and contribute to a better understanding of the code logic and algorithms. BEACON also features dynamic storage allocation, in which memory is allocated at program execution time to meet the data storage requirements of the problem being executed. This mode of operation results in a significant computer cost savings.

III. MODEL DESCRIPTIONS

This section provides a description of the modeling features available in the BEACON/MOD2A code. They are categorized into the BEACON/MOD2A code. They are categorized into four major groups: (a) Eulerian region modeling, (b) Mixed-dimensional, multi-region modeling, (c) Wall film and heat structure modeling, and (d) Thermodynamic modeling.

1. EULERIAN REGION MODELING

The Eulerian region modeling is the basic mode of modeling rooms, ducts, and other fluid regions of interest in the BEACON code. The geometric configuration of the region to be modeled is specified in one- or two-dimensional nodalization, depending on the general nature of the flow or the degree of flow resolution desired. The flow transient is solved by a finite-difference numerical technique which allows the modeling of two-phase and two-component, nonhomogeneous and nonequilibrium flow. Other modeling features associated with the Eulerian region are described in the following sections.

1.1 Numerical Technique

The BEACON numerical technique is based on the K-FIX method⁽³⁾. Each phase (gas and liquid) is described by its own density, velocity, and temperature as determined by separate sets of mass, momentum, and energy equations. The two phases are coupled by exchange parameters which model the exchange of mass, momentum, and energy between the two phases. The two sets of field equations are solved with a Eulerian finite difference technique, basically an extension of the implicit multifield (IMF) method developed in the KACHINA code^(4,5). The K-FIX numerical technique differs from that of KACHINA in that phase transitions and interphasic heat transfer are treated implicitly in the pressure iteration. The implicit solution

is accomplished iteratively without linearization and allows both phases to be compressible. The coupling between the two phases can be very loose as occurs with separated flow or very tight as with finely dispersed flow. The K-FIX numerical technique also allows computations for single phase gas flow without special treatment. The version of K-FIX used in BEACON can handle air as a second vapor component.

Appendix A summarizes the K-FIX numerical technique and presents the equations as they appear in the BEACON code, modified for the modeling capabilities of BEACON.

1.2 Coordinate Systems

The Eulerian flow field computations may be performed in any of the following coordinate systems depicted in Figure 2.

- (a) Cartesian - Calculations are two-dimensional in the r and z directions. A depth dimension is added to calculate actual volume and changes in cross sectional flow area in the coupling of Cartesian regions. However, no velocities are calculated in the depth direction.
- (b) Cylindrical - Calculations are two-dimensional in the r and z directions with symmetry about the z -axis. An offset from the axis of symmetry is also provided to model annular regions and coupled axisymmetric regions.
- (c) Spherical - Calculations are one-dimensional in the r direction with symmetry in the ϕ and θ directions.

In the Cartesian coordinate system, the gravity vector may be oriented in any direction in the two-dimensional computing plane. In

- Cartesian

- Cylindrical or axisymmetric

- Spherical

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Fig. 2 BEACON geometry modeling options.

cylindrical coordinates, the gravity vector must be parallel to the axis of symmetry and is defaulted as such. For spherical coordinates, the gravity vector is nullified.

The computing mesh and indexing notation used in the K-FIX numerical technique and applicable to the preceding coordinate systems is shown in Figure 3. The axis of symmetry is in the ordinate direction. The computing mesh is surrounded by a set of exterior cells which are not part of the defined region but are used to simplify boundary computations.

1.3 Variable Mesh Spacing

The Eulerian computational equations have been modified to provide for the variable nodalization of a mesh as illustrated in Figure 4. The spatial dimensions of each cell are stored in row-wide and column-wide arrays. Thus, each mesh may have its own set of cell dimensions. For constant mesh spacing, these arrays are automatically defined.

One restriction on the variability of these dimensions is that neither dimension should vary between adjacent cells by more than a factor of about 2. This restriction is imposed to preserve mathematical correctness and computational stability. A second restriction, which is automatically controlled by the nature of the input for this option, is that the centers of adjacent cells must align either in the radial (abscissa) or the vertical (ordinate) direction. Boundary cell dimensions are set equal to that of the immediately adjacent interior cells. A final restriction is that no mesh, whether variable or constant cell dimension, may have more than 50 interior cells in either the abscissa or the ordinate direction.

Fig. 3 Computing mesh and indexing notation.

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Fig. 4 Variable cell dimension in a computing mesh.

1.4 Boundary Modeling

Several types of boundary conditions may be specified for each computing mesh as illustrated in Figure 5:

- (1) No-slip rigid walls
- (2) Free-slip rigid walls
- (3) Prescribed inflow
- (4) Continuitive outflow
- (5) Constant pressure

The boundary conditions are implemented by the use of fictitious exterior cells which surround the computing mesh. The rigid walls are nonconducting and can be specified along any boundary of the mesh. A free-slip, rigid wall can serve as a reflective plane of symmetry. For free-slip walls, the tangential velocities in the exterior cells are a direct reflection of the interior cell velocities. For no-slip walls, the tangential velocities in the exterior cell are also set by reflections but with a change in sign so that velocities computed at the wall surface are zero.

The prescribed inflow boundary specifies a constant flux of mass, momentum, and internal energy across a boundary opening. The inflow may be any mixture of liquid, steam, and air. Both radial and axial inflow velocities may be specified, allowing the inflow to be diagonally oriented if desired. Any number of prescribed inflow openings can be specified along the left and bottom boundaries of the mesh.

Fig. 5 Boundary modeling options.

The continuative outflow boundary allows fluid to leave the system at a computed rate. The continuative outflow boundary may become a continuative inflow boundary if the velocity field at the boundary reverses because of computational results. Any number of continuative outflow openings may be specified along the right and top boundaries of the mesh.

The constant pressure boundary holds the state conditions in the exterior boundary cell constant throughout the transient computations. The velocity and flux computations will vary according to the pressure differential and other cell quantity differences that develop across the boundary opening. Any number of constant pressure boundary openings may be specified along the right and top boundaries of the mesh. Each opening may have its own state conditions specified.

As noted, inflow boundaries are restricted to the left and bottom boundaries at the mesh, and outflow and constant pressure boundaries are restricted to the right and top boundaries of the mesh.

1.5 Obstacle Cells

The obstacle cell feature is provided to permit the modeling of a wall or other solid obstruction in the interior of a mesh as shown in Figure 6. An obstacle cell is simply a cell in the mesh that will not permit fluid to cross any of its boundaries. Thus, an interior wall can be represented by a row of obstacle cells, and any obstruction by a cluster of obstacle cells. Obstacle cells are not restricted to any specific location and may be placed anywhere in the computing mesh. The obstacle region formed must be at least two cells across in any direction and the boundary conditions may be either free-slip or no-slip. Obstacle regions located adjacent to a mesh wall need to be only one cell deep.

Fig. 6 Obstacle cell modeling.

Specified flow boundaries may also be prescribed for interior boundaries formed by obstacle cells. The preceding restrictions on the orientation of flow boundaries still apply, however.

1.6 Partial Flow Modeling

In many modeling situations, obstacle cells cannot be used effectively to model obstructions in a room because of the smallness of the obstruction or because of the limitation on obstacle regions having to be at least two cells wide. As shown in Figure 7, the partial flow modeling allows the user to model the flow effects of an obstruction that is smaller in size (volume) than a computational cell. This features allows the user to use a coarse nodalization for a region but at the same time factor in the effects of small obstructions.

The presence of an obstruction within a computational cell is modeled by including two different effects:

- (1) a reduction in volume and flow area of the cell
- (2) a resistance to flow.

The first effect utilizes the flow area and volume multipliers introduced into the numerical equations for unequal flow area coupling modeling as discussed in Appendix A. The reduced cell volume is user input. Both the flow area and volume are reduced by the same proportion. That is, a 50 percent reduction in cell volume also reduces the flow area by 50 percent. The reduction in flow area is the same in all directions.

The second effect, flow resistance, is modeled by including additional force terms to the momentum equations. Flow resistances in the radial and axial directions are computed separately so that

Fig. 7 Partial flow modeling.

non-isotropic force effects may be modeled. The radial and axial flow resistances are user input in coefficient form. The flow resistance is assumed to be proportional to the flow kinetic energy, and is treated independently of the cell volume reduction. These two separately treated effects allow the user to model any type of partial flow obstruction, ranging from smooth reduced passageways to packed porous media.

1.7 Mass, Momentum, and Energy Source

Time-dependent, explicit source terms have been added to the computational equations for both the gas and liquid phases. These sources allow the modeling of mass, momentum, and energy addition (or deletion) to any given cell in fluid computing mesh. The source capability can be used to model steam, liquid, or mixture line breaks into a containment as well as user controlled simulation of cooling sprays, fans, pumps, or similar features.

As many as 20 separate sources and 20 time-dependent source tables may be modeled. Each source may refer to a common table or to its own table. Time-offset and source multipliers are also provided for scaling and parametric studies. Each source is a single substance, liquid, steam, or air. Mixtures are formed by overlaying more than one source.

2. MIXED DIMENSIONAL, MULTIREGIONAL MODELING

The BEACON code provides additional capability in modeling multicompartment containment systems by modeling regions or volumes of different size and geometry. For example, two-dimensional regions may be used to describe regions requiring detailed flow resolution, one-dimensional regions may be used to model pipes and ducts, and lumped-parameter volumes may be used to model compartments of large volume having negligible flow dynamics. The major modeling features of the mixed-dimensional, multi-region capability are discussed in this section.

2.1 One-Dimensional Flow Model

Pipes and passageways in a containment system may be modeled as one-dimensional flow. The one-dimensional flow modeling is obtained by forming a one-dimensional flow channel with obstacle cells in a two-dimensional computing mesh, or by specifying a one-dimensional mesh and coupling this region to either a two-dimensional, one-dimensional or lumped-parameter region. The Eulerian flow field computations automatically nullify any cross flow or gradient terms by appropriate indexing and reflecting operations at rigid boundaries.

An additional capability associated with one-dimensional flow is the coupling of one-dimensional regions of different cross-sectional flow area. This capability is referred to unequal area coupling (UAC) and is part of the mixed-dimensional, multiregion coupling capability described in Section 2.3.

The unequal area coupling capability is obtained by modifying the basic fluid computation equations to include multipliers which reflect the change in flow area and control volume across an unequal area coupling boundary. These multipliers are applied in a manner so as to decrease or increase a convective flux quantity across the control volume boundary of the computational cell. Appendix A presents the definition of the unequal area coupling multipliers used and their computation in axisymmetric and Cartesian coordinates. The basic K-FIX fluid computation equations as modified for unequal area coupling, are also presented in Appendix A.

2.2 Lumped Parameter Model

The lumped parameter model was developed to model rooms whose volumes are much larger than the regions modeled by two-dimensional or one-dimensional flow. Interior velocities are assumed negligible and state conditions are characterized by a single set of stagnation

properties. Homogeneous conditions are assumed throughout the region. Separate mass and energy equations are retained for the vapor and liquid fields. These equations are also given in Appendix A. As in the Eulerian fluid computations, the vapor and liquid fields are coupled by mass and heat transfer exchange functions. The exchange function algorithms are the same as those used in the Eulerian computations.

Flow into and out of a lumped parameter region is restricted to one-dimensional flow. The one-dimensional flow calculations are part of the Eulerian fluid computations. Any number of one-dimensional regions up to a maximum of 20 may be connected to a lumped parameter region. Junction form losses are not accounted for at present.

The manner in which the lumped parameter calculations are integrated with the Eulerian fluid computations are more fully discussed in Section 2.3.

2.3 Coupling Methods

The capability of mixed dimensional, multi-region coupling is provided by the BEACON code. This section describes the details of Eulerian region coupling and lumped-parameter region coupling and explains the code control logic.

2.3.1 Eulerian Region Coupling Technique. All interconnected Eulerian regions are solved implicitly for each time advancement. The coupling technique for Eulerian regions is such that the interface between each coupled Eulerian region is transparent to the transient fluid dynamic computations. Eulerian regions that are connected together but separated from other Eulerian regions by lumped-parameter regions are treated as a single Eulerian computing region which can be advanced independently of the other Eulerian regions. For example, in Figure 8 there are three such Eulerian computing regions, one of which

consists of a single, one-dimensional region. In general, each Eulerian region or group of Eulerian regions separated by lumped-parameter regions may be treated as a single Eulerian computing region.

The computational procedure is to extend the K-FIX numerical computations to encompass all Eulerian regions that are connected to one another, and to treat these interconnected regions as one Eulerian computing region. Thus, each region is selected in sequential fashion and swept to perform a specific cell computation before advancing to the next computational step. For the implicit part of the calculations, each iteration pass is performed over the entire set of interconnected regions. The implicit solution is not considered converged unless the computational cells are converged in all computing regions comprising the set.

The numerical solution of a multi-region problem setup is basically equivalent to that of a single-mesh problem setup, wherein the various regions and compartments are formed by using obstacle cells. Slight numerical differences will exist between the results obtained with a multimesh problem setup and its equivalent single-mesh problem setup. This difference arises from the K-FIX relaxation method in which the latest numerical value of a computed cell variable is used as soon as it becomes available, resulting in the mixed usage of old and new iterative variable values. Consequently, the numerical solution becomes dependent upon the order or sequence in which each region is computed. The numerical difference may be made insignificant by using sufficiently small convergence criteria. Typically, the input convergence criteria on liquid and vapor continuity (see input description of Card 200) should be 0.0001 or less.

The Eulerian region coupling technique also permits the coupling of one-dimensional regions having different cross-sectional flow areas as depicted in Figure 8. This feature is accomplished by means of

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Fig. 8 Mixed-dimensional, multi-region problem example.

flow area and control volume multipliers inserted in the basic fluid computation equations. Details of the code modifications for this unequal area coupling are presented in Appendix A.

Computations at a given cell will generally require variable values from adjacently located cells. For multi-region problems, some means must be provided for accessing all data that are located in different Eulerian regions but which are computationally adjacent to one another. This means is provided for by storing the locations of computationally adjacent cells in the exterior cells of opposite meshes as shown in Figure 9. This coupling link is established at input time. During the transient computation, access to computationally adjacent cells is made through subroutine IJLINK. IJLINK establishes the other cell indices that may be required during each phase of computations, and also computes the flow area and control volume multipliers that are used for unequal flow area coupling.

The location and partitioning of coupled Eulerian regions is generalized. There are no restrictions other than the coupling must be on a cell-to-cell basis. All BEACON modeling capabilities have been extended to coupled Eulerian regions. These include the coupling of regions in axisymmetric or Cartesian coordinates (but not a mixture of both), obstacle or partial flow cells, source cells, and specified boundary conditions, heat structures, and film modeling.

Plot output for coupled problems are scaled and normalized. Velocity and contour plots of all Eulerian regions are scaled and normalized to the same base for proper visualization and interpretation of results.

2.3.2 Lumped-Parameter Coupling Technique. Lumped-parameter regions are coupled explicitly to one-dimensional Eulerian regions as shown in Figure 10. A larger timestep interval is generally taken in

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Fig. 9 Eulerian region coupling technique.

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Fig. 10 Lumped parameter coupling technique.

advancing the lumped-parameter regions than that used in the Eulerian regions. During a time advancement of the Eulerian regions, the boundary conditions at a lumped parameter interface in the one-dimensional region are held invariant. When a lumped-parameter region is advanced in time, these boundary conditions are then adjusted to reflect the net changes in the lumped-parameter state conditions.

Certain Eulerian-type computations are required in the boundary or exterior cell of a lumped-parameter interface. These computations include, for example, the computation of vapor-liquid momentum exchange function K and the computation of momentum fluxes of the vapor and liquid fields across the boundary. For the momentum flux computations, a jump is made into the exterior cell to perform these computations before they are normally performed in the interior cell. For the other Eulerian-type computations, a separate entry point calculation is provided for in the appropriate computational subroutine (for example, subroutine KDRAGS).

The lumped-parameter coupling scheme provides compatibility with the Eulerian two-fluid transient computations. The modeling and coupling of lumped-parameter regions are consistent with the two-phase, unequal velocity, unequal temperature flow computations of the Eulerian regions, thus allowing for nonhomogeneous, two-phase flow into and out of a lumped-parameter region and for flow reversal with inertial effects.

A maximum of 20 Eulerian regions and a maximum of 20 lumped-parameter regions are allowed per problem setup. The limit is due to array sizes in the code. Lumped-parameter regions are coupled to one-dimensional regions only. The coupling is explicit, allowing a larger timestep interval to be taken in advancing the lumped-parameter regions. Any number of one-dimensional regions may be connected to a given lumped-parameter region within array limits.

2.3.3 Timestep Advancement and Output Control Logic. The control logic for advancing coupled Eulerian and lumped parameter regions is shown in Figure 11. Basically, control of the time advancement and output is in the following manner:

- (1) A time level control value (TLC) is established which is either the time for output (TOUT) or the time to which lumped-parameter regions are advanced (TZD).
- (2) Each interconnected Eulerian computing region is advanced in time to the TLC time level value. The timestep interval for the Eulerian computations may be either a computed value (based, for example, on Courant conditions) or a user-specified value.
- (3) Interconnected Eulerian computing regions that are separated explicitly by lumped-parameter regions may be advanced independently. Thus, if Eulerian computing Region 1 has low flow dynamics or larger cell dimensions as compared to Eulerian computing Regions 2 or 3, it is allowed to take larger timestep intervals in advancing to the TLC time level. The advancement of the problem setup of Figure 11 is illustrated in Figure 12.
- (4) After all Eulerian regions have been advanced, the lumped-parameter regions are advanced to the TLC time level. The timestep interval used in advancing lumped-parameter regions is a user-specified value, generally larger than the timestep intervals taken in advancing the Eulerian regions. After the lumped-parameter regions have been advanced, the boundary cell conditions in the one-dimensional regions are then adjusted accordingly for the net changes in state conditions of the lumped-parameter regions.

Fig. 11 Timestep advancement control logic.

Fig. 12 Timestep advancement illustration of multi-region problems.

- (5) The time advancement procedure is repeated until the problem finish time is reached or computing time is exceeded. Plot or print output or both for all regions are obtained whenever $TLC = TOUT$.

3. WALL FILM AND HEAT STRUCTURE MODELING

The code is designed to account for heat transfer effects due to wall film and due to structures in contact with fluid regions. These models are described in the following sections.

3.1 Wall Film

The wall film model is used to track liquid films which may accumulate on walls and other surfaces due to the deentrainment of liquid water and the condensation of water vapor from the free-stream flow within a fluid cell. Any surface modeled by BEACON as an obstacle cell or boundary cell and which is exposed to an adjacent fluid cell can have film accumulation and tracking. In addition, films may accumulate on the front and back walls of the fluid mesh as shown in Figure 13. The BEACON film model determines the film velocity in each film node, performs a mass and energy balance on each node, and then modifies the fluid cell inventories to account for the fluid to film interaction. The following sections provide details of the calculational methods, the applicable correlations and the fluid to film calculation coupling.

3.1.1 Description of Film Models. The wall film tracking model accounts for wall to cell interactions in the case when the film option is turned on and a film is present. This model includes the effects of heat transfer between the cell and the film, evaporation and entrainment of the film liquid into the cell, and condensation of cell vapor and deentrainment of cell liquid onto the wall. The film calculations are performed in three mesh sweeps.

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Fig. 13 BEACON film accumulation model.

The first mesh sweep calculates all of the film parameters which are independent of the films in adjacent cells. This step includes the film node to cell interaction rates (heat transfer, condensation, evaporation, entrainment and deentrainment) and the film velocity. This step requires determining the film surface orientation and scanning the adjacent fluid cell properties.

The second sweep performs the mass and energy balance on each film node. The convection terms between film nodes are calculated and are used, along with the information obtained in the first sweep, to determine updated values for the film mass and temperature.

The third sweep is used to simply replace the old film variables with the updated values.

For each film node, two parameters (mass and temperature) are retained during an entire time step and are saved as part of the fluid cell data. All other pertinent data are also saved. After the film calculations have been performed another mesh sweep is performed to update the fluid cell properties.

For the film coupling model, each BEACON wall film node is identified with a KFIX cell and is assumed to have constant properties within the node. There are two distinct types of films in BEACON: the fluid cell film (2-D) and the boundary or obstacle cell film (1-D).

The fluid cell or 2-D films are associated with the front and back walls of the BEACON mesh and have both r - and z - direction velocity components. Therefore, the 2-D film may flow across all four edges (right, left, top, and bottom) of the fluid cell.

The 1-D films are associated with boundary or obstacle surfaces which are exposed to fluid regions. The velocity component is one-dimensional (in the x or y direction) and parallel to the

surface. Therefore, the film may only flow to adjacent 1-D film cells. Film may not flow from a boundary or obstacle surface to a 2-D surface since, consistent with the two-dimensional nature of BEACON, the velocity component in that direction is zero. However, film may flow from a 2-D film surface to a 1-D film surface.

The film nodes are coupled in a general manner such that the film liquid can flow over or around any combination of obstacle or boundary cells in a BEACON problem geometry. Provisions are also included for intermesh coupling of both types of films for multimesh problems.

Flow of film between the film nodes and special BEACON boundary cells are being handled as follows:

- (a) Outflow boundary - film may flow out of the mesh, but may not reverse.
- (b) Inflow boundary - film which flows into an inflow boundary cell is assumed to be entrained into the incoming flow and is added to the adjacent fluid cell. No film flow reversal is allowed.
- (c) Constant pressure - film may flow out of the mesh, but may not reverse.
- (d) Lumped parameter region (LPR) coupling cell - film may flow into an LPR coupling cell and is added to the lumped parameter region inventory. Reverse flow is not allowed.

The film velocity model assumes the existence a fully developed steady-state velocity profile. This fact implies that the film inertial forces are small compared to the shear forces in the film (that is, the film is thin). The assumption is also made that the film conditions are constant within a given cell. The film velocity

model parameters are shown in Figure 14. The preceding assumptions, and constant water properties, are used for a mass balance on the differential element, dy , which gives,

$$\frac{\partial V}{\partial x} = 0, \quad (1)$$

where V is the fluid velocity. The momentum balance gives

$$\frac{\partial \dot{m}V}{\partial x} \Delta x = - \frac{dP}{dx} \Delta x \Delta z \, dy + \rho g \, \Delta x \Delta z \, dy + \frac{d\tau}{dy} \Delta x \Delta z \, dy, \quad (2)$$

where

ρ = film density

P = bulk cell pressure

$\dot{m}$ = mass flow rate

τ = shear stress

g = gravitational acceleration

Using Equation 1, this becomes

$$\frac{d\tau}{dy} = \frac{dP}{dx} - \rho g. \quad (3)$$

Using a shear stress definition of

$$\tau = \mu \frac{dV}{dy}, \quad (4)$$

where μ is the film fluid viscosity, Equation (3) becomes

$$\frac{d^2V}{dy^2} = \frac{1}{\mu} \frac{dP}{dx} - \frac{g}{\mu}. \quad (5)$$

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Fig. 14 BEACON film velocity model parameters.

This is integrated to determine the local film velocity

$$V = -\frac{\alpha}{2} y^2 + C_1 y + C_2, \quad (6)$$

where C_1 and C_2 are constants of integration and

$$\alpha = -\frac{1}{\mu} \frac{dP}{dx} + \frac{\rho g}{\mu}. \quad (7)$$

At the wall surface ($y = 0$), a no-slip condition is assumed to exist ($V = 0$). Substitution of these conditions into Equation (6) shows that C_2 is zero.

For the other boundary condition, momentum balance at the film surface gives:

$$\Delta x \Delta z (G_{en} + G_{ev}) V_\delta - \Delta x \Delta z G_d V_l - \Delta x \Delta z G_c V_g = F_D - \mu \left(\frac{dV}{dy} \right)_\delta \Delta x \Delta z, \quad (8)$$

where

G_{en} = entrainment mass flux

G_{ev} = evaporation mass flux

G_d = deentrainment mass flux

G_c = condensation mass flux

V_δ = film surface velocity

V_l = free-stream liquid velocity

V_g = free-stream vapor velocity

F_D = interface drag force.

Friction coefficient is defined

$$F_D = \pm \frac{\rho f}{2} (V_\infty - V_\delta)^2 \Delta x \Delta z \quad (9)$$

where

f = friction coefficient

V_∞ = void fraction weighted free stream velocity.

The sign of Equation (9) is determined as

$$\text{Positive if } V_\infty > V_\delta \quad (10)$$

$$\text{Negative if } V_\delta < V_\infty$$

Using (9), Equation (8) becomes,

$$\begin{aligned} & (G_{en} + G_{ev}) V_\delta - G_d V_\ell - G_c V_g \\ & = \pm \frac{\rho f}{2} (V_\infty^2 + V_\delta^2 - 2V_\infty V_\delta) - \mu \left(\frac{dV}{dy} \right)_\delta \end{aligned} \quad (11)$$

Solving for V gives

$$\begin{aligned} V_\delta &= (V_\infty + A) - \sqrt{(V_\infty + A)^2 - (V_\infty^2 + B)} \quad , V_\delta < V_\infty \\ \text{or} \quad V_\delta &= (V_\infty - A) + \sqrt{(V_\infty - A)^2 - (V_\infty^2 - B)} \quad , V_\delta > V_\infty \end{aligned} \quad (12)$$

where

$$A = \frac{G_{en} + G_{ev}}{\rho f} + \frac{\mu}{\rho f \delta}$$

$$B = \frac{2 (G_d V_\ell + G_c V_g)}{\rho f} + \frac{\mu \alpha \delta}{\rho f}$$

Use of the binomial expansion to evaluate the square roots in Equation (12) is recommended when $|V_\infty|/A \ll 1$ and $|B|/A \ll 1$. Neglecting second order terms in the expansion results in,

$$V_\delta = \frac{V_\infty^2 + B}{2(V_\infty + A)} \quad , \quad V_\delta < V_\infty$$

or

$$V_\delta = \frac{V_\infty^2 - B}{2(V_\infty - A)} \quad , \quad V_\delta > V_\infty$$
(13)

The constant of integrations, C_1 , in Equation (6) is therefore calculated in terms of V_δ as

$$C_1 = \frac{V_\delta}{\delta} + \frac{\alpha \delta}{2} .$$
(14)

The average velocity of the film is

$$\bar{V} = \frac{\int_0^\delta V \, dy}{\delta} .$$
(15)

Equation (6) is used to show,

$$\bar{V} = \frac{1}{\delta} \int_0^\delta \left(-\frac{\alpha}{2} y^2 + C_1 y \right) dy$$
(16)

or

$$\bar{V} = \delta - \frac{\alpha \delta}{6} + \frac{C_1}{2}$$
(17)

Equation (14), is substituted to give

$$\bar{V} = \frac{V_\delta}{2} + \frac{\alpha \delta^2}{12} .$$
(18)

This expression is evaluated using Equation (13) or (12) for V_δ .

When the film thickness approaches zero, the last term of Equation (18) can be neglected giving,

$$\bar{V} = \frac{V\delta}{2} \quad (19)$$

The average film velocity is used to calculate the node-centered, average velocity of a film node. The average velocity of the film at a node boundary is determined as the average of the node-centered velocities of the adjacent film nodes.

At each timestep, mass and energy balances are performed on each film node to update the film temperature and mass (see Figure 15). The mass balance on the node is

$$\frac{dm}{dt} = (G_d + G_c + G_{en} + G_{ev}) \Delta x \Delta y - \sum \dot{m}_o, \quad (20)$$

where

m = mass in the film

$\dot{m}_o$ = convective mass flow rate out of the node.

The energy balance is,

$$\frac{dE}{dt} = (G_d h_d + G_c h_c - G_{en} h_{en} - G_{ev} h_{ev} + q_i - q_o) \Delta x \Delta z - \sum \dot{m}_o h_o, \quad (21)$$

where

h_d = deentrainment enthalpy

h_c = condensation enthalpy

h_{en} = entrainment enthalpy

Fig. 15 BEACON film mass/energy balance model.

h_{ev} = evaporation enthalpy

h_o = convection enthalpy

q_i = heat flux from the wall

q_o = heat flux to the fluid cell.

The surface mass fluxes and heat transfer are determined from film surface conditions and bulk cell conditions. The wall heat transfer is determined from the BEACON heat transfer package. The surface mass flux enthalpies are determined as follows:

- (a) Condensation enthalpy is equal to the saturated water vapor enthalpy corresponding to the film surface temperature.
- (b) Deentrainment enthalpy is equal to the bulk liquid enthalpy in the adjacent fluid cell.
- (c) Entrainment enthalpy is equal to the liquid enthalpy at the surface of the film.
- (d) Evaporation enthalpy is the same as the condensation enthalpy.

The average convection temperature is assumed to be equal to the average film temperature of the donor film node and the enthalpy is a function of this temperature and the adjacent fluid cell pressure.

Due to the explicit nature of the film calculations, instabilities can occur in the film temperature calculations where the film mass is small. Therefore, when the film thickness is less than or equal to an arbitrary value the film temperature is calculated from an energy balance at the film interface. This energy balance enables an implicit calculation of the interface temperature and yields

$$T_i = \frac{C_{p\ell} \left[273.15 G_{ev} - G_D T_{\ell\infty} - (1-\Theta) g_\ell T_{\ell\infty} \right] + \Theta (g_m + \dot{m}_c) w_{vi} (h_{fg} - 273.15 C_{p\ell}) - g_m h_{m\infty} - \frac{k_\ell}{\delta} T_w}{C_{p\ell} \left[G_{ev} - G_D - (1-\Theta) g_\ell \right] - \Theta (g_m + \dot{m}_c) (w_{ai} C_{pa} + w_{vi} C_{p\ell}) - \frac{k_\ell}{\delta}} \quad (22)$$

where

$C_{p\ell}$ = Specific heat of liquid water

C_{pa} = Specific heat of air at constant pressure

$T_{\ell\infty}$ = Temperature of free stream liquid

Θ = Free-stream void fraction

g_ℓ = Heat transfer coefficient for liquid based on enthalpy difference

g_m = Mass transfer coefficient

$\dot{m}_c$ = Net rate of evaporation or condensation per unit film area exposed to gas (positive for evaporation)

w_{vi} = Vapor mass fraction at the interface

h_{fg} = Heat of vaporization

$h_{m\infty}$ = Free stream mixture enthalpy

k_ℓ = Thermal conductivity coefficient of liquid

T_w = Wall temperature

w_{ai} = Air mass fraction at the interface

If a linear temperature profile in the film, which is true for one-dimensional, quasi-steady conditions with negligible convection, is assumed

$$T_f = \frac{T_w + T_i}{2} \quad (23)$$

When the film is not connected to a heat structure and the thickness is less than or equal to an arbitrary value, the film temperature is set equal to the ambient gas temperature.

3.1.2 Correlations. This section describes the correlations used to determine the interactions between the film surface and the fluid cell. The correlations for heat transfer from the wall are given in Section 3.2.

In the development of heat and mass transfer correlations from the film boundary to the cell, constant property, two-dimensional, quasi-steady flow assumptions have been made. In the presence of mass diffusion, a Lewis number of unity is assumed to take advantage of the analogous form of the boundary layer differential equations and boundary conditions to deduce solutions to the specie equation from heat transfer solutions.

In the presence of film, the mass fraction of vapor at the interface corresponds to the saturation pressure at the interface temperature. In other words, the vapor must diffuse through air, requiring a change in vapor partial pressure toward the liquid-gas interface. Even for minute quantities of air (noncondensable gas) in the system, the process is diffusion limited.

Mass balance at the interface as shown in Figure 16 gives

$$\dot{m}_c = \frac{j_v}{1-w_{vi}} = - \frac{\rho_m D}{1-w_{vi}} \left(\frac{\partial w_v}{\partial x} \right)_i = g_m \left(\frac{w_{vi} - w_{v\infty}}{1-w_{vi}} \right) , \quad (24)$$

Fig. 16 Schematic of mesh boundary with film.

where

$\dot{m}_c$ = net rate of evaporation or condensation (positive for evaporation)

j = diffusion flux

w = mass fraction

ρ = density

D = diffusion coefficient for Fick's law

g_m = mass transfer coefficient

i = interface

m = air and vapor mixture

v = vapor.

The energy balance at the interface similarly yields,

$$\begin{aligned} \dot{e}_{i-m} &= -\frac{k_m}{c_{pm}} \frac{\partial h_m}{\partial x} \Big|_i + \dot{m}_c h_{mi} + \frac{k_m}{c_{pm}} (1-Le) \left[h_a \frac{\partial w_a}{\partial x} + h_v \frac{\partial w_v}{\partial x} \right] \Big|_i \\ &= g_h (h_{mi} - h_{m\infty}) + \dot{m}_c h_{mi} + \frac{k_m}{c_{pm}} (1-Le) \left[h_a \frac{\partial w_a}{\partial x} + h_v \frac{\partial w_v}{\partial x} \right] \Big|_i \end{aligned} \quad (25)$$

where

$\dot{e}_{i-m}$ = energy transfer rate from the interface to the gas

g_h = heat transfer coefficient based on enthalpy difference
in the presence of mass transfer

Le = Lewis number

a = air.

For $Le = 1$, which is indeed the case for air-vapor mixture, the last term in Equation (25) is zero.

With these boundary conditions at the interface, for $Le = 1$, and no natural convection, the specie and energy differential equations and their boundary conditions become exactly identical in terms of

$$\bar{w}_v = \frac{w_v - w_{v\infty}}{1 - w_{vi}}; \quad \text{and} \quad \bar{h}_m = \frac{h_m - h_{m\infty}}{\dot{e}_{i-m\infty}/\dot{m}_c - h_{mi}} \quad (26)$$

From definitions of the mass and heat transfer coefficients [Equations (24) and (25)],

$$g_m = g_h \quad (27)$$

Only one of these quantities is required. Equations (24) and (25) can then be used for the mass and energy transfer rate calculations. Solution for the specie equation in the cell is readily obtained following Kays^[6], which gives

$$\frac{g_m^*}{g_m} = \frac{g_h^*}{g_h} = \frac{1 - w_{vi}}{w_{vi} - w_{v\infty}} \ln \frac{1 - w_{v\infty}}{1 - w_{vi}}, \quad (28)$$

where

g_m^* = mass transfer coefficient as mass transfer approaches zero

g_h^* = heat transfer coefficient as mass transfer approaches zero.

The heat or mass transfer coefficient, in the limit when the mass transfer approaches zero, can be calculated using the methods described in Section 3.2. The actual heat or mass coefficient can then be calculated from Equation (28), which is valid for both laminar and turbulent flows.

When air is not present in the system, the above treatment no longer applies, as the diffusion phenomenon is nonexistent. In this case, $\dot{m}_c$ is calculated from the work of Schrage^[7],

$$\dot{m}_c = P_v \left(\frac{2}{\pi R_v T_s} \right)^{1/2} \left[\frac{P_s - P_v}{P_v} - \frac{T_s - T_v}{2 T_v} \right], \quad (29)$$

where

P = pressure

T = Temperature

s = Saturation

R = Gas constant

Equation (25) is still applicable for this case with the last term dropped. Since there is no mass diffusion, the methods of Section 3.2 for no film present can be directly used to calculate the heat transfer coefficient.

Evaporation or condensation is not possible from the film area exposed to liquid. Thus, only the heat transfer calculation needs to be made, for which, Section 3.2 methods are directly applicable.

The total energy transfer from the interface to the cell is given by

$$\dot{e}_{i-\infty} = \dot{e}_{i-m\infty} + (1-\theta) \dot{e}_{i-l\infty} \quad (30)$$

When the film is absent and the condensation takes place due to a cold wall, the energy transfer is calculated including the mass transfer. However, the condensed liquid is assumed to remain in the ambient stream. This essentially implies dropwise condensation.

The deentrainment liquid out of the ambient free-stream flow is calculated as a fraction of the liquid striking a surface. From the BEACON calculations, the cell-centered liquid velocity component perpendicular to the wall is obtained. If a liquid velocity component toward the wall exists, the deentrainment mass flux is obtained as,

$$G_D = F_D (1-\theta) \rho V_p \quad (31)$$

where

F_D = Deentrainment multiplier.

θ = Void fraction

ρ = Liquid density

V_p = Liquid velocity component toward the wall.

The multiplier, F , accounts for the change in velocity component between the cell center and the wall. That is, the liquid will be diverted to some extent by the gas phase which does not strike the wall and can only have a velocity component parallel to the wall at or near the wall. Therefore, the value of F should be between zero and one.

The entrainment of liquid from the film layer into the free-stream flow occurs as the result of two mechanisms.

The first mechanism is the result of instabilities in the film surface in the presence of a high-speed fluid flow. The onset of entrainment is defined by Ishii and Grolmes^[8] in terms of critical film Reynolds number as a function of dimensionless film interface velocity relative to the ambient stream, as shown in Figure 17. The film Reynolds number is defined by

$$Re_f = \frac{4 \rho_f U_f \delta}{\mu_f} = \frac{4 \Gamma}{\mu_f}, \quad (32)$$

where Γ is the mass flow rate per unit wetted perimeter; and ρ_f , U_f , and μ_f are the density, velocity, and viscosity respectively. The dimensionless relative film interface velocity, $\bar{U}_{ri}$, is defined as

$$\bar{U}_{ri} = \frac{\mu_f |U_\infty - U_f|}{\sigma} \left(\frac{\rho_\infty}{\rho_f} \right)^{1/2}, \quad (33)$$

where σ is the surface tension, ρ_∞ is the ambient fluid density, and U_∞ is the free stream velocity parallel to the film.

Different inception criteria are given for three different flow regimes shown in Figure 17. Minimum Reynolds number regime is defined for $Re_f \leq 160$, below which no entrainment is possible, irrespective of the gas velocity. In the transition regime, which is the region between points 1 and 2, the inception criterion is given by

$$\bar{U}_{ri,c} = \begin{cases} 167.73 (f)^{1/2} N_\mu^{0.8} Re_{f,c}^{-1/3}, & N_\mu \leq \frac{1}{15} \\ 19.22 (f)^{1/2} Re_{f,c}^{-1/3}, & N_\mu \geq \frac{1}{15} \end{cases} \quad (34)$$

Fig. 17 Critical film Reynolds Number curve with various entrainment regimes.

where the viscosity number, N_μ , is defined as

$$N_\mu = \frac{\mu_f}{\left[\rho_f \sigma \left(\frac{\sigma}{g \Delta \rho} \right)^{1/2} \right]^{1/2}}, \quad (35)$$

where g is the acceleration due to gravity, and $\Delta \rho$ is the difference in film and ambient stream densities. In the rough turbulent regime, where $Re_f \geq 1635$, the inception criterion is still given by equation (34) with $Re_{f,c} = 1635$.

On the left side of the inception boundary shown in Figure 17, there is no entrainment. On the right side of the boundary, the entrainment increases as the flow condition moves away from the critical Reynolds number curve. The entrainment rate is calculated from the maximum allowable final film thickness after entrainment, deentrainment, evaporation, and condensation; which in turn is calculated from the maximum allowable film Reynolds number. The sequence of calculations is as follows:

1. Intermediate film thickness δ^* , is calculated by accounting for deentrainment, condensation, and evaporation as

$$\delta^* = \delta + \frac{(G_d + G_c - G_{ev}) \delta t}{f}, \quad (36)$$

where δt is the time step size, and δ is the old film thickness.

2. The intermediate value of film Reynolds number, Re_f^* , is calculated corresponding to the above δ^* and equation (32). Also $\bar{U}_{ri}$ is calculated from equation (33). point A is located on Figure 17 corresponding to these conditions. If point A lies inside the inception boundary, the entrainment is zero. If the point is outside this boundary, the calculation proceeds to the next step.

3. Maximum allowable final film Reynolds number, Re_f^+ , is calculated from the expression

$$\frac{Re_f^* - Re_f^+}{Re_f^* - Re_{f,c}^+} = 1 - \exp \left[- \frac{\bar{U}_{ri} - \bar{U}_{ri,c}}{\bar{U}_{ri,c}} \right], \quad (37)$$

which implies an exponentially increasing entrainment as the point A moves away from the inception boundary. Point B shown in Figure 17 corresponds to this final condition, after accounting for deentrainment, evaporation, condensation, and entrainment.

4. Final film thickness δ^+ is calculated as

$$\delta^+ = \frac{\mu_f Re_f^+}{4 \rho_f U_f}. \quad (38)$$

5. The entrainment rate is calculated as

$$G_{en} = (G_d + G_c - G_{ev}) - \frac{\rho_f (\delta^+ - \delta)}{\delta t}. \quad (39)$$

The second mechanism which can cause the deentrainment of a liquid film is the effect of gravity on downward-facing surfaces. To evaluate this effect, a force balance is made on an ideal droplet (Figure 18), which gives the maximum stable film thickness as

$$\delta_{max} = F_{en} (1 + \cos \phi) \left(\frac{3\sigma}{g\Delta\rho} \right)^{1/2}. \quad (40)$$

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Fig. 18 Force balance on a droplet.

where F_{en} is an arbitrary multiplier. Unity F_{en} implies film interface location as shown in Figure 18. For a downward facing surface, the final film thickness is calculated as the minimum of the two values given by equations (38) and (40).

To recapitulate, the limiting stable film thickness is used to define the maximum allowable film thickness. If the thickness of the film node is less than the maximum, no deentrainment is assumed to occur. If it is greater than the maximum, the excess film is assumed to be entrained into the free stream during the timestep in order to achieve the stable film conditions.

3.1.3 Coupling of the Film Calculations to the Fluid Calculations. The wall film model (like the wall heat transfer model) is incorporated into BEACON in such a manner that the basic fluid calculations numerical scheme is not disturbed. This requires that the film calculations be handled explicitly with respect to the fluid calculations. Figure 19 shows the sequencing of the heat transfer calculations the film calculations and the fluid cell calculations.

The heat transfer rates are calculated first followed by the film calculations. At this time, all of the structure-to-cell interaction parameters have been determined for the timestep. Next a sweep of all of the meshes is made updating each fluid cell. This is achieved by modifying the total cell mass and energy based on assuming the calculated wall transfer rates will remain constant during the timestep. The BEACON fluid calculations are then performed. The result is that each timestep will begin with slightly different cell conditions than it would if no wall interaction had existed.

After the fluid conditions have been calculated, checks are made as to whether the problem is finished and, if not, whether the heat transfer rates are to be updated. Since the film calculations are relatively inexpensive, the film conditions are updated at every

(Transient
computations
control)

Fig. 19 Time advancement logic with wall film and heat conduction.

timestep. The heat transfer calculations, on the other hand, can be significantly time consuming. They are therefore controlled by a separate timestep as described in Section 3.2.

3.2 Heat Structures

The effects of the heat transfer to or from structures which are in contact with any fluid regions are included in the BEACON heat structure models. Any structures representing boundaries, obstacle regions, the front and back walls of Eulerian mesh regions, and nonoriented structures in both mesh and lumped parameter regions are included. Following are the heat structure model descriptions and details of the calculations and correlations.

3.2.1 Model Description. A heat conducting structure analytical model has been provided which can simulate heat transfer to equipment and structures. Up to 99 heat conducting structures of rectangular, cylindrical or spherical geometries of can be described. The program user supplies heat structure boundary conditions, compositions, and locations. The temperature distribution within each heat structure is then computed by the one-dimensional, time-dependent or steady state heat conduction subcode HEAT-1^[9] which obtains a numerical solution of the one-dimensional heat conduction equations.

The modeling of individual heat structures is illustrated in Figure 20. Each heat structure is described in one space dimension by a series of mesh points, placed such that these points lie on the exterior boundaries of the problem, at the interfaces between materials, and at equal intervals between the interfaces or boundaries. Up to 51 mesh points and ten regions for each structure are allowed, and each region may contain a different material. A region is a segment of space which contains the same material throughout and has a constant mesh spacing. A new region is required whenever a material interface exists or a different mesh point spacing is desired. Mesh

Fig. 20 Heat structure mesh point layout.

spacing change should not occur at interfaces of significantly dissimilar materials, and also mesh spacing should not change by more than a factor of three within the same or similar materials. Structures which have coarser mesh spacing will have significantly faster computing times than the same structures which have finer mesh spacing. All of the preceding modeling recommendations and criteria are at the control of the program user.

The temperature distribution within each heat structure is computed by the HEAT-1 subcode at a time interval independent of the time step used for the BEACON fluid cell computations. This time interval is currently a constant input value supplied by the user. This option allows the heat structures to be updated only once for several cell regions' updates, thus lowering computing costs without compromising accuracy.

Additional information needed to fully describe a heat structure in BEACON concerns the assignment of boundary conditions, the specification of several fluid cells adjacent to a heat structure boundary, and the coupling of structure heat transfer to a film layer.

Temperatures are calculated by the HEAT-1 subcode at each mesh point within a heat structure once the boundary conditions selected by the user have been determined. The boundary conditions are of the general form

$$-k \left(\frac{\partial T_w}{\partial n} \right)_w = h(T, t) \left[T_w - T_B(t) \right] \quad (41)$$

where

T_w = wall temperature

T_B = bulk fluid temperature

$\bar{n}$ = a vector in the direction out of the heat conducting structure

k = thermal conductivity of the conducting material

$h(T,t)$ = convection heat transfer coefficient.

Specification of the option for determining $h(T,t)$ for each boundary of every structure is made in the input data. The determination of T_B depends on whether the heat transfer is between the structure and the liquid component (T_B is the liquid component temperature), or the vapor component (T_B is the vapor component temperature), or the film layer (T_B is the average film temperature).

Boundary conditions are specified by the program user by selection of four heat transfer coefficient options for each structure: two for the right boundary (side) which are used individually for the vapor and liquid components; and, two for the left side. The heat transfer coefficient can be specified as any of the following:

- (1) An insulated or symmetrical condition where no heat transfer is allowed across the heat structure boundary
- (2) A best estimate correlation applicable as described in Section 3.2.3.
- (3) A constant value from an input set of heat transfer coefficients.
- (4) Tabular heat transfer coefficient tables input by the program user as a function of time, vapor component temperatures, or the mass ratio of air to steam.

A method is available whereby several cells can be attached to a single heat structure. In such case the value of $h(T,t)$ is imposed on each of these cells and T_B is chosen as described above.

The convective heat transfer boundary condition option in HEAT-1 calculates the heat flux from the structure using

$$Q = h A_T (T_W - T_B) \quad (42)$$

where

Q = rate of heat transfer between wall and region(s)

h = convective heat transfer coefficient

T_B = bulk fluid temperature

T_W = heat structure wall temperature

A_T = total heat transfer surface area.

At user option each side of a heat structure may be bound to either a single cell, a group of cells, a lumped parameter region or nothing (which the code treats as an insulated condition). One heat structure could account for heat transfer for many cells, several of which may be on each side. This is termed the multicell model. There is no limit on the number of cells which may be lumped together on a given side of a heat structure. The program user specifies which cells are to be included in a multicell region by defining a rectangular array in the input description, similar to that used to describe the fluid cell thermodynamic conditions. Only BEACON fluid cells and partial flow cells within the multicell region will be

involved in heat structure calculations; all other types are ignored. If possible special boundary cells (inflow, outflow, etc.) should not be included in multicell regions since they have no film layers. All cells in a single multicell region (attached to a given heat surface) must be in the same mesh. The heat transfer surface area is distributed among all active cells in a multicell region as a ratio of the individual cell area to the total cell area. In the case of the heat structure not associated with a given cell surface, the front and back cell wall area are used for this rationing. Further restraints on the multicell model are mentioned in the discussion of coupling film layers to heat structures.

For a group of cells adjacent to a heat structure boundary, the heat transfer rate is based on the average heat transfer coefficient for each cell to the structure from both the vapor and liquid components (or from the film layer). Each cell has either one or two heat transfer rates associated with an adjacent heat structure: one rate if a film layer is present and coupled to the heat structure; or two rates for the liquid component and vapor component if a film layer is either not present or not coupled to the heat structure. Thus, two steps are necessary in computing the average heat transfer coefficient and average bulk temperature between a multicell region and a heat structure. First, individual values of heat transfer coefficient and bulk temperature for each component (or the film layer) are determined. Second, these individual values are averaged to determine the overall heat transfer rate.

For a group of n cells adjacent to a structure the heat transfer is based on an average of the heat transfer from each cell to the structure. Thus, equation (42) becomes

$$Q = \sum_{i=1}^n h_i A_i (T_w - T_i) = \bar{h} A_T (T_w - \bar{T}_B) \quad (43)$$

where

Q = heat transfer out of the structure

i = cell counter

A_i = individual cell heat transfer area.

The average values for heat transfer coefficient and bulk temperature are calculated from

$$\bar{h} = \frac{1}{A_T} \sum_{i=1}^n h_i A_i \quad (44)$$

$$\bar{T}_B = T_w - \frac{1}{\bar{h} A_T} \sum_{i=1}^n h_i A_i (T_w - T_i) \quad (45)$$

where

h_i = cell heat transfer coefficient

T_w = initial wall temperature

T_i = cell bulk temperature

In the event heat transfer in a particular cell is between the film layer and the structure, h_i is the heat transfer coefficient between the structure and the film layer and T_i is the average film temperature.

In the event heat transfer in a cell is between the liquid and vapor components and the structure, h_i and T_i must be determined based on the void fraction of that cell. Thus,

$$h_i = \theta h_v + (1 - \theta) h_\ell \quad (46)$$

$$T_i = T_w - \frac{1}{h_i} \left[\theta h_v (T_w - T_v) + (1 - \theta) h_\ell (T_w - T_\ell) \right] \quad (47)$$

where

θ = void fraction in cell i

h_v = vapor heat transfer coefficient in cell i

h_ℓ = liquid heat transfer coefficient in cell i

T_v = vapor bulk temperature in cell i

T_ℓ = liquid bulk temperature in cell i

Heat transfer between structure and lumped parameter regions is treated in the same manner as for single cells with the exception that no film layer may be specified in a lumped parameter region.

As a user convenience, an option is provided which allows the user to define an insulated or symmetrical condition on one side of a heat structure. In this case no region need be specified on that side. The code will ensure that no film is selected and that zero heat transfer occurs through that side.

Heat transfer between cell regions and heat conducting structures can be greatly influenced by the presence of a liquid film layer on the structure. This procedure is the means by which the user may selectively associate a film layer with a heat structure. Since no film may be specified in a lumped parameter region, this procedure is applicable only to heat structures attached to mesh regions.

Five types of film layers are designated according to their location, as shown in Figure 21. Because of limitations on the placement of obstacle cells (an obstacle region cannot be less than two cells in any dimension), all of these film types are not usually present in a given cell. Film layers may only be present in cells which are interior fluid cells or partial flow cells.

Each cell is treated separately when the user specifies which film layer is adjacent to which heat structure. Film layers and heat structures need not be associated with each other. However, only one heat structure can be coupled to a single film layer. Similarly, if the user has selected the multicell coupling model the selected film layer must be present in all cells specified and must not be coupled to another heat structure. The only exception to this is the case where the user describes a multicell region which includes obstacle cells and then selects the faces' (front and back) film. In this case the code will ignore the obstacle cells and assume that the film is attached only to the fluid cell faces.

3.2.2 Method of Calculation. In incorporating the heat structure calculations into BEACON, an effort was made to minimize the impact of these calculations on the existing numerical scheme. The heat transfer model was therefore coded outside of the main fluid calculations loop in a manner similar to that of the wall film calculations. However, unlike the wall film calculations, the timestep used for the heat transfer calculations is not necessarily the same as that of the fluid calculations. This was done for strictly economic reasons.

Depending upon the complexity and quantity of the heat structures, the computer time required for the heat transfer calculations in a given problem could rival or exceed that of the fluid calculations. Since the heat structure transient will generally be much slower than the fluid flow transient, the heat transfer time

Fig. 21 Designation of film layers in a mesh.

step is, in general, different from that of the fluid calculations. This allows multiple fluid calculation updates to be performed between heat structure calculation updates, thus reducing the required run time of the problem. Note that in some cases where the heat structure calculations are changing rapidly, this option may cause numerical instabilities.

For further information on the sequencing of the heat structure calculations within BEACON, see Section 3.1 concerning wall film calculations.

3.2.3 Heat Transfer Correlations. The correlations used to calculate the heat transfer coefficients for the energy transfer to or from a wall depend on whether or not a film is attached to the given surface. The correlations used for calculating the coefficient between the film and the cell are given in Section 3.1 which describes the wall film model.

In calculating the wall-to-cell heat transfer coefficient when no wall film is attached, it is assumed that constant properties, and two dimensional, quasi-steady flow conditions exist. It is further assumed that forced convection dominates the heat transfer calculations, with conditions at the adjacent cell centerline known from the BEACON calculations. In other words, since BEACON computations include free convection, gravitational effects are already accounted for in the cell velocities being used for the heat and mass transfer calculations. Thus, the natural convection effects are of only secondary importance.

A direct approach to calculate the heat transfer coefficient would be to use an extremely fine nodalization near the wall, and to calculate the heat transfer coefficient from the temperature gradient

at the wall. This, however, is economically prohibitive for most problems. Thus, the problem is formulated as turbulent flow over a flat plate which results in the following solution:

$$St = \frac{(f/2)^{1/2}}{\left[5 Pr + 5 \ln (5 Pr + 1) + (f/2)^{-1/2} - 14 \right]}, \quad (48)$$

where

St = Stanton Number

f = Friction Coefficient

Pr = Prandtl Number

and the friction coefficient is defined as,

$$\tau_w = \frac{f \rho U_\infty^2}{2}, \quad (49)$$

where

τ_w = Wall shear stress

ρ = Density

U_∞ = Velocity of the free stream.

The details of this solution are discussed by Kays^[6].

If the heat transfer coefficient in the absence of mass transfer is defined as

$$q_{w-\infty} = - \frac{k}{c_p} \left(\frac{\partial h}{\partial x} \right)_w = g_h^* (h_w - h_\infty) , \quad (50)$$

where

$q_{w-\infty}$ = heat flux

k = thermal conductivity

c_p = specific heat at constant pressure

h = enthalpy

g_h^* = heat transfer coefficient in the absence of mass transfer

w = wall conditions

∞ = cell conditions,

then,

$$g_h^* = \rho u_\infty St \quad (51)$$

In this special case, the heat transfer coefficient turns out to be equal to the conventional heat transfer coefficient based on temperature differential divided by the specific heat. The reason for defining it in terms of enthalpy is to be able to apply heat and mass transfer analogy directly, when mass diffusion is important.

In the presence of two phases (liquid and air-vapor mixture), the total heat transfer is thus given by

$$q_{w-\infty} = q_{w-m\infty} + (1 - \theta) q_{w-l} \quad (52)$$

where

θ = void fraction

$q_{w-m\infty}$ = heat flux from the wall to the vapor/air phase

$q_{w-l\infty}$ = heat flux from the wall to the liquid phase.

Film would start to build when either of the following occurs:
 (1) the wall temperature decreases to a point where the mass fraction of vapor corresponding to saturation pressure at the wall temperature is less than the vapor mass fraction in the cell, forcing the vapor to condense on the wall; (2) film is de-entrained from the adjacent fluid cell; (3) the film progresses from an adjacent film node.

Heat transfer from wall to film, assuming a linear temperature profile, is given by

$$q_{w-f} = \frac{2k_l}{\delta_l} (T_w - T_f) \quad (53)$$

where

k_l = liquid thermal conductivity

δ_l = film thickness

T_w = wall temperature

T_f = average film temperature,

which gives the wall-to-film heat transfer coefficient based on temperature differential,

$$H_{w-f} = \frac{2k_l}{\delta_l} \quad (54)$$

4. THERMODYNAMIC MODELS

Two groups of thermodynamic models are included in the BEACON/MOD2A code, and they are presented in the following sections. Three types of interphasic exchange phenomena and two cases of equation of state are described.

4.1 Interphasic Exchange Functions

The three interphasic exchange phenomena of interest are heat transfer, mass transfer, and momentum transfer. They are treated in the BEACON code, as described in the following sections.

4.1.1 Heat Transfer. The interphasic heat transfer is the product of an interphasic heat transfer coefficient and the differential temperature between the two phases. The coefficient is an input constant selected by the user.

4.1.2 Mass Transfer. There are several interphasic mass transfer options available in BEACON, only one of which has been tested so far. All these models assume that the rate of energy transfer within the gas and liquid is large relative to the rate of energy exchange between the phases. In accord with this assumption, the bulk liquid and vapor temperatures are used to determine the mass

transfer rates. Furthermore, all these models presuppose only a single component with no inert gas present in the system. Even small amounts of air in the system may change the mass transfer rates significantly by making the phenomenon diffusion limited. The models should therefore be used with caution for containment applications.

The Rivard-Torrey^[10] mass transfer model is the only mass transfer model which has been tested in BEACON. The rates are determined by the following expressions:

$$\begin{aligned} J_e &= \lambda_e A \rho'_l \theta (T_s R_v)^{1/2} (T_l - T_s) / (3T_s), \text{ for } T_l \geq T_s \\ &= 0, \text{ otherwise} \end{aligned} \quad (55)$$

$$\begin{aligned} J_c &= \lambda_c A \rho'_v (1-\theta) (T_s R_v)^{1/2} (T_s - T_v) / (3T_s), \text{ for } T_v \leq T_s \\ &= 0, \text{ otherwise} \end{aligned} \quad (56)$$

where

A = area of contact between the two phases per unit volume

J = mass transfer rate per unit volume

R = gas constant

T = temperature

θ = void fraction

λ = rate multiplier

ρ' = macroscopic density

and the subscripts

c = condensation

e = evaporation

l = liquid

s = saturation

v = vapor

For N equal size spherical bubbles or droplets per unit volume, A is given by

$$A = \begin{cases} 6(\pi N_b/6)^{1/3} \theta^{2/3} & , \theta \leq 0.5 \end{cases} \quad (57a)$$

$$A = \begin{cases} 6(\pi N_d/6)^{1/3} (1 - \theta)^{2/3} & , \theta > 0.5, \end{cases} \quad (57b)$$

where subscripts b and d refer to bubble and droplet respectively.

The mass transfer rates for the Jones-Saha^[11] mass transfer models are calculated as

$$\begin{aligned} J_e &= e A h_e (T_l - T_s) / h_{fg}, \text{ for } T_l \geq T_s \\ &= 0, \text{ otherwise} \end{aligned} \quad (58)$$

$$\begin{aligned} J_c &= \lambda_c A h_c (T_s - T_v) / h_{fg}, \text{ for } T_v \leq T_s \\ &= 0, \text{ otherwise} \end{aligned} \quad (58)$$

where h is the interfacial heat transfer coefficient, and h_{fg} is the heat of evaporation. The interfacial heat transfer coefficients h_e and h_c are calculated as follows:

$$h_e = \frac{\pi}{2} \frac{k_\ell}{(\pi \alpha_\ell t)^{1/2}}, \text{ and } h_c = \frac{\pi}{2} \frac{k_v}{(\pi \alpha_v t)^{1/2}}, \quad (60)$$

where k and α are thermal conductivity and diffusivity respectively. Variable t is defined as

$$t = \frac{\left(\frac{3CR}{B^2}\right)^2 \left(2 - \frac{3CR}{B^2}\right)^2}{4\left(\frac{C^2}{B^2}\right) \left[1 - \frac{3CR}{B^2} \left(2 - \frac{3CR}{B^2}\right)\right]},$$

with R , C , and B given by

$$R = \begin{cases} \left(\frac{3\theta}{4\pi N_b}\right)^{1/3}, & \text{when } \theta \leq \frac{1}{2} \\ \left[3 - \frac{(1-\theta)}{4\pi N_d}\right]^{1/3}, & \text{when } \theta > \frac{1}{2} \end{cases}, \quad C = \begin{cases} \frac{2}{3} \left[\frac{h_{fg} \rho_v (T_\ell - T_s)}{\rho_\ell T_s} \right]^{\frac{1}{2}}, & \text{for } h_e \\ \frac{2}{3} \left[\frac{h_{fg} \rho_v (T_s - T_v)}{\rho_\ell T_s} \right]^{\frac{1}{2}}, & \text{for } h_c \end{cases},$$

$$\text{and } B = \begin{cases} \left(\frac{12}{\pi} \alpha_\ell\right)^{\frac{1}{2}} \frac{\alpha_\ell \rho_\ell (T_\ell - T_s)}{h_{fg} \rho_v}, & \text{for } h_e \\ \left(\frac{12}{\pi} \alpha_v\right)^{\frac{1}{2}} \frac{\alpha_v \rho_\ell (T_s - T_v)}{h_{fg} \rho_v}, & \text{for } h_c. \end{cases}$$

The interphasic area density, A , is evaluated according to the flow regime. However, the code does not contain the logic to determine the type of flow and choose the proper formulation. The user may select the desired flow regime modeling as input; but, once selected the flow regime is fixed for the remainder of the problem.

For dispersed bubbly flow, the area is given by Equation (57a).

For dispersed droplet flow, the area is given by Equation (57b).

For slug flow, the interphasic area is calculated as

$$A = \frac{4.3268}{D} \left[\frac{\theta - \theta_{\text{film}}}{1 - \theta_{\text{film}}} \right]^{2/3} + \frac{1 - \theta}{(1 - \theta_{\text{film}})} 6 \left(\frac{\pi}{6} N_b \right)^{1/3} \theta_{\text{film}}^{2/3}, \quad (61)$$

where D is a characteristic length (diameter in case of flow through a pipe). θ_{film} is given by, $\theta_{\text{film}} = (\theta + 0.2)/2$.

For mist-annular flow, the area is given by

$$A = \frac{4}{D} \left(\frac{\theta}{\theta_{\text{core}}} \right)^{1/2} \frac{\theta}{\theta_{\text{core}}} 6 \left(\frac{\pi}{6} N_d \right)^{1/3} (1 - \theta_{\text{core}})^{2/3}, \quad (62)$$

where

$$\theta_{\text{core}} = \begin{cases} 1 - 0.5 (\theta - 0.7), & \text{for } 0.7 \leq \theta \leq 0.85 \\ 1 - 0.5 (1 - \theta), & \text{for } 0.85 \leq \theta \leq 1.0. \end{cases}$$

The corresponding energy transfer rate associated with the mass transfer is calculated by multiplying the net mass transfer rate with gas enthalpy.

4.1.3 Momentum Transfer. The momentum exchange between phases is the product of a momentum exchange coefficient, and the velocity vector difference between the two phases. The modeling options available for computing the coefficient include two described below plus that of input constant selected by the user.

For Amsden-Harlow^[5] Dispersed Flow Momentum Exchange the momentum exchange coefficient, K , is calculated assuming a constant bubble/droplet size.

$$K_{i,j} = \frac{3(\rho_g)_{i,j} (1-\theta_{i,j})}{2 \theta_{i,j}^2 r_p^2} \left[3 \nu_g + \frac{r_p C_{DR}}{4} \left| \frac{u_g}{g} - \frac{u_l}{l} \right| \right] , \quad (63)$$

where

C_{dr} = drag coefficient

r_p = mean linear dimension of a bubble/droplet

$\underline{u}$ = velocity vector

ν = kinematic viscosity

and the subscripts

g = gas phase

i,j = cell designations

l = liquid

The absolute value of the difference between the two velocity vectors is calculated as

$$\begin{aligned}
|\underline{u}_g - \underline{u}_l| = \frac{1}{2} \left\{ \left[\zeta_R (\underline{u}_g - \underline{u}_l)_{i+1/2,j} + \zeta_L (\underline{u}_g - \underline{u}_l)_{i-1/2,j} \right]^2 \right. \\
\left. + \left[\zeta_T (\underline{v}_g - \underline{v}_l)_{i,j+1/2} + \zeta_B (\underline{v}_g - \underline{v}_l)_{i,j-1/2} \right]^2 \right\}^{1/2}, \quad (64)
\end{aligned}$$

where ζ 's are multipliers for unequal area coupling, and are defined in Appendix A.

For Rivard-Torrey^[10] Dispersed Flow Momentum Exchange the momentum exchange coefficient is calculated assuming a constant bubble/droplet density.

$$K_{i,j} = \frac{A\rho}{8} \frac{12\nu}{r_p} + C_{DR} |\underline{u}_g - \underline{u}_l|, \quad (65)$$

where

$$\rho = \rho'_g + \rho'_l, \quad (66)$$

$$\nu = \theta \nu_g + (1-\theta) \nu_l \quad (67)$$

$$r_p = \begin{cases} (3\theta/4 \pi N)^{1/3}, & \theta \leq 1/2 \\ 3(1-\theta)/4 \pi N^{1/3}, & \theta > 1/2, \end{cases} \quad (68)$$

and A is defined in equation (57).

4.2 Equation of State

The BEACON code is designed modularly and the equation of state package herein referred to as (EOS) is one of these modules. Presently, two EOS options are available in the BEACON code. Air is assumed to behave as an ideal gas in both the options.

4.2.1 Ideal Gas, Ideal Liquid. This model uses incompressible liquid water with steam treated as an ideal gas. This model is not an upgraded version of the original K-FIX program EOS model in which constant heat of vaporization was assumed. This model assumes heat of evaporation to be a linear function of saturation temperature through the correlation,

$$h_{fg} = A - (B T_s) \quad , \quad (69)$$

where constants A and B are given by Sahota^[12] as $A = 3.18 \times 10^6$ J/kg and $B = 2470$ J/kg-K, and where

h_{fg} = heat of evaporation

T_s = saturation temperature

Substituting this value of h_{fg} in the Clausius-Clapeyron equation, and assuming vapor to be an ideal gas with much higher volume than liquid water, yields after integration,

$$P_s = C T_s \left(-\frac{B}{R_v} \right) \exp \left[-\frac{A}{R_v T_s} \right] \quad (70)$$

where

P_s = saturation pressure

R_v = gas constant for vapor

Constant C is given by Sahota^[12] as, $C = 6.05 \times 10^{26} \text{ N/m}^2$.

Equation (70) does not allow explicit calculation of T_s in terms of P_s , as desired in the code. To avoid iterating, the following sequence of T_s calculation is adopted in the code.

1. As a first estimate, the saturation temperature is calculated from the correlation

$$T_s = \frac{T_{s,o}}{1 - \frac{R_v T_{s,o}}{h_{fg}} \ln \left(\frac{P_s}{P_{s,o}} \right)}, \quad (71)$$

where subscript o implies any reference point.

Equation (71) is obtained by integrating the Clausius-Clapeyron equation assuming constant h_{fg} . For the first estimate, the reference point is chosen at 373.15 K.

2. Corresponding to the preceding value of T_s , h_{fg} and P_s are calculated from Equations (69) and (70).
3. The preceding set of T_s , h_{fg} , and P_s is considered as a reference point, and the final value of T_s is computed from equation (71).

This model calculates liquid and vapor internal energies as follows:

$$I = c_\ell (T_\ell - 273.15) \quad (72)$$

$$I_v = h_v - R_v T \quad (73)$$

$$= c_\ell (T_s - 273.15) + h_{fg,s} + c_{pv} (T - T_s) - R_v T$$

where

I_l = internal energy of liquid

C_l = specific heat of liquid

T_l = temperature of liquid

I_v = internal energy of vapor

h_v = enthalpy of vapor

$h_{fg,s}$ = heat of evaporation at saturation

p_v = specific heat of vapor at constant pressure

4.2.2 Real Gas, Real Liquid. This model utilizes real steam and liquid water properties and is based upon curve-fit functions developed at the Brookhaven National Laboratory (BNL). These routines have been installed in the BEACON code and have been extended to meet the requirements of the K-FIX numerical technique, namely the use of internal energy as a state point. In addition, mixture equations have been added to handle air-vapor mixtures.

This real gas, real liquid equation of state has two disadvantages relative to the other choice of ideal gas ideal liquid equation of state. First, it does not work properly at steam partial pressures well below atmospheric pressure. The BNL steam functions were designed for use at pressures above 1 atmosphere and become progressively inaccurate at lower pressures. Second, it significantly increases the computer time required to run a problem, approximately a five fold increase.

IV. PROGRAM APPLICATION

This section of the manual presents information for using the BEACON/MOD2A code. A general discussion of the input processing system used by BEACON is given, followed by detailed descriptions of all input cards. The output from BEACON is also sequentially outlined and described. Samplings of the different types of print and plot output are given to aid the code user. Lastly, instructions for restarting a BEACON problem from previously computed results stored on tape are given.

1. INPUT DESCRIPTION

The BEACON code utilizes the INEL INP input processing system to read and process input data. This system is commonly used in computer codes developed at INEL and offers a number of features convenient to the user. These features and general input instructions related to the INP system are discussed in Section 1.1. The BEACON input processing structure is also described in Section 1.1. Finally, Sections 1.2 through 1.7 describe all BEACON input as functionally categorized.

1.1 General Information

Input data consist of comment cards (optional), data cards and a terminator card. The order of the title, data, and comment cards is unimportant. If duplicate title or data cards are encountered, the last title card and the last data card will be used. Data may be carried over to successive problems in a problem set. Thus only the data that are changed need to be entered.

When a card format error is detected, a dollar sign (\$) is printed in the data card listing of the printout under the character

causing the problem. An appropriate error message is also printed. If an error is encountered, input processing is continued to detect additional errors but the job is terminated thereafter.

1.1.1 Comment Cards. An asterisk (*) or a dollar sign (\$) appearing as the first nonblank character identifies a card as a comment card. Any information may be entered on the remainder of the card. There is no processing of comment cards other than printing them and they may be placed anywhere in the input deck. Blank cards are treated as comment cards.

1.1.2 Data Cards. The data cards contain a varying number of fields which may be either integer, floating point, or alphanumeric. Blanks preceding and following fields are ignored and one or more blanks serve as separators between data fields. Commas (,) may also be used to separate data fields. For a continuative alphanumeric field, such as a title or case heading, apostrophes are used to enclose the field thus allowing imbedded blanks in the field.

The first field on a data card is for the card number and must be an unsigned integer. If the first field has an error or is not an integer, an error flag is set. Consequently, data on the card are not used and the card will be identified by the card sequence number in the list of unused data cards. After each card number and the accompanying data are converted, the card number is compared to previously entered card numbers. If a matching card number is found, the data entered on the previous card is replaced by the data of the current card. If the card being processed contains only a card number the data entered on the previous card are deleted. If a card causes replacement or deletion of data, a statement is printed indicating that the card is a replacement card.

Comment information may be made to follow the data fields on any data card by preceding the comments with an asterisk or dollar sign.

A number field is started by either a digit (0 through 9), a sign (+ or -), or a decimal point (.). A comma or a blank (with one exception to be noted) terminates the number field. The number field has a number part and, optionally, an exponent part. A number field without a decimal point or an exponent is an integer field; a number field with either a decimal point, an exponent, or both is a floating point field. A floating point field without a decimal point is assumed to have a decimal point immediately in front of the first digit. These rules for floating point numbers are identical to those for entering data in FORTRAN E or F formatted fields except that no blanks (one exception) are allowed between characters. Floating-point data punched by FORTRAN programs have a blank, treated as plus sign, following an E or D denoting an exponent. Acceptable ways of entering floating point numbers are illustrated by the following six fields all containing the quantity 12.45.

12.45,+12.45 1245+2 .1245E2,1.245E 1 1.245E+1

An integer zero (0) in a floating point field will be treated as a floating point zero (0.0).

A field starting with a letter is an alphanumeric field. The field is terminated by a comma, a blank, or the end of the card. All characters except commas and blanks are allowed.

1.1.3 Continuation Cards. In INP a data card may be continued under the same card number by beginning each continuation card with a plus sign (+) instead of a card number. A data value started on one card must be completed on that card and may not be continued onto the next card. Continuation cards must immediately follow the numbered data card that is continued. While the continuation card feature may be used, it is discouraged since it introduces order dependence into an otherwise order independent set of cards.

1.1.4 Terminator Cards. The input data for sucessively executed BEACON/MOD2 problems are separated by slash cards; the final problem is terminated by a period card. The slash and period cards have a (/) and (.), respectively, as the first non-blank character.

When a slash card is used as a problem terminator, the list of card numbers (and associated data used in a problem) is passed to the next problem. Cards entered for the next problem are added to the passed list or act as replacement cards depending on the card number. The resulting input is the same as if all previous slash cards were removed from the input to the problem set.

The period card may also be used as the separator between problem cases. However, input cards for the next case are not treated as replacement cards to the previous case, and, therefore, a full data set must be input.

The BEACON input and initialization code structure for the processing of mixed-dimensional, multiregion input data is illustrated in Figure 22. A list of all BEACON input cards is given in Table III. Input data may be categorized into the following groups:

Group (1), Basic BEACON Input Data. These data cards define the input variables that are common to the whole problem. These include problem start and finish time, output options, and iteration and fluid interchange parameters.

Group (2), Eulerian Region Input Data. These data cards describe the variables that define each mesh such as mesh size (IBAR, JBAR), define each cells is dimensions (DR, DZ), boundary conditions, fluid region properties, and obstacle regions.

Group (3), Lumped-Parameter Region Input Data. These data cards define the volume, initial state conditions, and timestep interval for lumped-parameter regions.

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Fig. 22 Input processing organization.

TABLE III
LIST OF BEACON INPUT CARDS
(Cards marked with an asterisk are optional)

00100*	Alphanumeric case title (up to 80 characters): NAME
00105*	Restart options: ITD, NTD, NSDMP
00110	Execution parameters: TI, TSTOP, DTI, UNITS, CPTMIN, NTSO, XEQ
00120	Output interval tables: (DTO(N), TOC(N) N=1,10)
00130*	Automatic timestep parameters: AUTODT, NCYDT, XDTC, XMDT
00140*	Output options: PROPT, XCPRNT, SLPRNT, SCPRNT, DBPRINT
00145*	Cell variable mapping option: (ISEE(N), IOPT(N), N=1,10)
00150*	Plot options: PLOPT, SCALEI, (ICN(I), I=1,14)
00160*	Problem geometric indicators: XMODE, CELDIM
00170*	Computing region setup: NMTOT, NCRTOT, (MITAB(N), MFTAB(N), N=1,NCRTOT)
00180*	Lumped parameter region setup: NZDTOT, DTZD
00200	Iteration parameters: OMEGA, EPSG, EPSL, ITMAX, LMAX, KMAX
00210	Physical parameters: GRAV, UNITS, UNITS, KAPGI, KAPLI, UNITS, RHEATI
00220	Drag parameters: NUV, NUD, UNITS, CDR, RPAR, UNITS, PDENS, UNITS, KDRAGI, KOPT
00230*	Mass transfer parameters: JOPT, RLAME, RLAMC
00240	Equation of state parameters: EOSOPT, EOSINP, UNITS, UNITS, UNITS, UNITS

TABLE III (continued)

00250*	Wall film modeling parameters: THKMIN, FDRAG, FDEN, FENT, DFUSON, PRM, SURTEN
M1000	Mesh and cell dimensions: GEOM, IBAR, JBAR, DRCON, DZCON, DEPTH/RO, UNITS, PHI, XGR
M1010*	Mesh wall slip indicators: LWALL, RWALL, BWALL, TWALL
M1020*	Variable DR spacing: (DR(N), N=1,IBAR)
M1030*	Variable DZ spacing: (DZ(N), N=1,JBAR)
M1050*	Wall film option: FLMOPT
M1101- M1199	Fluid region input: FLUID, IXI, JXI, IXF, JXF, NPUA, SPV1, SPV2, SPV3, THIN, XAIR
M1201- M1299*	Initial fluid velocity input: IXI, JXI, IXF, JXF, UGIN, ULIN, VGIN, VLIN
M1301- M1399*	Partial flow option: IXI, JXI, IXF, JXF, FLOI, FRICT, FZICT
M1401- M1499*	Obstacle cell input: OCTYPE, IXI, JXI, IXF, JXF
M1501- M1599*	Boundary inflow/outflow options: BTYPE, IXI, JXI, IXF, JXF
M1601- M1699*	Inflow state conditions: FLUID, SPV1, SPV2, SPV3, XAIR
M1701- M1799*	Inflow velocities: UGIN, VGIN, ULIN, VLIN
L2000*	Lumped parameter region transfer functions and geometric inputs: ZEROD, VOLUME, UNITS, RHEAT, ZLAME, ZLAMC
L2010*	Lumped parameter region state conditions: FLUID, SPV1, SPV2, SPV3, THIN, XAIR
002950+ 50S*	Source description: SUBST, MESHNO/NZD, ISTAR, JSTAR, NTABLE, ANGLE, UNITS, XMASS, XENRGY, VEL, TOFSET
002961+ 50S*	Table units specification: UNITS, UNITS, UNITS, UNITS UNITS

TABLE III (continued)

002962+ 50S*	Source tabular inputs: TSOURCE, FLOMAS, FLONRG, FLOVEL
006001- NCX, 006999*	Eulerian region coupling data: SIDEX, MESHX, IX, JX, MESHY, IY, JY, NCY
007001- 007050*	Lumped parameter region coupling data: SIDE, MESHNO, IID, JID, NZD
1YY0000*	Heat Structure Title
1000001*	Heat Structure Description Units
1000002*	Heat Structure Common Data
1YY0001*	Heat Structure Control
1YY0002	Heat Structure Connection
1YY0003	Heat Structure Miscellaneous Data
1YY0200	Mesh Increment Format
1YY0201- 1YY0299	Mesh Increment Description
1YY0301- 1YY0399	Composition Overlay Description
1YY0300*	Composition Overlay Repeat
1YY0401- 1YY0499	Source Distribution Description
1YY0400	Source Distribution Repeat
1YY0601- 1YY0699	Initial Temperature Estimate
1YY0600*	Initial Temperature Estimate Repeat
1YY0009	Heat Transfer Coefficient Control
1000000	Common Data Units
1000101-	Material Properties

TABLE III (continued)

1000201*	Miscellaneous Heat Transfer Coefficient
21XX000*	Tabular Heat Transfer Coefficient Title
21XX001*	Tabular Heat Transfer Coefficient Units
21XX001- 21XX099*	Tabular Heat Transfer Coefficient Table

Group (4), Source Cell Input Data. These data cards define source cell locations and time-dependent mass, energy, and momentum arrays. Source cells may be placed in any of the Eulerian or lumped-parameter regions.

Group (5), Region Coupling Input Data. These data cards define the interface boundaries that are to be coupled. There are two types of coupling input. One type couples Eulerian regions to Eulerian regions. The other type couples lumped-parameter regions to 1-D Eulerian regions.

Group (6), Heat Structure Input Data. These cards describe the material properties, geometries, connections, and heat transfer coefficient options for heat conducting structures.

In a typical multi-region problem setup, the first group of input cards, group (1), is processed first and only once. The Eulerian region input cards, group (2), are then processed in a sequential-set fashion. Each Eulerian region is assigned a number by the user. This number is incorporated in the card number of each data card that pertains to a given region and identifies the set of input data cards unique to each region. Each set of mesh input data cards are then processed sequentially until all such regions are processed. During the input processing of each mesh:

- (1) cell storage space is allocated continuously to the storage space of the mesh previously processed,

- (2) the properties of each cell are defined (fluid, obstacle, specified boundary) and cell flags set, and

- (3) pertinent data for each mesh, such as its location in core memory, mesh size, cell dimensions, and boundary conditions are stored in arrays for future referencing in the transient flow computations.

After the mesh region input data are processed, the Eulerian region interface input data cards, group (5), are processed. Here, the cell flag is used in a dual manner, as a flag to denote a special type of computational cell, and as a pointer to specify the storage location of a computational cell array. As each interface data card is processed, the storage location of each interface cell is computed. An interface cell is defined as an interior fluid cell, lying along a mesh wall boundary, that is computationally adjacent to an interface cell located in another computing mesh region. These storage locations are then stored as cell flag variables in opposite exterior cells as illustrated in Figure 22. This then provides a communication or coupling link between the meshes.

The processing of lumped-parameter region and interface data, groups (3) and (5), proceeds in a similar manner. Each lumped-parameter region is assigned a number and this number is appended to each lumped-parameter data card number. As the region input cards are processed, cell space is allocated, and total mass and initial state conditions of the lumped-parameter regions are defined. In the processing of interface cards, cell flags and location pointers are set, arrays for the current time level state variables are initialized, and the one-dimensional boundary exterior cells at the interface are reset to reflect the lumped parameter state condition.

Source cell input data, group (4), are processed after all regions have been defined. The user-assigned region number is part of the source cell input data and is interpreted to be either a lumped-parameter region number or a Eulerian region number, depending upon the input values normally defining the location of a source cell in a mesh (ISTAR and JSTAR).

The cell flags of all computational regions are now checked to see that they have been set and a map printout of the cell flags for each region is obtained.

Heat Structure Input Data, Group (6), are processed last. Heat structures are linked computationally with the appropriate fluid regions and arrays defining mesh point temperatures and mesh space composition are set up.

As many as 20 Eulerian regions and 20 lumped-parameter regions may be defined for a given problem. These limits are set by array dimensions and may be easily changed for future problem requirements. The total number of computational cells for a problem must not exceed the maximum available (presently, 1985 cells).

BEACON allows input to be in SI units or non-SI units. Table IV presents a list of the allowable units specifications which may be used for the data input. The appropriate conversion is made at input time and all subsequent internal computations are performed in SI units.

1.2 Basic Input Data

These cards contain information which is common to the entire problem.

00100 CARD - PROBLEM TITLE (Optional)

W1-A	NAME	Problem title. Up to 80 characters to be printed at the top of each page of output. The problem title is enclosed by apostrophes.
------	------	--

Example:

00100 'INFLOW, OUTFLOW, OBSTACLE CASE'

Default:

00100

TABLE IV

ALLOWABLE UNITS SPECIFICATION

Below is the exact alphanumeric input allowed to enter units specifications into BEACON runs. Some classes of units are not used by the code input or processing routines. They are included for completeness and possible future use, as all the units below can be processed by subroutine UNITSI, which converts to appropriate SI units.

LENGTH	ENERGY
MM	CAL
CM	J
M	ERG
KM	BTU
IN	FT-LBF
FT	
YD	
AREA	VOLUME/TIME
MM2	M3/SEC
CM2	M3/MIN
M2	M3/HR
KM2	LTR/SEC
IN2	LTR/MIN
FT2	LTR/HR
YD2	FT3/SEC
	FT3/MIN
	FT3/HR
	GAL/SEC
	GAL/MIN
	GAL/HR
VOLUME	MASS/TIME
MM3	KG/SEC
CM3	KG/MIN
M3	KG/HR
LTR	LB/SEC
IN3	LB/MIN
FT3	LB/HR
YD3	
GAL	

TABLE IV (continued)

MASS	POWER
GM	CAL/SEC
KG	WATT
LB	KW
	MW
	BTU/SEC
	BTU/MIN
	BTU/HR
TIME	ENERGY/MASS
SEC	J/KG
MIN	BTU/LB
HR	CAL/GM
	J/GM
FORCE	THERMAL CONDUCTIVITY
DYN	WATT/M-DEGC
N	WATT/M-DEGK
GMF	CAL/SEC-CM-DEGC
KGf	BTU/SEC-FT-DEGF
LBf	BTU/HR-FT-DEGF
PNDL	
PRESSURE	HEAT CAPACITY
N/M2	J/KG-DEGC
DYN/CM2	J/KG-DEGK
BAR	CAL/GM-DEGC
KGf/M2	BTU/LB-DEGF
GMf/CM2	
LBf/IN2	
LBf/FT2	
ATM	
PNDL/FT2	
TEMPERATURE	VOLUMETRIC HEAT CAPACITY
DEGK	J/M3-DEGC
DEGC	J/M3-DEGK
DEGF	CAL/CM3-DEGC
DEGR	BTU/FT3-DEGF

TABLE IV (continued)

RECIPROCAL	DENSITY
CEL-1	KG/M3
MIN-1	GM/CM3
HR-1	LB/FT3
HEAT TRANSFER COEFFICIENT	SPECIFIC VOLUME
WATT/M2-DEGC	M3/KG
WATT/M2-DEGK	CM3/GM
KW/M2-DEGC	FT3/LB
KW/M2-DEGK	
MW/M2-DEGC	
MW/M2-DEGK	
CAL/SEC-CM2-DEGC	
BTU/SEC-FT2-DEGF	
BTU/HR-FT2-DEGF	

00105 CARD - RESTART OPTION (Optional)

W1-I	ITD	Restart indicator. =0 for no restart and no restart tape creation, =1 for restart tape creation only, =2 for restart only, =3 for restart and restart tape creation.
W2-I	NTD	Cycle on the restart tape at which restart is to occur.
W3-I	NSDMP	The frequency in cycles with which data are written to the restart tape. This should occur at an integer multiple of the output frequency.

Example:

00105 2 10 100

Default:

00105 0 0 0

00110 CARD - PROBLEM EXECUTION PARAMETERS (Required)

W1-R	TI	Transient start time, usually zero.
W2-R	TSTOP	Transient stop time.
W3-R	DTI	Timestep interval used prior to NCYDT (see Card 00130). After NCYDT the timestep interval is determined internally.

W4-A	UNITS	Time units specification.
W5-R	CPTMIN	Computer time limit in seconds allowed for normal program termination.
W6-I	NTSO	Output frequency. Output will be printed at every NTSO of the intervals specified in the DT0 table (see Card 00120).
W7-A	XEQ	Transient execution indicator. =XEQ to run transient, =NOXEQ to read and process input data only.

Example:

00110 0. 0.5 0.001 SEC 10. 20 XEQ

00120 CARD - OUTPUT INTERVAL TABLES (Required)

W1-R	DT0(1)	Output time interval DT0(1) used until the specified time TOC(1) . Up to ten pairs may
W2-R	TOC(1)	be used.
W3-R	DT0(2)	
W4-R	TOC(2)	
	...	
	...	
	...	

Example:

00120 0.001 0.1 0.0025 2.

The example card will cause output to be printed at an interval of 0.001 until time 0.1 and at an interval of 0.0025 between times 0.1 and 2.0. Note that if the specified interval is less than the timestep interval specified by DTI (Card 00110) or that which is automatically calculated, the DT0 array will control the calculation timestep.

00130 CARD - AUTOMATIC TIMESTEP COMPUTATION PARAMETERS (Optional)

W1-A	AUTODT	Not currently used, but must be input with nonblank characters.
W2-I	NCYDT	Cycle after which the automatic timestep control commences. Prior to cycle NCYDT, the timestep is specified by DTI (Card 00110).
W3-R	XDTC	Courant restriction multiplier. This is a multiplier used to limit the calculational timestep to a fraction of the internally calculated timestep. ($0.<XDTC\leq 1.$).
W4-R	XMDT	Multiplier used to restrict the increase in timestep. The current timestep is less than or equal to XMDT times the previous timestep. ($XMDT>1.$).

Example:

00130 AUTODT 1 0.1 1.E2

Default:

00130 AUTODT 0 0.1 10.

00140 CARD - OUTPUT OPTIONS (Optional. Default as shown.)

W1-A	PROPT	Option to print interior cell data. =PRINT for printout, =NOPRINT for no printout.
W2-A	XCPRNT	Option to print exterior cell data. =PRINT for printout, =NOPRINT for no printout.
W3-A	SLPRNT	Option to print abbreviated information for each iteration. =PRINT for printout, =NOPRINT for no printout.
W4-A	SCPRNT	Option to print source cell data. =PRINT for printout, =NOPRINT for no printout.
W5-A	DBPRNT	Option to print film debug information. =PRINT for printout, =NOPRINT for no printout.

Example:

00140 PRINT,NOPRINT,PRINT,NOPRINT,PRINT

Default:

00140 PRINT,PRINT,PRINT,PRINT,NOPRINT

00145 CARD CELL VARIABLE MAPPING OPTION (Optional. If missing, no
maps of cell variables are obtained.)

W1-I	ISEE(N)	Number identification of variable to be mapped (see below).
------	---------	--

W2-I	IOPT(N)	Normalization option for variable ISEE(N).
	.	= 0 for no normalization, actual values will be printed,
	.	= 1 for normalize to highest value of this variable among all mesh regions in the problem (ignored if ISEE(N) is an integer variable).

Up to ten variables (each requiring 2 values) may be input on this card. This will cause a map of all specified variables for all meshes to be printed at each output step (see Cards 00110 and 00120). Number identifications of some selected variables are shown below. Any variable in CELCOM common block may be mapped using this option, with the identifying number equal to the index of the variable AASC to which the variable is equivalenced. For this information, see subroutine COMDEF in BEACON program listing.

Pressure = 18
 Void Fraction = 44
 Wall Film Mass = 57
 Horizontal Vapor Velocity = 48
 Horizontal Liquid Velocity = 49
 Vertical Vapor Velocity = 50
 Vertical Liquid Velocity = 51
 Horizontal Wall Film Velocity = 64
 Vertical Wall Film Velocity = 65
 Vapor Temperature = 43
 Liquid Temperature = 46
 Wall Film Temperature = 58
 Internal Energy of Vapor = 39
 Internal Energy of Liquid = 41
 Saturation Temperature = 47
 Partial Density of Gas = 23
 Partial Density of Liquid = 31
 Interphasic Drag Coefficient = 14
 Interphasic Heat Transfer Coefficient = 27

Example:

00145 18, 1, 43, 0, 46, 0

00150 CARD - PLOT OPTIONS

(Optional. If missing, no plots are obtained.)

W1-A	PLOPT	Plot output option. = PLOTS for plots, including all velocity plots, = NOPLOTS for no plots.
W2-R	SCALEI	Plot scale factor. Reduces the plot size to SCALEI times the maximum plot size. ($0.1 \leq \text{SCALE} \leq 1.0$)
	ICN(N)	Contour plot options (N=1,14) = 1 for plot, = 0 for no plot.
W3-I	ICN(1)	Plot of void fraction.
W4-I	ICN(2)	Plot of pressure.
W5-I	ICN(3)	Plot of partial density of steam.
W6-I	ICN(4)	Plot of partial density of gas.
W7-I	ICN(5)	Plot of partial density of liquid.
W8-I	ICN(6)	Plot of vapor internal energy.
W9-I	ICN(7)	Plot of liquid internal energy.
W10-I	ICN(8)	Plot of phase change rate (net evaporation).

W11-I	ICN(9)	Plot of interphasic drag.
W12-I	ICN(10)	Plot of gas temperature.
W13-I	ICN(11)	Plot of liquid temperature.
W14-I	ICN(12)	Plot of saturation temperature.
W15-I	ICN(13)	Plot of wall film temperature.
W16-I	ICN(14)	Plot of wall film mass.

Example:

00150 PLOTS 0.9 1 1 0 0 0 0 0 0 0 0 0 0 0

00160 CARD - PROBLEM GEOMETRIC INDICATORS (Optional)

W1-A	XMODE	Problem type indicator = MULTI for multiple regions (lumped and/or mesh), = SINGLE for single mesh region.
W2-A	CELDIM	Unequal flow area coupling indicator. = CONST if there is no change in flow area across the coupling interface. ≠ CONST if there is a change in flow area across the coupling interface.

Example:

00160 MULTI,CONST

Default:

00160 SINGLE,CONST

00170 CARD - COMPUTING REGIONS SETUP (required if XMODE=MULTI. See
Card 00160.)

W1-I	NMTOT	Total number of meshes.
W2-I	NCRTOT	Total number of mesh computing regions (mesh groups which are separated by lumped parameter regions).
W3-I	MITAB(1)	The first, MITAB(N), and last, MFTAB(N), mesh of each computing region (N = 1,NCRTOT).
W4-I	MFTAB(1)	
W5-I	MITAB(2)	
W6-I	MFTAB(2)	
...	...	
...	...	
...	...	

Example:

00170 7 3 1 2 3 6 7 7

The input example is for the multi-region illustration of Figure 8. Referring to Figure 8 there are 7 separate mesh regions which make up 3 Eulerian computing regions. The first region consists of meshes 1 and 2, the second of meshes 3 through 6, and the third of mesh 7.

00180 CARD - LUMPED PARAMETER REGION SETUP (Required if XMODE=MULTI.
See Card 00160.)

W1-I	NZDTOT	Total number of lumped parameter regions.
W2-R	DTZD	Timestep used to calculate the lumped parameter region transients. This should be an integer multiple of DTI (Card 00110).

Example:

00180 2 0.1

00200 CARD - ITERATION PARAMETERS (Required)

W1-R	OMEGA	Relaxation parameter for iterations. Usually 1.5, but must be greater than or equal to 1.0.
W2-R	EPSG	Maximum relative error allowed in the gas field density calculation.
W3-R	EPSL	Maximum relative error allowed in the liquid field density calculation.
W4-I	ITMAX	Maximum number of iterations allowed for convergence during a timestep.
W5-I	LMAX	Maximum number of inner passes within each cell allowed for pressure convergence.

W6-I	KMAX	Maximum number of inner passes allowed within each cell to improve the accuracy of the density discrepancy calculation.
------	------	---

Example:

00200 1.5 0.0001 0.0001 300 5 5

00210 CARD - PHYSICAL PARAMETERS (Required)

W1-R	GRAV	External body force, normally the numerical value of acceleration of gravity.
W2-A	UNITS	Length units specification for gravity.
W3-A	UNITS	Reciprocal-of-time-squared specification for units for gravity.
W4-R	KAPGI	Thermal conductivity of the gas field.
W5-R	KAPLI	Thermal conductivity of the liquid field.
W6-A	UNITS	Thermal conductivity units specification.
W7-R	RHEATI	Overall interphasic heat transfer coefficient per unit volume:

RHEATI=Q/DELTEMP

where: Q=heat transfer rate per
unit volume,

DELTEMP=interphasic temperature
differences.

The units for RHEATI are specified
as joules/(second-cubic meter-degree
Kelvin).

Example:

00210 -32.174 FT SEC-2 0.02 0.38 BTU/HR-FT-DEGF 1.E4

00220 CARD - INTERPHASIC DRAG PARAMETERS (Required)

W1-R	NUV	Kinematic viscosity for the gas field.
W2-R	NUD	Kinematic viscosity for the liquid field.
W3-A	UNITS	Kinematic viscosity units specification.
W4-R	CDR	Droplet drag coefficient.
W5-R	RPAR	Droplet/bubble radius to be used in the drag calculations.
W6-A	UNITS	Length units specification for RPAR.
W7-R	PDENS	Number of droplets/bubbles per unit volume.
W8-A	UNITS	Volume units specification for PDENS.
W9-R	KDRAGI	Constant drag coefficient to be used (see KOPT) in newton-second/metre 4.

W10-I

KOPT

Drag model selection indicator.

=1 for constant drag equal to KDRAGI,
=2 for drag computation based on constant
bubble/droplet size, RPAR, using NUV,
NUD, CDR, and RPAR to calculate KDRAG,
(original KACHINA drag model),
=3 for drag computation based on constant
bubble/droplet density, PDENS, using
NUV,NUD,CDR, and PDENS to calculate
KDRAG, (Rivard drag model).

Example:

00220 4.E-5 2.E-6 FT2-SEC 1. 1. MM 1.E4 FT3 1.E4 1

00230 CARD - MASS TRANSFER PARAMETERS (Optional)

W1-I

JOPT

Mass transfer model option.

=0 for no mass transfer,
=1 for Rivard mass transfer,^[10]
=2 for dispersed flow model per Jones
and Saha^[11], (untested in BEACON).
=3 for slug flow per Jones and
Saha^[11], (untested in BEACON),
=4 for mist annular flow per Jones and
Saha^[11] (untested in BEACON).

W2-R

RLAME

Evaporation rate multiplier.

W3-R

RLAMC

Condensation rate multiplier.

Example:

00230 1 0.1 0.1

Default:

00230 0 0.0 0.0

00240 CARD - EQUATION OF STATE PARAMETERS (Required)

W1-A	EOSOPT	Equation of state model option indicator. =LASL to use the equation of state assumed by LASL in the KFIX code, (perfect gas and incompressible liquid), =BNL to use the BNL-based equations of state package, (real steam and liquid properties).
W2-A	EOSINP	Equation of state input pair indicator, must be input as PT as the code is presently restricted to pressure-temperature paired input.
W3-A	UNITS	Pressure units for first equation of state point input.
W4-A	UNITS	Temperature units for second equation of state point input.
W5-A	UNITS	Length unit specification for velocity inputs.
W6-A	UNITS	Reciprocal-time unit specification for velocity inputs.

Example:

00240 LASL PT LBF/IN2 DEGR FT SEC-1

00250 Card - WALL FILM MODELING PARAMETERS (Optional).

W1-R	THKMIN	Minimum film thickness (metre) at or below which the film temperature is calculated from the energy balance at the film/fluid interface and above which the film temperature is calculated from the solution of the transient energy equation.
W2-R	FDRAG	Friction Coefficient for film/fluid interface if film is present, or fluid/wall if film is not present.
W3-R	FDEN	Multiplier on film de-entrainment rate.
W4-R	FENT	Multiplier on film entrainment rate.
W5-R	DFUSON	Coefficient of diffusion for Fick's Law ($\text{metre}^2/\text{second}$).
W6-R	PRM	PRANDTL Number for air-vapor mixture.
W7-R	SURTEN	Liquid surface tension (newton/metre).

DEFAULT:

00250 0.01 0.0075 0.9 0.6 2.75E-05 0.7 0.07

1.3 Eulerian Region Input Data

The following cards contain information which is unique to Eulerian region geometry. For these cards, M denotes the mesh number to which the card applies. For example, card M1010 for mesh 12 of a problem would be labeled 121010. The same card for mesh 2 would be labeled 021010. All example cards will be shown for mesh 2. M=1,2,...20.

M1000 CARD - MESH AND CELL DIMENSIONS. (Required)

W1-A	GEOM	Geometry specification (See Figure 1) =CARTSN for Cartesian geometry, =AXISYM for axisymmetric geometry, =SPHERE for spherical geometry.
W2-I	IBAR	Number of interior cells in the radial /abscissa direction. ($1 \leq \text{IBAR} \leq 50$)
W3-I	JBAR	Number of interior cells in the axial /ordinate direction. Set to 1 if GEOM=SPHERE. ($1 \leq \text{JBAR} \leq 50$)
W4-R	DRCON	Cell dimension in the radial/abscissa direction.
W5-R	DZCON	Cell dimension in the axial/ordinate direction. Not used if GEOM=SPHERE.
W6-R	DEPTH/RO	Cell depth if GEOM=CARTSN or radius of the inside boundary if GEOM=AXISYM. Not used if GEOM=SPHERE.
W7-A	UNITS	Length units specification for the above dimensions.
W8-R	PHI	Orientation angle of external body force in degrees measured clockwise from the ordinate direction if GEOM=CARTSN. Internally set to zero if GEOM=AXISYM or SPHERE.
W9-R	XGR	Multiplier on gravity.

Example:

021000 CARTSN 11 14 1. 1. 1. FT 30. 1.

This card describes mesh 2 as being a rectangular region 11 feet high, 14 feet wide, and 1 foot deep which is tilted at a 30 degree angle from the vertical.

M1010 CARD - MESH WALL SLIP INDICATORS (Optional)

W1-A	LWALL	Left wall slip indicator. =SLIP for slip conditions, =NOSLIP for nonslip conditions.
W2-A	RWALL	Right wall slip indicator. =SLIP for slip conditions, =NOSLIP for nonslip conditions.
W3-A	BWALL	Bottom wall slip indicator. =SLIP for slip conditions, =NOSLIP for nonslip conditions.
W4-A	TWALL	Top wall slip indicator. =SLIP for slip conditions, =NOSLIP for nonslip conditions.

Example:

021010 SLIP NOSLIP NOSLIP NOSLIP

Default:

021010 SLIP SLIP SLIP SLIP

M1020 CARD - VARIABLE DR INPUT (Optional)

W(1)-R	DRTAB(1)	Array defining the DR dimension for
...	...	each interior column of the mesh.
...	...	Values override the value of DRCON
...	...	on the corresponding M1000 card.
W(IBAR)-R	DRTAB(IBAR)	IBAR on this card is the same value
		as IBAR on the corresponding card
		M1000. A maximum of 50 values is
		allowed due to memory allocations
		in the code.

Example:

021020 1.3 1.4 1.9 2.5 2.0 2.0 2.0 1.5 1.4 1.1 1.0

M1030 CARD - VARIABLE DZ INPUT (Optional)

W(1)-R	DZTAB(1)	Array defining the DZ dimension for
...	...	each row of the mesh. These values
...	...	override the value of DZCON on the
...	...	corresponding M1000 card. JBAR on
W(JBAR)-R	DZTAB(JBAR)	this card is the same value as JBAR
		on the corresponding card M1000. A
		maximum of 50 values is allowed due
		to memory allocations in the code.

Example:

021030 2.4 2.9 3.4 3.4 3.4 3.5 3.4 3.0 2.5 2.2 2.0
+ 2.0 2.0 2.0

M1050 CARD - WALL FILM (Optional)

W1-A	FLMOPT	Wall film indicator.
		= FILM for wall film,

= NOFILM for no wall film
for a given mesh.

Default:

021050 NOFILM

M1101-M1199 CARDS - FLUID REGION INPUT (Required. Note: Cards must be consecutively numbered. A skipped number will terminate reading of these cards.)

W1-A	FLUID	Type of fluid in the region of the mesh. = LIQUID for all liquid, = STEAM for all vapor, = AIR for all air, = MIXTURE for any combination of air, steam, and/or liquid.
W2,W3-I	IXI,JXI	I and J values ^[a] for the cell in the lower left corner of the fluid region.
W4,W5-I	IXF,JXF	I and J values ^[a] for the cell in the upper right corner of the fluid region.

[a] All cell indexing input, such as above and on subsequent input cards, are based upon the K-FIX cell indexing system. The computing mesh is surrounded by a layer of fictitious exterior cells and the indexing count starts at the first exterior cell. Thus, the first interior cell of the computing mesh (lower left corner) has the indices I=2 and J=2.

W6-I	NPUA	Number of plot particles per cell in this region. No particle plots are provided if NPUA = 0.
W7-R	SPV1	Fluid pressure in the region
W8-R	SPV2	Fluid temperature in the region. If FLUID = MIXTURE, SPV2 is the vapor field temperature.

The following are required if FLUID=MIXTURE

W9-R	SPV3	Liquid field temperature of the mixture.
W10-R	THIN	Void fraction of the mixture.
W11-R	XAIR	Mass fraction of the vapor field for air.

Example:

021101 MIXTURE 2 2 8 5 0 14.7 600. 600. 0.0 1.0

M1201-M1299 CARDS-INITIAL VELOCITY INPUT (Optional. NOTE:

Cards must be consecutively numbered. A skipped number will terminate reading of these cards.)

W1,W2-I	IXI,JXI	I and J values for the lower left cell in the velocity region.
W3,W4-I	IXF,JXF	I and J values for the upper right cell in the velocity region.

W5-R	UGIN	Abscissa/radial gas velocity at the right edge of each cell.
W6-R	ULIN	Abscissa/radial liquid velocity at the right edge of each cell.
W7-R	VGIN	Ordinate/axial gas velocity at the top edge of each cell.
W8-R	VLIN	Ordinate/axial liquid velocity at the top edge of each cell.

Note: All defined cell edges will be set to the specified values except where a rigid boundary is encountered. The velocities at rigid boundaries are set to zero. The component of velocity in the abscissa/radial direction at the center of each cell is the average of the velocities at the right and left edges of the cell. Similarly, the ordinate/axial velocity is the average of the top and bottom edges. The total velocity at the center of the cell is the vector sum of the averages.

Example:

021201 2 2 5 4 0.707 0.707 0.707 0.707

M1301-M1399 CARDS PARTIAL FLOW INPUT (Optional)

W1,W2-I	IXI,JXI	I and J values for the lower left cell of the partial flow region.
W3,W4-I	IXF,JXF	I and J values for the upper right cell of the partial flow region.
W5-R	FLOI	Multiplier on cell volume and flow area. Obstruction equals 1 minus FLOI.

W6-R	FRICT	Coefficient of friction in radial/ abscissa direction
W7-R	FZICT	Coefficient of friction in axial/ ordinate direction.

Example:

021301 4,3, 7,5, 0.7, 0.3, 0.1

Default:

021301 2,2, 12, 15, 1.0, 0.0, 0.0

M1401-M1499 CARDS - OBSTACLE REGION INPUT. (Optional)

W1-A	OCTYPE	Obstacle boundary slip indicator =SLIP for slip conditions, =NOSLIP for nonslip conditions.
W2,W3-I	IXI,JXI	I and J values for the lower left cell of the obstacle region.
W4,W5-I	IXF,JXF	I and J values for the upper right cell of the obstacle region.

Note: The minimum allowable obstacle region is 2 cells by 2 cells
when surrounded on all four sides by fluid cells.

Example:

021401 SLIP 2 2 4 4

M1501-M1599 CARDS - BOUNDARY FLOW OPTIONS. (Optional)

W1-A	BTYPE	Boundary flow type. =INFLOW for constant inflow, =OUTFLOW for constant outflow, =CONSTP for constant pressure boundary.
W2,W3-I	IXI,JXI	I and J values for the lower or left specified cell.
W4,W5-I	IXF,JXF	I and J values for the lower or left specified cell.

Note: Inflow boundaries may only be specified along a left or bottom wall boundary. Outflow and constant pressure boundaries may only be specified along a right or top wall boundary.

EXAMPLE:

021501 INFLOW 2 1 6 1

M1601-M1699 CARDS EXTERIOR BOUNDARY CELL STATE CONDITIONS.

(Required if BTYPE = INFLOW or CONSTP. See Cards M1501-M1500)

W1-A	FLUID	Type of fluid in the region of the mesh. =LIQUID for all liquid, =STEAM for all vapor, =AIR for all air, =MIXTURE for any combination of air, steam, and/or liquid.
------	-------	---

W2-R	SPV1	Fluid pressure in the region.
W3-R	SPV2	Fluid temperature in the region. If FLUID = MIXTURE, SPV2 is the vapor field temperature.

The following are required if FLUID = MIXTURE

W4-R	SPV3	Liquid field temperature of the mixture.
W5-R	THIN	Void fraction of the mixture.
W6-R	XAIR	Mass fraction of the vapor field for air.

Example:

021601 MIXTURE 14.7 100.0 600. 0.5 1.0

M1701-M1799 CARDS - INFLOW VELOCITIES (Required only if BTYPE = INFLOW.
See Cards M1501-M1599)

W1-R	UGIN	Abscissa-radial inflow velocity component of the air/vapor field.
W2-R	VGIN	Ordinate/axial inflow velocity com- ponent of the air/vapor field.
W3-R	ULIN	Abscissa-radial inflow velocity component of the liquid field.
W4-R	VLIN	Ordinate/axial inflow velocity com- ponent of the liquid field.

Example:

021701 20.0 50.0 20.0 50.0

1.4 Lumped-Parameter Region Input Data

For the following cards, L denotes the lumped parameter region to which the card applies. For example, card L2000 for lumped parameter region number 4 would be 042000. The example cards are shown for region 2. $L = 1, 2, 3, \dots$ These cards contain information required to describe lumped parameter regions.

L2000 CARD - GEOMETRIC AND INTERPHASIC TRANSFER FUNCTIONS FOR THE LUMPED PARAMETER REGIONS (Required for each lumped parameter region.)

W1-A	ZEROD	Not currently used, but must contain nonblank characters.
W2-R	VOLUME	Total fluid volume of the lumped parameter region.
W3-A	UNITS	Volume units specification.
W4-R	RHEAT	Overall interphasic heat transfer coefficient per unit volume.

$$RHEAT = Q/T$$

where: Q = heat transfer rate per unit volume.

T = the interphasic temperature difference.

Units for RHEAT are joules/(sec-
ond-meter²-degree Kelvin).

W5-R ZLAME Evaporation rate multiplier.

W6-R ZLAMC Condensation rate multiplier.

Example:

022000 ZEROD 10000. FT3 1.E4 0. 0.

L2010 CARD - LUMPED-PARAMETER REGION STATE CONDITIONS (Required for
each lumped parameter region.)

W1-A FLUID Type of fluid in the region.
=LIQUID for all liquid,
=STEAM for all vapor,
=AIR for all air,
=MIXTURE for any combination of
air, steam, and/or liquid.

W2-R SPV1 Fluid pressure in the region.

W3-R SPV2 Fluid temperature in the region.
If FLUID = MIXTURE, SPV2 is the
vapor field temperature.

The following are required if FLUID = MIXTURE

W4-R SPV3 Liquid field temperature of the
mixture.

W5-R THIN Void fraction of the mixture.

W6-R XAIR Mass fraction of the vapor field
for air.

Example:

022010 MIXTURE 14.7 100.0 600.0 0.5 1.0

1.5 Source Cell Input Data

Source cell data cards are described in this section. For the following cards, S denotes the source number to which the card applies. For example, card 2960 for source number 5 would be $2960 + 5 \times 50 = 3210$. All example cards will be shown for source 2.

S=1,2,3,...20

2960+50S CARD - SOURCE DESCRIPTION CARD (Optional)

W1-A	SUBST	Type of fluid from the source. =LIQUID for all liquid, =AIR for all air, =STEAM for all steam.
W2-I	MESHNO/NZD	Mesh number (MESHNO) in which the source is located if ISTAR and JSTAR are nonzero or the lumped parameter region number (NZD) if ISTAR or JSTAR are zero.
W3,W4-I	ISTAR,JSTAR	I and J values of the cell where source is located. Both if in lumped-parameter region.
W5-I	NTABLE	First card number on which the flow table for this source is located. Note that different sources may reference the same table.

The following inputs are optional. Default values are as shown.

W6-R	ANGLE	Angle at which the source fluid is entering the cell. ANGLE is measured counter-clockwise from the radial/abscissa direction. Default = 0.0.
W7-A	UNITS	Angular units specification for angle. (See Table II) Default = RADIANS.
W8-R	XMASS	Multiplier on the source mass flow rate. Default = 1.0.
W9-R	XENRGY	Multiplier on the source flow specific enthalpy. Default = 1.0.
W10-R	XVEL	Multiplier on the source velocity. Default = 1.0.
W11-R	TOFSET	Time offset on the table values. The computational time which corresponds to the zero table value. Default = 0.0.

Example:

003060 LIQUID 3 3 4 003062 30. DEG 1.0 1.0 0.5 0.

2961+50S CARD - TABLE UNITS SPECIFICATION (Required if a source exists.)

W1-A	UNITS	Time units specification.
W2-A	UNITS	Mass flow rate units specification.

W3-A	UNITS	Specific enthalpy units specification.
W4-A	UNITS	Length units specification for velocity.
W5-A	UNITS	Reciprocal-time units specification for velocity.

Example:

003061 SEC SEC LB/SEC BTU/LB FT SEC-1

2962+50S-2976+50S CARDS - SOURCE TABULAR INPUT VALUES (Required if source is present. Up to 15 inputs per source.)

W1-R	TSORCE	Time value at which the following values are defined.
W2-R	FLOMAS	Mass flow rate of the source.
W3-R	FLONRG	Specific enthalpy of the source flow.
W4-R	FLOVEL	Velocity of the source.

NOTE: The program will use linear interpolation between defined points and continue to use the final input values if the problem is run beyond the final time point for the source.

Example:

003062 0. 500. 1190. 200.
003063 10. 0. 1190. 0.

1.6 Region Coupling Input Data

The following cards are required when region coupling is specified.

006001-006999 CARDS - EULERIAN REGION INPUT (Optional. See Figure 8)

W1-A	SIDEX	Edge of the first mesh (number MESHX) which is coupled to the second (number MESHY). =LEFT for left edge, =RIGHT for right edge, =BOTTOM for bottom edge, =TOP for top edge.
W2-I	MESHX	Mesh number of the first coupled region.
W3,W4-I	IX,JX	I and J values of the first, (lower left) interface cell of mesh number MESHX.
W5-I	NCX	Total number of interface cells in mesh number MESHX.
W6-I	MESHY	Mesh number of the second coupled region.
W7,W8-I	IY,JY	I and J values of the first, (lower left) interface cell of mesh number MESHY.

W9-I NCY Total number of interface cells in
 mesh number MESHY.

NOTE: NCX must equal NCY.

Example:

006001 LEFT 2 2 4 5 1 9 4 5

007001-007050 CARD - LUMPED-PARAMETER COUPLING INPUT (Optional. See
Figure 9)

W1-A	SIDE	Edge of the one-dimensional mesh to which the lumped parameter region is coupled. =LEFT for left edge, =RIGHT for right edge, =BOTTOM for bottom edge, =TOP for top edge.
W2-I	MESHNO	Mesh region number to which the lumped parameter region is coupled.
W3,4-I	I1D,J1D	I and J value of the interface cell.
W5-1	NZD	Number of the coupled lumped para- meter region.
W6-R	ARJZ	Area ratio for form loss calcula- tions, not presently used.

Example:

007001 LEFT 1 2 2 1 1.0

1.7 Heat Structure Input Data

This card series describes the configuration of heat structures and boundary conditions and controls needed for the solution process. Heat structures may be attached to any cell, group of cells, or lumped parameter region. The term "mesh point" will be used in referring to one of the NCOL points in the calculational grid. The term "mesh space" refers to one of the (NCOL-1) spaces between mesh points (see Figure 20). The numbering of mesh points and mesh spaces begins at the nominal left end of the heat structure.

Data common to all heat structures must be input whenever a heat structure is present.

Heat structures must be numbered sequentially beginning with one. The symbol YY will be used for the heat structure identifier as a reminder of this constraint.

1000001 CARD-HEAT STRUCTURE DESCRIPTION UNITS. This card is required if heat structure is present.

W1-A	Length units for geometry data.
W2-A	Power units for heat source data.
W3-A	Temperature units.

1000002 CARD-HEAT STRUCTURE COMMON DATA. This card is required if heat structure is present.

W1-I	IFGSS	Initialization option flag =0 for the code to calculate initial mesh point temperatures based on steady state conditions in the heat structure. = -1 for transient start
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W2-A Time units for time step size.

W3-R DTHSI Time step size for heat structure calculation. This should be an integer multiple of DTZD (Card 00180), or DTI (Card 00110).

1000000 CARD - COMMON DATA UNITS. If heat structure is present the first two fields on this card are required. The third field is entered only if needed.

W1-A Thermal conductivity units for material properties.

W2-A Volumetric heat capacity units for material properties.

W3-A Heat transfer coefficient units for miscellaneous Heat Transfer Coefficient Card 10002II.

1000101 CARD - MATERIAL PROPERTIES. This card is required if any heat structure is present. These words are grouped in pairs, with each pair numbered sequentially from one, referring to the composition numbers on the Composition Overlay Description Card 1YY03II. Up to ten different material compositions may be entered.

W1-R Thermal conductivity for material one.

W2-R Volumetric heat capacity for material one.

... Up to ten pairs of thermal conductivity and volumetric heat capacity may be entered until the different materials present in all heat structures have been entered.

1000201 CARD - MISCELLANEOUS HEAT TRANSFER COEFFICIENT.

This card is required if option 1 through 10 is entered for either IHTCVL, IHTCLL, IHTCVR or IHTCLR on Card 1YY0009. Word 3 on Card 1000000 must also be entered.

W1-R through W10-R Heat transfer coefficient for Option 1.
An arbitrary number of additional values
may be entered, up to a maximum of 10,
with the second value representing
Option 2, and so forth.

21XX000 CARDS - TABULAR HEAT TRANSFER COEFFICIENT TITLE. This
card is optional, and may contain up to 64 columns of title information enclosed in apostrophes (') for tabular data table 1XX.

21XX001 CARDS - TABULAR HEAT TRANSFER COEFFICIENT UNITS. This
card is required if option 1XX which indicates the presence of a table is entered for either IHTCVL, IHTCLL, IHTCVR or IHTCLR on Card 1YY0009. The index 1XX for the table is the same as the option index 1XX. One table may be referenced by one or several heat structures.

W1-A Table type identifier switch.
= TIME for a time-dependent table.
= TEMP for a temperature-dependent table.
= RATIO for a table which is a function of the
mass ratio of air to steam ($m_{\text{air}}/m_{\text{steam}}$) in
either a lumped-parameter region, single cell, or
group of cells, depending on heat structure
connection.

W2-A Enter units corresponding to Word 1 for either
time, temperature, or dimensionless quantities.
For dimensionless quantities, enter NONE.

W3-A

Enter heat transfer coefficient units.

21XX002-21XX099 CARDS - TABULAR HEAT TRANSFER COEFFICIENT TABLE.

These cards follow the Units Specification Card 21XX001, and, consequently, must begin at 02.

W1-R HTV1 Independent variable value for table. Type of variable is specified by Word 1 on Card 21XX001.

W2-R HTV2 Heat transfer coefficient value.

. . . An arbitrary number of pairs of values up to 100 may be entered. The range of this table must include all values of the independent variable which may be encountered in the problem.

1YY0000 CARD HEAT STRUCTURE TITLE. This optional card contains up to 64 columns of title information for heat structure, YY, enclosed in apostrophes (').

1YY0001 CARD - HEAT STRUCTURE CONTROL. This card is required for each heat structure.

W1-I NCOL Number of mesh points (must be greater than 2 and less than 52).

W2-I IGEOM Geometry type.
 = 1 for rectangular,
 = 2 for cylindrical,
 = 3 for spherical.

W3-R X0 Arbitrary coordinate for mesh point one (the nominal left boundary).

W4-R	FCTR	Heat source multiplier.
W5-I	MAXIT	Iteration limit for initial steady state solution. A value of 100 is recommended.
W6-R	EPS	Convergence criterion on heat structure mesh temperatures for steady state solution in initial- ization section. Always enter 0.01.
W7-R		Always enter 0.0.

CARD 1YY0002 HEAT STRUCTURE CONNECTION. This card is required for each heat structure. Valid regions or cells must be entered for both sides of the structure unless the DUMMY option is used.

W1-A

Left boundary selection switch.
 =LUMPED if left boundary is adjacent to a
 lumped-parameter region,
 =SINGLE if left boundary is adjacent to a
 single cell.
 =MULTI if left boundary is adjacent to a
 group of cells (this is the multicell model),
 =DUMMY if the user wishes the code to esta-
 blish an insulated condition on the left
 boundary. BEACON will automatically choose
 no film and zero heat transfer for this sur-
 face, regardless of user input on
 Cards 1YY0003 and 1YY0009.

W2-I

IHMSHL

Left boundary location identifier.
 =lumped-parameter region number if Word 1 is
 LUMPED,

=mesh number where cell(s) is located if
Word 1 is SINGLE or MULTI,
=enter zero if Word 1 is DUMMY.

W3-I,W4-I

Left boundary cell identifiers.
=zero for each word if Word 1 is LUMPED or
DUMMY,
=the I and J values, respectively for the
single cell if Word 1 is SINGLE,
=the I and J values, respectively, for the
cell in the lower left corner of the multi-
cell region if Word 1 is MULTI.

W5-I,W6-I

Left boundary cell identifiers.
=zero for each word if Word 1 is LUMPED or
DUMMY or SINGLE,
=the I and J values, respectively, for the
cell in the upper right corner of the multi-
cell region if Word 1 is MULTI. Obstacle
cells inside this rectangular array of cells
are bypassed in the calculation.

W7 through W12

The right boundary is described using the
last six words. The format is identical to
the first six words except now the right
boundary is referred to instead of the left
boundary.

1YY0003 CARD - SURFACE AREA AND FILM TYPE. This card is required
for each heat structure. FACES option may be specified for multicell
regions regardless of obstacle cells. No more than one heat structure
may be connected to each side (top, bottom left, right, and faces) or
any cell in a Eulerian Region.

W1-A

Units for ARA. Enter area units for rectangular, length units for cylindrical, or none for spherical geometry.

W2-R

ARA

Heat transfer surface multiplier for boundaries. The HEAT1 subcode computes heat flux per unit area for rectangular geometry, heat flux per unit height for cylindrical geometry, and for the entire sphere for spherical geometry. The heat transfer from the subcode is then multiplied by ARA to obtain actual heat transfer. Thus ARA may be slab surface area, cylinder height, or sphere fraction, and may be further modified to reflect incomplete surfaces; e.g., use height/2 for a half cylinder.

W3-A

IFILML

Connection type for left side of heat structure.

=NONE if no coupling to this side of heat structure is desired. Use this option for all insulated (DUMMY) surfaces and lumped parameter connections. NONE will default to FACES if connected to Eulerian region; therefore, no other NONE or FACES connections may be specified for the cells on this card;

=LEFT for connection on left side of cell,

=RIGHT for connection on right side of cell,

=TOP for connection on top of cell,

=BOTTOM for connection on bottom of cell,

=FACES for connection on front and back surfaces of cell.

W4-A IFILMR Connection type for right side of heat structure. The same choices available under Word 3 are used here.

1YY0200 CARD - MESH INCREMENT FORMAT. This card is required for each heat structure.

W1-I If the mesh increment data from a previously described structure are being used, enter the number of that heat structure, YY. Otherwise, enter zero.

W2-I If the mesh increment data from a previously described structure are being used, omit this field and ignore the next card. If not, enter the format (either 1 or 2, as described below) of the Mesh Increment Cards
1YY0201-1YY0299.

1YY0201-1YY0299 CARDS MESH INCREMENT DESCRIPTION. This card is required only if Word 2 on Card 1YY0200 is 1 or 2. Use the format specified on Card 1YY0200. A mesh interval is a set of mesh spaces that are the same length.

Format 1:

W1-I Number of mesh spaces in this mesh interval.

W2-R Coordinate of the mesh point forming the nominal right boundary of this mesh interval with respect to coordinate X0 on Card 1YY0001.

...

An arbitrary number of pairs of mesh space number and mesh point coordinate may be entered until all the mesh spaces (NCOL-1 from Card 1YY0001) have been described.

Format 2:

W1-R

Length of each mesh space in this interval.

W2-I

Number of mesh space forming the nominal right boundary of this mesh interval.

...

An arbitrary number of pairs of mesh space length and mesh point number may be entered until all the mesh spaces (NCOL-1 from Card 1YY0001) have been described.

1YY0301-1YY0399 COMPOSITION OVERLAY DESCRIPTION. Either this card or the following card is required for each heat structure. Composition numbers are keyed to the values on the Material Property Card 1000101 e.g. composition number 1 refers to the first pair of values on the material properties cards. Composition numbers apply to each mesh space in the region.

W1-I

Composition number.

W2-I

Mesh space number of the right-hand space in the region of composition listed for Word 1.

...

An arbitrary number of pairs of composition number and mesh space number may be entered until all mesh spaces (NCOL-1 from Card 1YY0001) have been described.

1YY0300 CARD - COMPOSITION OVERLAY REPEAT. This card is required for each heat structure which does not use the 1YY0301-1YY0399 cards.

W1-I Number of heat structure, YY, for which composition overlay was previously described. That structure must have the same mesh description as the present heat structure.

1YY0401-1YY0499 CARDS - SOURCE DISTRIBUTION DESCRIPTION. Either this card or the following card is required for each heat structure. Heat source values apply to mesh spaces. A heat source value of zero means there are no heat sources present in the heat structure.

W1-R Heat source value.

W2-I Mesh space number of the rightmost mesh space in region with source of Word 1.

... An arbitrary number of pairs of heat source value and mesh space number may be entered until all mesh spaces (NCOL-1 from Card 1YY0001) have been described.

1YY0400 CARD - SOURCE DISTRIBUTION REPEAT. This card is required for each heat structure which does not use the previous card.

W1-I Number of heat structure for which source distribution was previously described. That structure must have the same mesh description as the present heat structure.

1YY0601-1YY0699 CARDS - INITIAL TEMPERATURE ESTIMATE. Either this card or the following card is required for each heat structure. An estimated initial temperature distribution must be supplied to

begin the steady state solution process. Temperature values apply to mesh points. If steady-state initialization has been selected, the values on this card will be ignored (See Card 1000002).

W1-R Estimated initial temperature for mesh points
in region described by Word 2 on this card.

W2-I Mesh point number at nominal right boundary
of region of constant estimated initial
temperature.

... An arbitrary number of pairs of initial
temperature and mesh number may be entered
until all mesh points (NCOL from
Card 1YY0001) have been described.

1YY0600 CARD - INITIAL TEMPERATURE ESTIMATE REPEAT. The card is
required for each heat structure which does not use the previous card.

W1-I Number of heat structure for which initial
temperature estimate was previously given.
That structure must have been the same mesh
description as the present heat structure.

1YY0009 CARD - HEAT TRANSFER COEFFICIENT CONTROL. This card is
required for each heat structure. Valid choices for heat transfer
coefficient control options are listed following the fourth word. At
least one of the four words must be nonzero; i.e., both sides of a
heat structure cannot be specified as being insulated.

W1-I IHTCVL Left boundary vapor heat transfer coefficient
option.

W2-I	IHTCLL	Left boundary liquid heat transfer coefficient option.
W3-I	IHTCVR	Right boundary vapor heat transfer coefficient option.
W4-I	IHTCLR	Right boundary liquid heat transfer coefficient option.

Valid options are:

= 0 for heat transfer coefficient of 0.0 indicating a symmetrical or insulated (DUMMY) condition.

=1 through 10 for heat transfer coefficient of corresponding entry on Miscellaneous Heat Transfer Coefficient Card 1000201 which is a constant value.

=11 for best estimate heat transfer coefficient calculated within the BEACON Code.

=101 through 199 for input tabular heat transfer coefficient values. Types of tables available are listed under Tabular Heat Transfer Coefficient Units Card 21XX001. The corresponding table number, 1XX, is the heat transfer coefficient option number on this card.

2. OUTPUT DESCRIPTION

Output from the BEACON code includes print output, plot output, and post-processed plot output. These are described in the following sections. Certain portions of the print output are optional, selected by user input. Plot output, also optional, consists of time-frame plots of marker particles, velocity vectors, and contour maps of selected cell quantities. Time-history plots are also optionally available by means of post-processing of a plot file tape.

2.1 Print Output

The print output consists of a sequence of different types or groupings of printed data as depicted in Figure 23. These types of output are discussed as follows:

- (1) CARD IMAGE LISTING. The first section of output consists of a listing of the input data deck for the case exactly as it appears on the cards and as is shown in Figure 24.
- (2) BASIC PROGRAM AND FLUID REGION INPUT EDIT. The input edit is printed by BEACON as each set of data is processed. The value of each parameter is printed after it has been operated upon and converted to SI units, if necessary, and stored in its working location. Any errors or disallowed inputs will be flagged including any required input which is missing. Figures 25 and 26 present sample input edits of the basic program input and of the input for Eulerian regions. Similar input edits are obtained for the lumped parameter input, coupling input, and source input.

Fig. 23 Sequence of printed output.

LISTING OF INPUT DATA FOR CASE 1

```

1  00100  'PARTIAL FLOW TEST CASE, DUCT FLOW, MAZE'
2  00110  0.0, 0.5, 0.0001, SEC, 2.0, 1, NDXEQ
3  00120  0.050, 2.0
4  00130  AUTUDT, 0, 0.1, 1.5
5  00140  PRINT, NOPRINT, PRINT, NOPRINT, NOPRINT
6  00150  PLOTS, 0.9, 1 1 0 0 0 0 0 0 0 0 0 0
7  00200  1.5, 0.00010, 0.00010, 300, 5, 0
8  00210  0.0, FT SEC-2, 0.020, 0.38, BTU/HR-FT-DEGF, 1.0E06
9  00220  0.0, 0.0, FT2/SEC, 1.0, 1.0, MM, 23800.0, FT3, 1.0E04, 1
10 00230  0, 0.0, 0.0
11 00240  LASL, PT, N/M2, DEGK, M, SEC-1
12 11000  CARTSN, 5, 12, 4.0, 4.0, 2.6667, FT, 0.0, 1.0
13 11101  MIXTURE 2, 2, 6, 13, 0, 1.0E05, 309.1, 309.1, 0.999, 0.9
14 11501  INFLOW 2, 1, 6, 1
15 11601  MIXTURE 2.0E05, 309.1, 309.1, 0.999, 0.9
16 11701  0.0, 20.0, 0.0, 20.0
17 11502  OUTFLOW 2, 14, 6, 14
18 11301  2, 4, 4, 4, 0.1, 3.0, 3.0
19 11302  4, 7, 6, 7, 0.1, 3.0, 3.0
20 11303  2, 10, 4, 10, 0.1, 3.0, 3.0
21 .

```

Fig. 24 Input card image.

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```

      INP COMPUTING TIME= 1.60000E-02 SEC      INP DATA STORAGE REQUIRED= 174 WORDS
PROBLEM DESCRIPTION:  PARTIAL FLOW TEST CASE, DUCT FLOW, HAZE
RESTART PARAMETERS:  ITD= 0  NTD= 1  NSDMP= 1
PROBLEM TIMES:  TI= 0.          TSTOP= 5.000E-01  DTI= 1.000E-04  CPTAIN= 2.0  NTSO= 1  XEQ=NOXEQ
DTD(1-10)= 5.000E-02  0.          0.          0.          0.          0.          0.          0.          0.          0.
TOC(1-10)= 2.000E+00  0.          0.          0.          0.          0.          0.          0.          0.          0.
AUTO.DT PARAMETERS:  AUTODT=AUTODT  NCYDT= 0  XDTC= 1.000E-01  XMDT= 1.500E+00
PRINT OPTIONS:  PROPT=PRINT  XCPRNT=NOPRINT  SLPRNT=PRINT  SCPRNT=NOPRINT  DBPRNT=NOPRINT  NCYDB=9999
PLOTS OPTIONS:  PLOPT=PLOTS  SCALEI= 9.000E-01
CONTOUR PLOT SELECTION ARRAY, 0=NO PLOT, 1=PLOT
      TH  P  RGP1  RGP  RLP  SIEG  SIEL  JE-JC  KORAG  TG  TL  TS  FTEMP  FMASS
      1  1  0  0  0  0  0  0  0  0  0  0  0  0
COUPLING MODE INPUT:  XMODE=SINGLE  CELDIM=CONST  FLOPT=NOFLOSS
ITERATION PARAMETERS:  OMEGA= 1.500E+00  EPSG= 1.000E-04  EPSL= 1.000E-04  ITMAX= 300  LMAX= 5  KMAX= 0
PHYSICAL PARAMETERS:  GRAV= 0.          KAPGI= 3.461E-02  KAPLI= 6.577E-01  RHEATI= 1.000E+06
DRAG PARAMETERS:  NUV= 0.          NUD= 0.          CDR= 1.000E+00  RPAR= 1.000E-03  PDENS= 8.405E+05  KORAGI= 1.000E+04  KOPT= 1
PHASE CHANGE PARAMETERS:  JUPT= 0  RLAME= 0.          RLAMC= 0.
EOS INPUT UNITS:  EOSOPT=LASL  EOSINP=PT  USPV1=N/M2  USPV2=DEGK  UVEL1=M  UVEL2=SEC-1
EOS UNITS FACTORS:  XSPV1(1,2)= 1.000E+00  0.          XSPV2(1,2)= 1.000E+00  0.          XVEL= 1.000E+00
WALL FILM MODELING PARAMETERS:  THKMIN= 1.0000E-02  FDRAG= 7.5000E-03  FDEN= 9.0000E-01  FENT= 6.0000E-01
      DFUSON= 2.7500E-05  PRM= 7.0000E-01  SURTEN= 7.0000E-02

```

Fig. 25 Edit of basic program input.

-----COMPUTING MESH INPUT DATA, MESHNO= 1

GEOM IBAR JBAR DRCON DZCON DEPTH PHI XGR RO
 CARTSN 5 12 1.2192E+00 1.2192E+00 8.1281E-01 0. 1.0000E+00 0.
 RIGID WALL BOUNDARY CONDITIONS: LSIDE=SLIP RSIDE=SLIP BSIDE=SLIP TSIDE=SLIP

RADIAL ARRAYS, I=1,IB2

I	R	1/R	1/RDR	RB	1/RB	RPLT
1	1.0000E+00	1.0000E+00	8.2021E-01	1.0000E+00	1.0000E+00	-6.0960E-01
2	1.0000E+00	1.0000E+00	8.2021E-01	1.0000E+00	1.0000E+00	6.0960E-01
3	1.0000E+00	1.0000E+00	8.2021E-01	1.0000E+00	1.0000E+00	1.8288E+00
4	1.0000E+00	1.0000E+00	8.2021E-01	1.0000E+00	1.0000E+00	3.0480E+00
5	1.0000E+00	1.0000E+00	8.2021E-01	1.0000E+00	1.0000E+00	4.2672E+00
6	1.0000E+00	1.0000E+00	8.2021E-01	1.0000E+00	1.0000E+00	5.4864E+00
7	1.0000E+00	1.0000E+00	8.2021E-01	1.0000E+00	1.0000E+00	6.7056E+00

FLUID REGION INITIAL CONDITIONS, MESHNO= 1

NREG	FLUID	IXI	JXI	IXF	JXF	PIN THIN	TGIN TLIN	RGIN RUGIN	RGPLIN XAIR	RLPIN ROLIN	CGIN CLIN	SIEGIN SIELIN
1	MIXTURE	2	2	6	13	1.00000E+05 9.99000E-01	3.09100E+02 3.09100E+02	1.06149E+00 1.06255E+00	1.06149E-01 9.00000E-01	9.90000E-01 9.90000E+02	7.88280E+02 4.18680E+03	4.41875E+05 1.50515E+05

FLUID REGION INPUT PROCESSED-NO ERRORS

THERE ARE NO OBSTACLE REGIONS DEFINED

PARTIAL BLOCKAGE REGIONS FOR MESHNO= 1

NOPB	IXI	JXI	IXF	JXF	FLU
1	2	4	4	4	1.00000E-01
2	4	7	6	7	1.00000E-01
3	2	10	4	10	1.00000E-01

PARTIAL BLOCKAGE REGION INPUT PROCESSED - NO ERRORS

NON-RIGID BOUNDARIES FOR MESHNO= 1

NBDY	BTYPE	IXI	JXI	IXF	JXF	PIN THIN UGIN	TGIN TLIN VGIN	RGIN RUGIN ULIN	RGPLIN XAIR VLIN	RLPIN ROLIN	CGIN CLIN	SIEGIN SIELIN
1	INFLOW	2	1	6	1	2.00000E+05 9.99000E-01 0.	3.09100E+02 3.09100E+02 2.00000E+01	2.12298E+00 2.12510E+00 0.	2.12298E-01 9.00000E-01 2.00000E+01	9.90000E-01 9.90000E+02	7.88280E+02 4.18680E+03	4.41620E+05 1.50515E+05

2. OUTFLOW 2 14 6 14

BOUNDARY INPUT PROCESSED-NO ERRORS

THERE ARE NO INITIAL VELOCITY INPUT

WALL FILM OPTION=NOFILM

PROCESSING COMPLETED FOR MESHNO= 1 NQI= 462 NCMESH= 98 NCLEFT=1887

ECHO PRINT OF STORED MULTIMESH DATA ARRAYS

MESHNO	GEOM	IJ11	IBAR	JBAR	DEPTH	PHI	XGR	RO	NOBST	FLHOPT
1	CARTSN	1	5	12	8.1281E-01	0.	1.0000E+00	0.	0	NOFILM
DRTAB, MESHNO= 1 I=1, 7										
1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00		
DZTAB, MESHNO= 1 J=1, 14										
1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00
1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00	1.219E+00

-----SOURCE CELL INPUT DATA

THERE ARE NO SOURCE ADDITIONS

Fig. 26 Edit of Eulerian region input.

- (3) MESH MAPS. This output includes a printout of the mesh cell flags and cell locations in map or matrix form, i.e., by rows and columns, as shown in Figures 27 and 28, respectively. The cell flag map provides a final check on the correctness of the mesh setup. The cell location map is useful for debug purposes and for defining specific cell quantities to be post-processed by the BEACON plot file program.
- (4) HEAT STRUCTURE INPUT EDIT. The echo print of the heat structure input is after the input edits for the fluid regions setup. Figure 29 presents a sampling of the heat structure input edit.
- (5) TRANSIENT OUTPUT. Transient data are printed periodically as specified by the output time control parameters. This output set shows the current state conditions existing in each cell for each mesh, as well as summations of the mass, momentum, and, energy for each mesh. All values shown in this set of output are in the International System (SI) of Units. Figure 30 shows a portion of the cell data output for a typical mesh. Output for lumped parameter regions is similar to the above.

Transient output for heat structures is also obtained at the same time that output for fluid regions is obtained. Figure 31 shows the sample output for heat structures.

		MAP OF CELL FLAGS FOR MESH NO. 1											
CELL I=	TYPE: CELL FLAG:	CELL FLUID		RIGID/SLIP		RIGID/NOSLIP		OUTFLOW 4	INFLOW 5	PARTIAL BLOCKAGE 6	CONSTP 7	ZEROD 8	INTERFACE .GT. 50
		1	2	3	4	5	6						
14	2	4	4	4	4	4	2						
13	2	1	1	1	1	1	2						
12	2	1	1	1	1	1	2						
11	2	1	1	1	1	1	2						
10	2	6	6	6	1	1	2						
9	2	1	1	1	1	1	2						
8	2	1	1	1	1	1	2						
7	2	1	1	6	6	6	2						
6	2	1	1	1	1	1	2						
5	2	1	1	1	1	1	2						
4	2	6	6	6	1	1	2						
3	2	1	1	1	1	1	2						
2	2	1	1	1	1	1	2						
1	2	5	5	5	5	5	2						

CELCHK-ALL CELLS HAVE BEEN DEFINED FOR MESH NO. 1

Fig. 27 Map of cell flags.

CELL IJ VALUES FOR MESH NO. 1

I=	1	2	3	4	5	6	7
J=							
14	6007	6073	6139	6205	6271	6337	6403
13	5545	5611	5677	5743	5809	5875	5941
12	5083	5149	5215	5281	5347	5413	5479
11	4621	4687	4753	4819	4885	4951	5017
10	4159	4225	4291	4357	4423	4489	4555
9	3697	3763	3829	3895	3961	4027	4093
8	3235	3301	3367	3433	3499	3565	3631
7	2773	2839	2905	2971	3037	3103	3169
6	2311	2377	2443	2509	2575	2641	2707
5	1849	1915	1981	2047	2113	2179	2245
4	1387	1453	1519	1585	1651	1717	1783
3	925	991	1057	1123	1189	1255	1321
2	463	529	595	661	727	793	859
1	1	67	133	199	265	331	397

Fig. 28 Map of cell locations.

--- HEAT-1 ARRAYS INITIAL DATA SETUP IN SI UNITS

```

-----DATA FOR HEAT STRUCTURE NO. 1-----GEOM=RECTAN  NO.NODES= 6  MAXIT=100  EPS= 1.000E-02
MESH INCR.= 5.081E-02  5.081E-02  5.081E-02  5.081E-02  5.061E-02
SURF. WGT.= 1.968E+01  1.968E+01  1.968E+01  1.968E+01  1.968E+01
VOL. WGT.= 2.541E-02  2.541E-02  2.541E-02  2.541E-02  2.541E-02  0.  0.  2.541E-02  2.541E-02
V.W.SOURCE.= 0.  0.  0.  0.  0.  0.
SOURCE.= 0.  0.  0.  0.  0.  0.
INI. TEMP.= 2.864E+02  2.864E+02  2.864E+02  2.864E+02  2.864E+02  2.864E+02
INTEG.SOURCE.= 0.  0.  0.  0.  0.  0.  LEFT BDRY= 0.  LEFT AREA= 1.000E+00  RIGHT AREA= 1.000E+00

-----DATA FOR HEAT STRUCTURE NO. 2-----GEOM=RECTAN  NO.NODES= 3  MAXIT=100  EPS= 1.000E-02
MESH INCR.= 2.134E-03  2.134E-03
SURF. WGT.= 4.687E+02  4.687E+02
VOL. WGT.= 1.067E-03  1.067E-03  0.  0.  1.067E-03  1.067E-03
V.W.SOURCE.= 0.  0.  0.
SOURCE.= 0.  0.  0.
INI. TEMP.= 2.864E+02  2.864E+02  2.864E+02
INTEG.SOURCE.= 0.  0.  0.  LEFT BDRY= 0.  LEFT AREA= 1.000E+00  RIGHT AREA= 1.000E+00

```

HEAT STRUCTURE INITIALIZATION AND TIMESTEP IFGSS= -1 OTHSI= 1.00000E-03

-----MATERIAL THERMAL PROPERTIES

MATL. NO.	THERMAL CONDUCTIVITY (WATT/M-DEGK)	VOL. HEAT CAPACITY (J/M3-DEGK)
1	1.73073E+00	2.21452E+06
2	5.20086E+01	3.68931E+06
3	2.05957E+02	2.37951E+06

-----HEAT STRUCTURE DESCRIPTIONS

HEAT STRUCTURE NO.	DESCRIPTION
1	ROOM 4 (MESH 3), LEFT CONCRETE
2	ROOM 4 (MESH 3), STEEL
3	ROOM 4 (MESH 3), ALUMINUM

-----HEAT STRUCTURES BOUNDARY CONDITIONS

HEAT STRUCT. NO.	DSA INDEX	H.T. SURF. MULTIPLIER	SURFACE FILM		HEAT TRANSFER COEF. OPTION					
			LEFT SIDE	RIGHT SIDE	L.VAP.	L.LIQ.	R.VAP.	R.LIQ.		
NO.	(II)	(ARA)	(IFILML)	TYPE	(IFILMR)	TYPE	(IHTCVL)	(IHTCLL)	(IHTCVR)	(IHTCLR)
1	201	3.86198E+01	6	FACES	0	NONE	11	11	11	11
2	231	3.16688E+01	6	FACES	0	NONE	11	11	0	0
3	261	1.20031E+00	6	FACES	0	NONE	11	11	0	0

Fig. 29 Edit of heat structure input.

RJDTB7E MESHNO		12.1/78 NCR= 1	06.31.08. TIME= 1.60000E-02	SAMPLE OUTPUT PR CYCLE= 20		JEDN=CARTSN	XMODE=MULTI		EOSOPT=LASL	KOP.
I	J	FL	P TH FMAS	UG UL VFLMX	VG VL VFLMY	TG TL FTEMP	SIEG SIEL TS	RGP RLP XMG1	KDRAG RHEAT JE-JC	
2	2	1	1.00009E+05 1.00000E+00 0.	2.43716E-03 2.43716E-03 0.	-1.05586E-02 -1.05586E-02 0.	2.86398E+02 2.86398E+02 2.86350E+02	2.22014E+05 5.54673E+04 2.82744E+02	1.21109E+00 0. 7.50000E-03	1.00000E+20 1.00000E+05 0.	
3	2	1	1.00010E+05 1.00000E+00 0.	-9.27824E-03 -9.27824E-03 0.	-2.72848E-03 -2.72848E-03 0.	2.86363E+02 2.86363E+02 2.86350E+02	2.21989E+05 5.53206E+04 2.82745E+02	1.21124E+00 8.73914E-17 7.50000E-03	1.00000E+20 1.00000E+05 9.68448E-20	
4	2	1	1.00022E+05 1.00000E+00 0.	-9.07328E-02 -9.07328E-02 0.	-1.26150E-02 -1.26150E-02 0.	2.86388E+02 2.86388E+02 2.86350E+02	2.22007E+05 5.54250E+04 2.82746E+02	1.21131E+00 8.22748E-16 7.50000E-03	1.00000E+20 1.00000E+05 9.72923E-20	
5	2	1	1.00116E+05 1.00000E+00 0.	-6.14125E-01 -6.14125E-01 0.	-1.17185E-01 -1.17185E-01 0.	2.86498E+02 2.86498E+02 2.86350E+02	2.22086E+05 5.58854E+04 2.82760E+02	1.21218E+00 6.17272E-15 7.50000E-03	1.00000E+20 1.00000E+05 9.85840E-20	
6	2	1	1.00746E+05 1.00000E+00 0.	-2.71408E+00 -2.71408E+00 0.	-1.02943E+00 -1.02943E+00 0.	2.87138E+02 2.87138E+02 2.86350E+02	2.22549E+05 5.55663E+04 2.82854E+02	1.21805E+00 4.08646E-14 7.50008E-03	1.00000E+20 1.00000E+05 1.07125E-19	
7	2	1	1.03431E+05 1.00000E+00 1.35998E-46	0. 0. 0.	-7.28992E+00 -7.28992E+00 0.	2.89245E+02 2.89245E+02 2.86350E+02	2.24156E+05 6.73847E+04 2.83322E+02	1.24406E+00 2.59685E-12 7.53844E-03	1.00000E+20 1.00000E+05 1.34271E-19	
2	3	1	1.00006E+05 1.00000E+00 0.	9.10848E-03 9.10848E-03 0.	9.11744E-03 9.11744E-03 0.	2.86357E+02 2.86357E+02 2.86350E+02	2.21984E+05 5.52941E+04 2.82744E+02	1.21122E+00 0. 7.50000E-03	1.00000E+20 1.00000E+05 0.	
3	3	1	1.00006E+05 1.00000E+00 0.	-1.55041E-02 -1.55041E-02 0.	5.55392E-04 5.55392E-04 0.	2.86361E+02 2.86361E+02 2.86350E+02	2.21987E+05 5.53115E+04 2.82744E+02	1.21120E+00 1.03378E-16 7.50000E-03	1.00000E+20 1.00000E+05 9.68044E-20	
4	3	1	1.00022E+05 1.00000E+00 0.	-1.44598E-01 -1.44598E-01 0.	-1.39361E-02 -1.39361E-02 0.	2.86381E+02 2.86381E+02 2.86350E+02	2.22001E+05 5.53954E+04 2.82746E+02	1.21136E+00 1.25464E-15 7.50000E-03	1.00000E+20 1.00000E+05 9.70186E-20	
5	3	1	1.00154E+05 1.00000E+00 0.	-1.02172E+00 -1.02172E+00 0.	-1.38223E-01 -1.38223E-01 0.	2.86520E+02 2.86520E+02 2.86350E+02	2.22102E+05 5.59774E+04 2.82766E+02	1.21259E+00 7.97672E-15 7.50001E-03	1.00000E+20 1.00000E+05 9.87834E-20	
6	3	1	1.01028E+05 1.00000E+00 0.	-5.07904E+00 -5.07904E+00 0.	-1.31302E+00 -1.31302E+00 0.	2.87244E+02 2.87244E+02 2.86350E+02	2.22650E+05 5.90077E+04 2.82918E+02	1.22091E+00 7.55171E-13 7.51140E-03	1.00000E+20 1.00000E+05 1.08855E-19	
7	3	1	1.04748E+05 1.00000E+00 0.	0. 0. 0.	-1.76933E+01 -1.76933E+01 -7.08193E-21	2.90349E+02 2.90349E+02 2.86350E+02	2.30303E+05 7.20098E+04 2.87756E+02	1.26519E+00 1.89677E-10 9.97944E-03	1.00000E+20 1.00000E+05 -2.90161E-08	
2	4	1	1.00001E+05 1.00000E+00 0.	1.61813E-03 1.61813E-03 0.	0. 0. 0.	2.86367E+02 2.86367E+02 2.86350E+02	2.21991E+05 5.53364E+04 2.82743E+02	1.21111E+00 0. 7.50000E-03	1.00000E+20 1.00000E+05 0.	

150

Fig. 30 Output of cell variables.

HEAT STRUCTURE EDITING

HEAT STRUCTURE NO.	---CONNECTION TYPE---		---BULK TEMPERATURE---		---HEAT TRANSFER COEF.---		---ENERGY TRANSFER RATE---	
	LEFT SIDE	RIGHT SIDE	LEFT SIDE (KELVIN)	RIGHT SIDE	LEFT SIDE (W/M2-K)	RIGHT SIDE	LEFT SIDE (WATT)	RIGHT SIDE
1	ROOM 4 (MESH 3), LEFT CONCRETE	MULTI-CELL LUMPED P	286.374	286.350	.561874	.765009	-.523742	2.662838E-03
2	ROOM 4 (MESH 3), STEEL	MULTI-CELL DUMMY CELL	286.329	286.350	.641510	0.	.424305	0.
3	ROOM 4 (MESH 3), ALUMINUM	ONE CELL DUMMY CELL	286.427	286.350	.561963	0.	-5.172984E-02	0.
4	ROOM 6 (MESH 1), LOWER CONCRETE	MULTI-CELL LUMPED P	286.153	286.350	5.05878	.760339	-410.550	3.085300E-03
5	ROOM 6 (MESH 1), STEEL	MULTI-CELL DUMMY CELL	286.350	286.350	3.653773E+09	0.	-30.8992	0.
6	ROOM 6 (MESH 1), ALUMINUM	ONE CELL DUMMY CELL	286.355	286.350	.561917	0.	-2.856871E-02	0.
7	ROOM 9 (LPR 1), CONCRETE	LUMPED P DUMMY CELL	286.350	286.350	.760339	0.	6.100356E-02	0.
8	ROOM 9 (LPR 1), STEEL	LUMPED P DUMMY CELL	286.350	286.350	.760339	0.	2.185422E-02	0.
9	ROOM 9 (LPR 1), ALUMINUM	LUMPED P DUMMY CELL	286.350	286.350	.760339	0.	1.390711E-03	0.
10	ROOM 6 (MESH 1), UPPER CONCRETE	MULTI-CELL LUMPED P	286.350	286.350	4.157146E+09	.760339	-7829.23	3.085300E-03
11	ROOM 4 (MESH 3), RIGHT CONCRETE	MULTI-CELL LUMPED P	286.363	286.350	.561890	.765009	-.291442	2.662838E-03

STRUCT. NO.	NO. PTS.	MESH POINT TEMPERATURES					
1	6	286.35	286.35	286.35	286.35	286.35	286.35
2	3	286.35	286.35	286.35			
3	3	286.35	286.35	286.35			
4	6	286.35	286.35	286.35	286.35	286.35	286.35
5	3	286.35	286.35	286.35			
6	3	286.35	286.35	286.35			
7	6	286.35	286.35	286.35	286.35	286.35	286.35
8	3	286.35	286.35	286.35			
9	3	286.35	286.35	286.35			
10	6	286.35	286.35	286.35	286.35	286.35	286.35
11	6	286.35	286.35	286.35	286.35	286.35	286.35

Fig. 31 Output of heat structures.

- (6) ITERATION STATUS. An optional output is a single-line iteration status report printed for every computational cycle, Figure 32. This print shows the current time, the timestep interval taken, the iteration passes required, maximum fluid velocities in the radial and axial directions, and the Courant timestep. This output provides a convenient check on how well the transient computations are proceeding and will generally denote any impending stability problems.
- (7) OUTPUT IN MAP FORM. As in printing cell flags and cell locations in (3) above, other cell variables may be printed in map form as part of the transient output. This is an optional output and any cell variable may be selected. Figure 33 shows a sample print of gas temperature (variable 43 as defined in the input section). The variable output may also be normalized to the maximum value of the selected variable as an added option.

Other types of output are obtained from BEACON but are not specifically shown or described. These include: computing times for different computational parts of the code; total system mass and energy summations and fractional changes from initial values thereof; and job summary execution statistics.

To assist the user in interpreting the output, Table V presents a list of output variable definitions. This is in addition to the definitions given in the input section. For the most part, code variable names are mnemonically oriented and can be readily interpreted.

T= 1.700E-02	DT= 1.000E-03	CTL= 14.0	NCR= 1	NCYC=	21	NIT= 5	NCF=***	VNR= 1.365E+01	VMZ= 2.022E+01	DTC= 4.203E-02
T= 1.800E-02	DT= 1.000E-03	CTL= 14.0	NCR= 1	NCYC=	22	NIT= 5	NCF=***	VNR= 1.625E+01	VMZ= 2.252E+01	DTC= 3.774E-02
T= 1.900E-02	DT= 1.000E-03	CTL= 14.0	NCR= 1	NCYC=	23	NIT= 5	NCF=***	VNR= 1.897E+01	VMZ= 2.461E+01	DTC= 3.454E-02
T= 2.000E-02	DT= 1.000E-03	CTL= 14.0	NCR= 1	NCYC=	24	NIT= 5	NCF=***	VNR= 2.178E+01	VMZ= 2.650E+01	DTC= 3.207E-02

Fig. 32 Output of iteration status.

VARIABLE 43 FOR MESHNO= 1									
I=	1	2	3	4	5	6	7	8	
J=									
5	0.	0.	0.	0.	0.	0.	0.	0.	0.
4	0.	2.06367E+02	2.86364E+02	2.86367E+02	2.06566E+02	2.87449E+02	3.04069E+02	0.	0.
3	0.	2.86357E+02	2.86361E+02	2.86381E+02	2.86520E+02	2.87244E+02	2.90349E+02	0.	0.
2	0.	2.86398E+02	2.86363E+02	2.86388E+02	2.86498E+02	2.87138E+02	2.89245E+02	0.	0.
1	0.	0.	0.	0.	0.	0.	0.	0.	0.

Fig. 33 Map output of cell variables.

TABLE V

DEFINITION OF OUTPUT VARIABLES

ARJTAB	Table of Junction Area Ratios, not used at present.
ARJZ	Junction Area Ratio, not used at present.
CGIN	Initial gas specific heat.
CLIN	Initial liquid specific heat.
CTL	Computing time left.
CYCLE	Computation cycle number.
DEDEDO	Fractional change in total liquid energy of system.
DEVEVO	Fractional change in total gas energy of system.
DMDMDO	Fractional change in total liquid mass of system.
DMVMVO	Fractional change in total gas mass of system.
DV1V10	Fractional change in total steam mass of system.
DT	Timestep interval.
DTC	Courant timestep interval.
E	Summation of total liquid and gas energy.
ED	Summation of total liquid energy.
EGTOT	Total gas energy.
ELTOT	Total liquid energy.
EV	Summation of total gas energy.
FL	Cell flag.
FMASS	Film mass.

TABLE V (continued)

FMASS1	Film mass on a side of convex corner.
FTEMP	Film temperature.
FTEMP1	Film temperature on a side of convex corner.
I	Column index of mesh.
IALL	Final memory location used in the cell data storage array AASC.
IBARX	Number of interior cells in the radial/abscissa direction for MESHX.
IBARY	Number of interior cells in the radial/abscissa direction for MESHY.
IE	Summation of internal energy.
IED	Summation of liquid internal energy.
IEV	Summation of gas internal energy.
IJ	Storage location in the data storage array for a cell.
IJX	Storage location of a coupled cell in MESHX.
IJY	Storage location of a coupled cell in MESHY.
IJZD	Storage location of a lumped parameter region.
IJID	Storage location of a I-D/lumped parameter coupled cell.
IJIDX	Storage location of the exterior cell of a I-D/lumped parameter coupled cell.
IJ11	Storage location of the first cell in a mesh.
IJ11X	First storage location of MESHX.

TABLE V (continued)

IJ11Y	First storage location of MESHY.
I1DTAB	I-value storage array for lumped parameter coupling cells.
J	Row index of mesh.
JBARX	Number of interior cells in the axial/ordinate direction of MESHX.
JBARY	Number of interior cells in the axial/ordinate direction of MESHY.
JC	Condensation Rate.
JE	Evaporation Rate.
J1DTAB	J-value storage array for lumped parameter coupling cells.
KDRAG	Momentum exchange function.
KE	Summation of total liquid and gas kinetic energy.
KED	Summation of liquid kinetic energy.
KEV	Summation of gas kinetic energy.
MD	Summation of liquid mass.
MD1	Summation of liquid mass (same as above).
MD2	Not used.
MESHNO	Mesh number.
MLTOT	Total mass of liquid.
MNTAB	Mesh number storage array.
MOMR	Summation of momentum in the radial/abscissa direction.
MOMZ	Summation of momentum in the axial/ordinate direction.

TABLE V (continued)

MOMZD	Summation of momentum of liquid in the axial/ordinate direction.
MOMZV	Summation of momentum of gas in the axial/ordinate direction.
MV	Summation of gas mass.
MVTOT	Total gas mass in system.
MV1	Summation of steam mass.
MV1TOT	Total steam mass in system.
MV2	Summation of air mass.
NCF	Number of cells that failed to converge, not used at present.
NCLEFT	Number of unused cell spaces.
NCMESH	Number of cells in the mesh.
NCR	Computing region number.
NCYC	Computation cycle number, same as CYCLE.
NDATA	Total number of words of memory required to store the input data.
NJCT	Junction number for inter-mesh coupling.
NJZ	Coupling number.
NJZTOT	Total number of 1-D/lumped-parameter couplings.
NOBST	Number of obstacle regions.
NQI	Number of variables in the mesh array in the I-direction.
NVAP	Gas field indicator =0 for no air vapor region. =1 for vapor only. =2 for air only. =3 for air-vapor mixture.

TABLE V (continued)

NZDTAB	Storage array for lumped parameter regions.
P	Pressure.
PIN	Initial pressure.
R	Radial distance of cell center.
RB	Radial distance of cell edge.
RDR	Product of R and DR.
RGP	Partial density of the gas.
RGPIN	Initial partial density of the gas.
RGP1	Partial density of the steam or water vapor.
RGP1IN	Initial partial density of the steam or water vapor.
RHEAT	Interphasic heat exchange function.

TABLE V (continued)

RLP	Partial density of the liquid.
RLPIN	Initial partial density of the liquid.
ROGIN	Initial density of the gas.
ROGIN	Initial density of the steam or water vapor.
ROLIN	Initial density of the liquid.
RPLT	Radial distance for plot output computations.
SEDT	Summation of liquid energy for total system.
SEVT	Summation of gas energy for total system.
SIDTAB	Storage array for boundary orientation of coupled cells.
SIEG	Specific internal energy of the gas.
SIEGIN	Initial specific internal energy of the gas.
SIEL	Specific internal energy of the liquid.
SIELIN	Initial specific internal energy of the liquid.
SMDT	Summation of liquid mass for total system.
SMVT	Summation of gas mass for total system.
SMV1T	Summation of water vapor mass for total system.
T	Time.
TG	Temperature of the gas.
TGIN	Initial temperature of the gas.
TH	Void fraction.
TL	Temperature of the liquid.

TABLE V (continued)

TLIN	Initial temperature of the liquid.
TS	Saturation temperature.
UG	Gas velocity in the radial/abscissa direction.
UL	Liquid velocity in the radial/abscissa direction.
USPV1	Pressure units for the equation of state input.
USPV2	Temperature units for the equation of state input.
UVEL1	Length units for velocity inputs.
UVEL2	Reciprocal time units for velocity input.
VFLMX	Film velocity in radial direction.
VFLMY	Film velocity in axial direction.
VG	Gas velocity in the axial/ordinate direction.
VL	Liquid velocity in the axial/ordinate direction.
VLIQ	Summation of liquid volume.
VMR	Maximum radial flow velocity in a mesh.
VMZ	Maximum axial flow velocity in a mesh.
VOLUME	Volume of the lumped parameter region.
XAIR	Mass fraction of gas that is air.
XMG1	Mass fraction of gas that is steam.
XSPV1	Conversion factors for input pressure to SI units.
XSPV2	Conversion factors for input temperature to SI units.
XVEL	Conversion factor for input velocity to SI units.

2.2 Plot Output

The plots output from BEACON are spatially dimensioned plots at a given problem time (time-frame plots). Three different types of these plots are obtained:

- (1) MARKER PARTICLE PLOTS. Marker particles can be specified for different parts of the mesh region in varying proportions. These particles are carried along with the flow but do not influence the flow. Particle plots are useful in following the motion of the components of each field. Figure 34 shows a sample particle plot at initial time and at some later time. Particle plots are restricted to single mesh problems.
- (2) VELOCITY VECTOR PLOTS. Velocity vector plots, Figure 35, are obtained for the vapor and liquid fields, and for liquid film on the mesh walls if present. A line is drawn outward from the center of each cell in the problem mesh (designated by a "+" on the plot) that is proportional to the magnitude of and in the direction of the velocity at the cell center. The vector length is scaled so that the longest vector will not reach past the center of an adjacent cell. The actual velocity corresponding to the longest vector is listed below each plot.
- (3) CONTOUR PLOTS. Contour plots are obtained for selected cell quantities, Figure 36. The contour plot quantity is selected by user input (See input description of card 150 for list of cell quantities). Contour plots are plots of lines joining equal-valued points of a cell quantity in the flow field and are generated by a

Fig. 34 Marker particle plot.

Fig. 35 Velocity vector plot.

Fig. 36 Contour plot of void fraction.

linear interpolation between the highest and lowest values of a cell quantity. Ten contour lines are drawn equally spaced between the highest and lowest values of the cell quantity plotted. The highest valued contour line is marked with an "H" on the plot, the lowest with an "L", and the corresponding numerical values are listed below each plot. The increment between contour values is denoted "DQ". The maximum and minimum values are also printed on the plot. Contour plotting requires at least a 2 by 2 fluid cell region. Therefore, contour plots for one-dimensional region are not obtained.

2.3 Postprocessed Plots

A post-processing plot program, PLTBCN, has been developed as part of the BEACON/MOD2A code. This program utilizes the BEACON restart tape to generate time-history plots of selectable cell quantities. Appendix B presents a description of the post-processing plot capabilities and required input.

3. TAPE RESTART

The purpose of tape restart is to reduce computer costs and facilitate parametric studies by providing the capability to make a computer run which starts with initial conditions that are calculated results from a previous run. This entails writing pertinent variables to a tape periodically during a run or reading a tape written by an earlier run to obtain initial conditions. A tape restart job is similar to a normal job in that all input cards are processed as before. Tape restart input parameters on card 105 then indicate the tape read and/or write mode, tape restart cycle number, and tape write frequency. The appropriate set of data from the restart tape is read which overrides the initial conditions established by the input cards.

Subroutine RESTART both reads and writes the restart tapes. For the write mode, that is, the creation of a restart tape, RESTART functions as follows: If at input time the variable ITD (Card Number 105) is set to 1 or 3, then the user wants to create a restart tape. The first information that is written to the restart tape is a non-time dependent array needed by the transient calculation areas of BEACON; this array is IJTAB. Then the variables IALL and ISUMM1 are written to the restart tape. These variables represent the length of the dynamic storage commons CELCOM and FAST. The above information is written exactly once to the restart tape and constitutes the first record on the tape. Record 2 on the tape is of the form NTD, NITTOT, DT, TIME, (AASC(K), K=1, IALL), ZTAB, NCYTAB where NTD is the number of the tape dump and the other arrays and variables are necessary to resume the transient calculations. Record (3) on the tape is of the form (DSA(K), K=1, ISUMM1). Then the rest of the tape contains another record like that of record (2), another record like that of record (3), and so on in repetitive manner. The tape writes are binary writes and their frequency is controlled by the input parameter NSDMP.

Subroutine RESTART works as follows in the read mode: If at input time the variable ITD is set to 2 or 3 this means that the current run is to start from a restart tape. The first record of the tape is read and is checked against the current input to see if there are any fatal errors. Fatal errors are caused by changes in mesh geometry, coupling information, number of Eulerian regions, and total number of computing regions between the original run that created the restart tape and the current one. If fatal errors are found, an error message is printed and the job is immediately aborted. If no fatal errors are found, the second record of the tape is read. If the input value of NTD does not match the value read from the tape, the next record on the tape is read. This process is repeated until the proper

starting point is found. In the event a mistake has been made with the input value of NTD, a match may never be found. In this case, the restart tape is then read to its end at which time an error message is issued and the run is aborted.

V. SAMPLE PROBLEMS

A series of seven sample problems has been selected to check out and demonstrate the various modeling features of the BEACON/MOD2A code. The problems range from a simple single-region example to the more complicated mixed-dimensional, multi-region setups. The first five problems have all been run before to check out previous versions of BEACON. They were rerun with MOD2A to insure that no errors were introduced into this new version of the code. The last two problems were designed specifically to check out the four new options developed for MOD2A, partial flow, variable mesh, wall film, and heat structures.

The seven problems presented are:

- (1) Single Eulerian region, closed boundaries
- (2) Flow boundaries and obstacle cells
- (3) Mixed-dimensional, multi-region coupling
- (4) Lumped parameter and unequal area coupling
- (5) Source cell addition
- (6) Partial flow
- (7) Dry, multicompartiment containment with wall film and heat structures.

The specific modeling features illustrated with each of the problems are noted in Table VI.

TABLE VI
SAMPLE PROBLEM MODELING FEATURES

MODELING FEATURE	1	2	3	4	5	6	7
Cartesian geometry		X	X	X	X	X	X
Axisymmetric geometry	X						
Variable mesh spacing [a]							X
Flow boundaries		X	X			X	
Obstacle cells		X					
Partial flow cells [a]						X	
Source Addition					X		X
One-Dimensional Flow				X			X
Lumped Parameter				X			X
Mixed-dimensional, Multi-region Coupling			X	X			X
Wall Film [a]							X
Heat Structures [a]							X

[a] New option added for MOD2A.

Each case is presented with a problem discussion, illustration of the configuration, and modeling description. The input data in card image form is also given.

Results for each problem are presented in the form of both plots and interpretive discussions. Vapor, liquid, and film velocity vector plots are shown, where applicable. Contour or time history plots of void fraction, pressure, temperature, and film mass are also given for various problems. Where the BEACON computer plots are presented, the legends are also included for interpretive purposes. For these plots, time is given in seconds, pressure in N/m^2 , velocity in m/s , temperature in K, and film mass in kg.

The results are to be interpreted qualitatively rather than quantitatively, inasmuch as each problem was only intended to check out certain modeling features of the BEACON code and they are not verification-type problems. In most cases, the expected flow phenomena and results are self-explanatory.

1. SINGLE EULERIAN REGION, CLOSED BOUNDARIES

This problem illustrates the use of the BEACON code with essentially the least number of modeling options exercised. It is therefore one of the more simple BEACON problems to set up. The problem models a rising slug of air in a circular tank as shown in Figure 37. At the initial problem time, an air bubble is released from the bottom of the tank and allowed to rise. The right half of the circular cylinder is divided into an axisymmetric computing mesh. There are 7 cells radially from the centerline and 10 cells axially along the line of symmetry. The air bubble is formed by a 2 by 2 cell region at the lower left corner of the computing mesh. All of the boundaries are assumed rigid with free-slip.

A listing of the necessary input data is shown in Figure 38. The left hand column of numbers lists the card number required to identify each input data card.

Plots output at a problem time of one second are presented to illustrate the resultant flow pattern. Vapor and liquid velocity vectors are shown in Figures 39 and 40, respectively. Void fraction and pressure gradients are shown in Figures 41 and 42, respectively.

The behavior of the problem is as expected. The air slug rises under the influence of gravity producing convection currents in the liquid. The rate of bubble rise is influenced by the interphasic momentum or drag force. In this example, the interphasic forces are modeled based on a dispersed or bubbly-type flow interaction. It is noted that in the time span computed, the vapor and liquid regions have become diffused. The diffusion occurs due to the lack of a sharp interface tracking capability in BEACON.

Fig. 37 Configuration for Sample Problem 1 which demonstrates a simple BEACON problem setup.

```

00100 'EXAMPLE PROBLEM 1: SINGLE EULERIAN REGION, CLOSED BOUNDARIES'
*****BASIC PROBLEM INPUT
00110 0.0, 1.0, 0.001, SEC, 2.0, 20, XEQ
00120 0.001, 0.02, 0.002, 0.1, 0.005, 2.0
00130 AUTODT, 10, 0.1, 1.0E06
00140 PRINT, NOPRINT, PRINT, PRINT, NOPRINT
00150 PLOTS, 0.9, 1 1 0 0 0 0 0 0 0 0
00200 1.5, 0.00001, 0.00001, 300, 5, 5
00210 -32.174, FT SEC-2, 0.020, 0.38, BTU/HR-FT-DEGF, 10000.0
00220 1.5E-04, 2.8E-06, FT2/SEC, 1.0, 1.0, MM, 23800.0, FT3, 1.0E04, 2
00230 0, 0.0, 0.0
00240 LASL, PT, N/M2, DEGK, M, SEC-1
*****EULERIAN REGION INPUT
11000 AXISYM 7, 10, 1.0, 1.0, 0.0, FT, 0.0, 1.0
11010 SLIP, SLIP, SLIP, SLIP
11101 MIXTURE 2,2,3,3, 0, 1.0E05, 350.0, 350.0, 1.00, 1.0
11102 MIXTURE 4,2,8,3, 0, 1.0E05, 350.0, 350.0, 0.00, 1.0
11103 MIXTURE 2,4,8,11, 0, 1.0E05, 350.0, 350.0, 0.00, 1.0

```

Fig. 38 Input card listing for Sample Problem 1.

EXAMPLE PROBLEM 1 SINGLE EULERIAN REGION, CLOSED BOUNDARIES

VAPOR, MAXIMUM VELOCITY = 2.62013+00
 TIME= 1.000+00 CYCLE= 242 MESH= 1 GEOM= AXISYM JNM= JARTBSS

Fig. 39 Vapor velocity vectors at 1s for Sample Problem 1.

EXAMPLE PROBLEM 1 SINGLE EULERIAN REGION. CLOSED BOUNDARIES

DROPLETS
TIME= 1.000+00
CYCLE= 242
MAXIMUM VELOCITY = 1.69127+00
MESH= 1
GEOM= AXISYM
JNM= JART055

Fig. 40 Liquid velocity vectors at 1s for Sample Problem 1.

EXAMPLE PROBLEM 1 SINGLE EULERIAN REGION, CLOSED BOUNDARIES

VOID FRACT
 TIME= 1.000+00 CYCLE= 242 MESH= 1 GEOM= AXISYM JNM= JARTBSS
 MIN= 1.279-12 MAX= 2.940-01 L= 1.279-12 H= 2.646-01 DQ= 2.940-02

Fig. 41 Void fraction contours at 1s for Sample Problem 1

EXAMPLE PROBLEM 1 SINGLE EULERIAN REGION, CLOSED BOUNDARIES

PRESSURE
 TIME= 1.000+00 CYCLE= 242 MESH= 1 GEOM= AXISYM JNM= JART855
 MIN= 8.817+04 MAX= 1.148+05 L= 8.817+04 H= 1.121+05 QQ= 2.663+03

Fig. 42 Pressure contours at 1s for Sample Problem 1.

2. FLOW BOUNDARIES AND OBSTACLE CELLS

The configuration shown in Figure 43 demonstrates the use of specified flow boundaries and obstacle cells for a typical containment subcompartment analysis problem. The input data cards are shown in Figure 44. In this problem, compartments and passageways are formed by specifying regions of nonfluid, or obstacle cells (cards 11401 through 11403).

The fluid regions initially contain a vapor-liquid mixture at atmospheric pressure and a void fraction of 0.9. A vapor-liquid inflow of constant density and velocity is specified along the bottom boundary and a continuative outflow is specified along the right boundary of the mesh. The configuration is formed in Cartesian coordinates with gravitational force set to zero.

Velocity vector and pressure contour plots are shown in Figures 45 and 46 to illustrate the flow behavior at 0.5 seconds. The behavior is as expected: (1) Flow is diverted by the presence of obstacle boundaries, (2) velocities are higher in the narrow constrictions, (3) stagnant regions develop in corners and localized recirculation occurs in base regions and (4) pressure buildup occurs in stagnating areas and gradients develop where velocities are generally rapidly changing.

Fig. 43 Initial configuration for Sample Problem 2 which demonstrates flow boundaries and obstacle cells.

```

00100 'EXAMPLE PROBLEM 2: FLOW BOUNDARIES AND OBSTACLE CELLS'
*****BASIC PROBLEM INPUT
00110 0.0, 1.0, 0.001, SEC, 10.0, 20, XEQ
00120 0.001, 0.1, 0.0025, 2.0
00130 AUTODT, 1, 0.1, 1.0E06
00140 PRINT, NOPRINT, PRINT, NOPRINT, NOPRINT
00150 PLOTS, 0.9, 1 1 0 0 0 0 0 0 0 0 0 0
00200 1.5, 0.00010, 0.00010, 300, 5, 5
00210 0.0, FT SEC-2, 0.020, 0.38, BTU/HR-FT-DEGF, 10000.0
00220 1.5E-04, 2.8E-06, FT2/SEC, 1.0, 1.0, MM, 23800.0, FT3, 1.0E04, 1
00230 0, 0.0, 0.0
00240 LASL, PT, LBF/IN2, DEGR, FT, SEC-1
*****EULERIAN REGION INPUT
11000 CARTSN, 11, 14, 1.0, 1.0, 1.0, FT, 0.0, 0.0
11010 NOSLIP, NOSLIP, NOSLIP, NOSLIP
11101 MIXTURE 2, 2, 8, 5, 0, 14.7, 600.0, 600.0, 0.9, 1.0
11102 MIXTURE 2, 6, 4, 9, 0, 14.7, 600.0, 600.0, 0.9, 1.0
11103 MIXTURE 2, 10, 6, 15, 0, 14.7, 600.0, 600.0, 0.9, 1.0
11104 MIXTURE 7, 10, 8, 12, 0, 14.7, 600.0, 600.0, 0.9, 1.0
11105 MIXTURE 9, 10, 12, 15, 0, 14.7, 600.0, 600.0, 0.9, 1.0
*****OBSTACLE CELL INPUT
11401 NOSLIP, 9, 2, 12, 5
11402 NOSLIP 5, 6, 12, 9
11403 NOSLIP 7, 13, 8, 15
*****SPECIFIED BOUNDARY INPUT
11501 INFLOW 2, 1, 8, 1
11601 MIXTURE 14.7, 600.0, 600.0, 0.5, 1.0
11701 0.0, 10.0, 0.0, 10.0
11502 OUTFLOW 13, 10, 13, 15

```

Fig. 44 Input card listing for Sample Problem 2.

EXAMPLE PROBLEM 2 FLOW BOUNDARIES AND OBSTACLE CELLS

Fig. 45 Vapor velocity vectors at 0.5s for Sample Problem 2.

EXAMPLE PROBLEM 2 FLOW BOUNDARIES AND OBSTACLE CELLS

PRESSURE
 TIME= 5.000-01 CYCLE= 260 MESH= 1 GEOM= CARTSN JNM= JARTBSH
 MIN= 1.238+05 MAX= 1.445+05 L= 1.238+05 H= 1.425+05 DQ= 2.079+03

Fig. 46 Pressure contours at 0.5s for Sample Problem 2.

3. MIXED-DIMENSIONAL, MULTI-REGION COUPLING

Problem 3 demonstrates the Eulerian region coupling capability of BEACON. The configuration used in Sample Problem 2 was modeled by connecting several Eulerian regions as shown in Figure 47, thus eliminating the need for using obstacle regions. This problem was run to demonstrate that the results of modeling a containment with coupled Eulerian regions were consistent with the results obtained by modeling with a single region containing obstacle cells.

In addition to defining the fluid properties of the Eulerian regions, the connections between each region need to be defined. Input cards 006001 through 006004 in Figure 48 contain the information necessary to connect the five regions together.

The vapor velocity results for this problem are shown in Figure 49. As expected, these results match the results of Problem 2, showing the validity of the BEACON coupling logic.

Fig. 47 Initial configuration for Sample Problem 3 which demonstrates Eulerian region coupling.

```

00100  'EXAMPLE PROBLEM 3: MIXED-DIMENSIONAL, MULTI-REGION COUPLING'
*****BASIC PROBLEM INPUT
00110  0.0, 1.0, 0.001, SEC, 10.0, 20, XEQ
00120  0.001, 0.1, 0.0025, 2.0
00130  AUTODT, 1, 0.1, 1.0E06
00140  PRINT, NOPRINT, PRINT, NOPRINT, NOPRINT
00150  PLOTS, 0.45, 1 1 0 0 0 0 0 0 0 0
00160  MULTI, CONST
00170  5, 1, 1, 5
00200  1.5, 0.00010, 0.00010, 300, 5, 5
00210  0.0, FT SEC-2, 0.020, 0.38, BTU/HR-FT-DEGF, 10000.0
00220  1.5E-04, 2.8E-06, FT2/SEC, 1.0, 1.0, MM, 23800.0, FT3, 1.0E04, 1
00230  0, 0.0, 0.0
00240  LASL, PT, LBF/IN2, DEGR, FT, SEC-1
*****EULERIAN REGION INPUT
11000  CARTSN, 7, 4, 1.0, 1.0, 1.0, FT, 0.0, 1.0
21000  CARTSN, 3, 4, 1.0, 1.0, 1.0, FT, 0.0, 1.0
31000  CARTSN, 5, 6, 1.0, 1.0, 1.0, FT, 0.0, 1.0
41000  CARTSN, 2, 3, 1.0, 1.0, 1.0, FT, 0.0, 1.0
51000  CARTSN, 4, 6, 1.0, 1.0, 1.0, FT, 0.0, 1.0
11010  NOSLIP, NOSLIP, NOSLIP, NOSLIP
21010  NOSLIP, NOSLIP, NOSLIP, NOSLIP
31010  NOSLIP, NOSLIP, NOSLIP, NOSLIP
41010  NOSLIP, NOSLIP, NOSLIP, NOSLIP
51010  NOSLIP, NOSLIP, NOSLIP, NOSLIP
11101  MIXTURE 2, 2, 8, 5, 0, 14.7, 600.0, 600.0, 0.9, 1.0
21101  MIXTURE 2, 2, 4, 5, 0, 14.7, 600.0, 600.0, 0.9, 1.0
31101  MIXTURE 2, 2, 6, 7, 0, 14.7, 600.0, 600.0, 0.9, 1.0
41101  MIXTURE 2, 2, 3, 4, 0, 14.7, 600.0, 600.0, 0.9, 1.0
51101  MIXTURE 2, 2, 5, 7, 0, 14.7, 600.0, 600.0, 0.9, 1.0
*****SPECIFIED BOUNDARY INPUT
11501  INFLOW 2, 1, 8, 1
11601  MIXTURE 14.7, 600.0, 600.0, 0.5, 1.0
11701  0.0, 10.0, 0.0, 10.0
51501  OUTFLOW 6, 2, 6, 7
*****EULERIAN REGION COUPLING INPUT
006001  TOP 1, 2, 5, 3, 2, 2, 2, 3
006002  TOP 2, 2, 5, 3, 3, 2, 2, 3
006003  RIGHT 3, 6, 2, 3, 4, 2, 2, 3
006004  RIGHT 4, 3, 2, 3, 5, 2, 2, 3

```

Fig. 48 Input card listing for Sample Problem 3.

EXAMPLE PROBLEM 3 MIXED-DIMENSIONAL, MULTI-REGION COUPLING

VAPOR,
TIME= 5.000-01

CYCLE= 260

MAXIMUM VELOCITY =
MESH= 1

6.66587+00
GEOM= CARTSN

JNM= JARTBTR

Fig. 49 Vapor velocity vectors for Sample Problem 3 showing consistent results with Sample Problem 2.

4. LUMPED-PARAMETER AND UNEQUAL AREA COUPLING

The configuration shown in Figure 50 demonstrates lumped-parameter modeling and other aspects of the BEACON mixed-dimensional, multi-region coupling capability.

The configuration is a steady state flow problem in which pressure differences between the two semi-infinite lumped-parameter volumes establish a flow from left to right, with flow accelerating and then decelerating in the 1-D regions. The two one-dimensional regions have different cross sectional flow areas with a ratio of one to two. Figure 51 shows the required input data. Whenever unequal flow area coupling is desired, card 00160 must so indicate. The change in flow area is obtained with the appropriate input of cell dimensions on cards 11000 and 21000. The lumped parameter regions are used in this particular case to model invariant flow boundaries. The flow is two-phase with a void fraction of 0.9. No interphasic mass transfer is assumed.

The pressure and velocity variation in the 1-D regions at steady-state conditions are shown in Figure 52. The variation is as expected and typical of the behavior expected from 1-D pipe flow analysis. The pressure rapidly decreases as flow velocity increases in the first 1-D region, and actually drops below the pressure of the receiving lumped parameter region due to the acceleration of the fluid. Then, in the second and larger 1-D region the flow starts to decelerate due to the change in flow area and continuity considerations. There is also a corresponding change in the pressure gradient.

This problem also demonstrates the separated flow, unequal velocity capability of BEACON. Initially, the liquid flow lags the vapor flow due to inertial differences and to a nonhomogeneous, interphasic momentum exchange function modeling. At the abrupt area change the

Fig. 50 Initial configuration for Sample Problem 4 which demonstrates lumped-parameter regions and unequal area coupling.

```

00100 'EXAMPLE PROBLEM 4: LUMPED PARAMETER AND UNEQUAL AREA COUPLING'
*****BASIC PROBLEM INPUT
00110 0.0, 1.0, 0.0010, SEC, 2.0, 20, XEQ
00120 0.0010, 0.02, 0.0020, 0.1, 0.0025, 5.0
00130 AUTODT, 10, 0.1, 10.0
00140 PRINT, NOPRINT, PRINT, PRINT, NOPRINT
00150 NOPLOTS, 0.45, 0 0 0 0 0 0 0 0 0 0 0
00160 MULTI, UNEQUAL
00170 2, 1, 1, 2
00180 2, 0.01
00200 1.5, 0.00010, 0.00010, 300, 5, 5
00210 -32.174, FT SEC-2, 0.020, 0.38, BTU/HR-FT-DEGF, 10000.0
00220 4.0E-06, 2.0E-06, FT2/SEC, 1.0, 1.0, MM, 500000.0, FT3, 1.0E20, 3
00230 0, 0.0, 0.0
00240 LASL, PT, LBF/IN2, DEGR, FT, SEC-1
*****EULERIAN REGION INPUT
11000 CARTSN 5, 1, 1.0, 0.5, 3.28084, FT, 0.0, 0.0
21000 CARTSN 5, 1, 1.0, 1.0, 3.28084, FT, 0.0, 0.0
11010 NOSLIP, NOSLIP, NOSLIP, NOSLIP
21010 NOSLIP, NOSLIP, NOSLIP, NOSLIP
11101 MIXTURE 2, 2, 6, 2, 0, 20.0, 700.0, 700.0, 0.9, 1.0
21101 MIXTURE 2, 2, 6, 2, 0, 20.0, 700.0, 700.0, 0.9, 1.0
*****LUMPED PARAMETER REGION INPUT
12000 ZEROD 1.0E20, FT3, 10000.0, 0.0, 0.0
12010 MIXTURE 30.0, 700.0, 700.0, 0.9, 1.0
22000 ZEROD 1.0E20, FT3, 10000.0, 0.0, 0.0
22010 MIXTURE 20.0, 700.0, 700.0, 0.9, 1.0
*****EULERIAN REGION COUPLING INPUT
06C01 RIGHT 1, 6, 2, 1, 2, 2, 2, 1
*****LUMPED PARAMETER COUPLING INPUT
07001 LEFT 1, 2, 2, 1, 1.0
07002 RIGHT 2, 6, 2, 2, 1.0

```

Fig. 51 Input card listing for Sample Problem 4.

Fig. 52 Pressure and velocity variation at steady state conditions for Sample Problem 4.

vapor undergoes a rapid deceleration and approaches a discontinuity at the sudden expansion. However, the inertia of the liquid resists the sudden velocity change, with the result being a less rapid deceleration of the liquid flow and liquid velocities higher than the vapor velocities in the larger 1-D region.

5. SOURCE CELL ADDITION

Source cell modeling is demonstrated with this sample problem. A two-compartment arrangement is configured as shown in Figure 53. Four source cells are located in the lower and smaller compartment to introduce a vapor mass at an appropriate enthalpy. This problem demonstrates how a steam pipe break in a hypothetical loss-of-coolant accident could be modeled. The mesh compartments initially contain a vapor-liquid mixture of void fraction 0.5. Interphasic mass transfer is assumed to be zero. The mesh and obstacle walls are assumed rigid with no-slip boundary conditions.

Input data for this problem are shown in Figure 54. The source input cards are the 3000 numbered series. For each source, the mass flow rate is initially zero, increasing to 100 kg/s at 0.01 second and remaining constant for the duration of the problem. The enthalpy level remains constant throughout, and must be input even if the mass flow rate is zero.

Plot output results are shown for a problem time of 1.0 seconds. The vapor velocity vector plot in Figure 55 shows that velocities in the constriction and in the lower compartment are still high but that in the upper compartment flow conditions are starting to stagnate due to the lack of any place for the flow to go. The void fraction contours in Figure 56 indicate that the vapor source has essentially displaced the initial vapor-liquid mixture in the lower compartment. Lastly, the pressure distribution shown in Figure 57 is as expected, with the location of highest pressure being farthest from the constriction and in an area of stagnation.

Fig. 53 Configuration for Sample Problem 5 which demonstrates the use of source cells.

```

00100 'EXAMPLE PROBLEM 5: SOURCE CELL ADDITION'
*****BASIC PROBLEM INPUT
00110 0.0, 1.00, 0.0005, SEC, 2.0, 20, XEQ
00120 0.0005, 0.020, 0.001, 0.1, 0.005, 3.0
00130 AUTODT, 10, 0.1, 10.0
00140 PRINT, NOPRINT, PRINT, PRINT, NOPRINT
00150 PLOTS, 0.9, 1 1 0 0 0 0 0 0 0 0
00200 1.5, 0.0001, 0.0001, 100, 5, 5
00210 0.0, FT SEC-2, 0.020, 0.38, BTU/HR-FT-DEGF, 20000.0
00220 4.0E-06, 2.0E-06, FT2/SEC, 1.0, 1.0, MM, 119000.0, FT3, 1.0E20, 3
00230 0, 0.0, 0.0
00240 LASL PT LBF/IN2 DEGR FT SEC-1
*****EULERIAN REGION INPUT
11000 CARTSN, 15, 15, 1.5, 2.0, 1.0, M, 0.0, 0.0
11010 NOSLIP, NOSLIP, NOSLIP, NOSLIP
11101 MIXTURE 2, 2, 5, 5, 0, 25.0, 700.0, 700.0, 0.5, 0.0
11102 MIXTURE 2, 6, 3, 7, 0, 25.0, 700.0, 700.0, 0.5, 0.0
11103 MIXTURE 2, 8, 16, 16, 0, 25.0, 700.0, 700.0, 0.5, 0.0
*****OBSTACLE CELL INPUT
11401 NOSLIP 6, 2, 16, 5
11402 NOSLIP 4, 6, 16, 7
*****SOURCE INPUT
003010 STEAM 1, 2, 2, 3011, 0.0, DEG, 1.0, 1.0, 1.0, 0.0
003060 STEAM 1, 3, 2, 3011, 0.0, DEG, 1.0, 1.0, 1.0, 0.0
003110 STEAM 1, 4, 2, 3011, 0.0, DEG, 1.0, 1.0, 1.0, 0.0
003160 STEAM 1, 5, 2, 3011, 0.0, DEG, 1.0, 1.0, 1.0, 0.0
003011 SEC, KG/SEC, J/KG, FT SEC-1
003012 0.0, 0.0, 2.8E06, 0.0
003013 0.01, 100.0, 2.8E06, 0.0
003014 3.00, 100.0, 2.8E06, 0.0

```

Fig. 54 Input card listing for Sample Problem 5.

EXAMPLE PROBLEM 5 SOURCE CELL ADDITION

Fig. 55 Vapor velocity vectors at 1s for Sample Problem 5.

EXAMPLE PROBLEM 5 SOURCE CELL ADDITION

Fig. 56 Void fraction contours at 1s for Sample Problem 5.

EXAMPLE PROBLEM 5 SOURCE CELL ADDITION

PRESSURE
 TIME= 1.000+00 CYCLE= 408 MESH= 1 GEOM= CARTSN JNM= JARTBMM
 MIN= 3.164+05 MAX= 1.356+06 L= 3.164+05 H= 1.252+06 OQ= 1.040+05

Fig. 57 Pressure contours at 1s for Sample Problem 5.

6. PARTIAL FLOW CELLS

This problem demonstrates the new partial flow capability of BEACON/MOD2A. This capability is used to model obstacles that are smaller in size (volume) than the computational fluid cells. In a partial flow cell or region, the volume and flow areas are reduced from their normal unrestricted values. Unlike an obstacle cell which has complete flow blockage, a partial flow cell still allows fluid to pass through but at a reduced level. The remaining fluid is diverted to the surrounding fluid cells subsequently changing the flow pattern in the vicinity of the partial flow cell. This allows the user to factor in the gross effects of obstructions in the flow without resorting to a fine nodalization, as would be the case if obstacle cells were used to model the obstruction.

In this problem configuration (Figure 58), partial flow barriers are alternately placed, forcing the flow to travel in a labyrinthine path. The regions of partial flow cells are specified by cards 11301 through 11303 of Figure 59. The flow areas and volumes of these regions are reduced to 0.1 of the normal unrestricted cell values. A flow resistance coefficient of 3.0 is specified for both the radial and axial directions. The top and bottom boundaries of the mesh are continuative outflow and inflow boundaries, respectively.

The effects of the partial flow regions on the flow can be seen by the fluid velocity vector and pressure gradient patterns shown in Figures 60 and 61, respectively. The flow is partially diverted as it approaches the restricted cells. The velocities increase and the pressure gradients steepen as the flow progresses through the reduced areas.

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Fig. 58 Configuration for Sample Problem 6 which demonstrates partial flow cells.

```

00100 'EXAMPLE PROBLEM 6: PARTIAL FLOW TEST CASE, DUCT FLOW, MAZE'
00110 0.0, 0.5, 0.0001, SEC, 2.0, 1, XEQ
00120 0.050, 2.0
00130 AUTODT, 0, 0.1, 1.5
00140 PRINT, NOPRINT, PRINT, NOPRINT, NOPRINT
00150 PLOTS, 0.9, 1 1 0 0 0 0 0 0 0 0 0 0 0 0
00200 1.5, 0.00010, 0.00010, 300, 5, 0
00210 0.0, FT SEC-2, 0.020, 0.38, BTU/HR-FT-DEGF, 1.0E06
00220 0.0, 0.0, FT2/SEC, 1.0, 1.0, MM, 23800.0, FT3, 1.0E04, 1
00230 0, 0.0, 0.0
00240 LASL, PT, N/M2, DEGK, M, SEC-1
11000 CARTSN, 5, 12, 4.0, 4.0, 2.6667, FT, 0.0, 1.0
11101 MIXTURE 2, 2, 6, 13, 0, 1.0E05, 309.1, 309.1, 0.999, 0.9
11501 INFLOW 2, 1, 6, 1
11601 MIXTURE 2.0E05, 309.1, 309.1, 0.999, 0.9
11701 0.0, 20.0, 0.0, 20.0
11502 OUTFLOW 2, 14, 6, 14
11301 2, 4, 4, 4, 0.1, 3.0, 3.0
11302 4, 7, 6, 7, 0.1, 3.0, 3.0
11303 2, 10, 4, 10, 0.1, 3.0, 3.0

```

Fig. 59 Input card listing for Sample Problem 6.

EXAMPLE PROBLEM 6 PARTIAL FLOW TEST CASE

Fig. 60 Vapor velocity vectors at 0.15s for Sample Problem 6.

EXAMPLE PROBLEM 6 PARTIAL FLOW TEST CASE

Fig. 61 Pressure contours at 0.15s for Sample Problem 6.

7. DRY, MULTI-COMPARTMENT CONTAINMENT WITH WALL FILM AND HEAT STRUCTURES

Sample problem 7 demonstrates three new modeling capabilities of BEACON/MOD2A:

- (1) Wall film modeling
- (2) Heat structure modeling
- (3) Variable mesh spacing.

The problem configuration in Figure 62, represents a typical dry containment subcompartment arrangement. The room designations, physical dimensions, and flow conditions were taken from a previous Battelle-Frankfurt experiment. However, since this problem was set up only for code checkout purposes, the results are not intended to be compared with test data. The rooms are connected by short flow nozzles. A steam break is assumed to occur in the far corner of Room 6.

This problem is modeled in Cartesian coordinates and the nodalization is shown in Figure 63. Rooms 6 and 4 are modeled by two-dimensional regions (meshes 1 and 3, respectively). Room 9 is much larger in volume than rooms 6 and 4 and therefore is modeled as a lumped-parameter region. The room connections are modeled by one-cell, one-dimensional meshes.

There are a large number of heat structures for this problem. Each material present in a room is represented by one heat structure as shown in Figure 64. Heat structures connected to lumped-parameter regions are not spatially oriented.

Input for variable mesh spacing are specified by cards 11020 and 31030 of Figure 65. Film modeling is specified only for the two-dimensional regions (cards 11050 and 31050). Card 250 specifies film modeling parameters.

Fig. 62 Configuration for Sample Problem 7 which simulates a primary coolant break into interconnected rooms.

Fig. 63 Variable mesh nodalization for Sample Problem 7.

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Fig. 64 Heat structure arrangement for Sample Problem 7.


```

100 "SAMPLE PROBLEM 7: DRY MULTI-COMPARTMENT CONTAINMENT"
110 0.0, 0.50, .0001, SEC, 10., 1, XEQ
120 0.004, 0.02, 0.02, 0.10, 0.05, 1.00, 0.10, 5.00
130 AUTODT, .000, 0.1, 2.0
140 PRINT, NOPRINT, PRINT, NOPRINT, NOPRINT
150 PLOTS, 0.9, 1, 1, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 1, 1
160 MULTI, VARI
170 4, 1, 1, 4
180 1, 0.001
200 1.0, 0.0001, 0.0001, 300, 5, 10
210 -9.8, M, SEC-2, 0.02, 0.38, BTU/HR-FT-DEGF, 1.0E5
220 4.5E-4, 5.0E-6, FT2/SEC, 1., 0.1, MM, 125., MM3, 1.E5, 1
230 1, 0.001, 0.001
240 LASL, PT, BAR, DEGC, M, SEC-1
*****DEFAULT WALL FILM PARAMETERS ON FOLLOWING CARD*****
250 0.01, 0.0075, 0.9, 0.6, 2.75E-05, 0.7, 0.07
*****MESH DIMENSIONS AND INITIAL CONDITIONS
11000 CARTSN, 6, 3, 0.98, .85, 1.65, M, 0., 1.
*****THE FOLLOWING CARD DESCRIBES VARIABLE DR DIMENSION****
*****FOR MESH 1 *****
11020 0.8, 1.2, 1.5, 1.8, 2.0, 2.5
21000 CARTSN, 1, 1, .49, .5183, .5183, M, 0., 1.
31000 CARTSN, 3, 4, .47, 0.94, 1.65, M, 0., 1.
*****THE FOLLOWING CARD DESCRIBES VARIABLE DZ DIMENSION****
*****FOR MESH 3 *****
31030 2.0, 1.5, 1.2, 0.94
41000 CARTSN, 1, 1, .5183, 1.0, 0.5183, M, 0., 1.
* NOTE: FLOW LENGTH OF 1x1 1-D MESHES ARE TWICE THAT
* USED IN THE FINE NODALIZATION CASE
11101 MIXTURE, 2, 2, 7, 4, 0, 1., 13.2, 13.2, 1.000, 0.9925
21101 MIXTURE, 2, 2, 2, 2, 0, 1., 13.2, 13.2, 1.000, 0.9925
31101 MIXTURE, 2, 2, 4, 5, 0, 1., 13.2, 13.2, 1.000, 0.9925
*****NEXT TWO CARDS ARE TO ACTIVATE WALL FILM MODEL*****
41101 MIXTURE, 2, 2, 2, 2, 0, 1., 13.2, 13.2, 1.000, 0.9925
11050 FILM
31050 FILM
*****LUMPED PARAMETER REGION MODELING
12000 ZEROED, 560.76, M3, 1.E4, 0.001, 0.001
12010 MIXTURE, 1., 13.2, 13.2, 1.000, 0.9925
*****BREAK MODELING
3010 STEAM, 1, 7, 4, 3011
3011 SEC, KG/SEC, J/GM, M, SEC-1
3012 .000, 0.0, 2774.1, 0.
3013 .007, 0.0, 2774.1, 0.
3014 .020, 72.4, 2774.1, 0.
3015 .050, 84.6, 2774.1, 0.
3016 .075, 86.6, 2774.1, 0.
3017 .100, 82.4, 2774.1, 0.
3018 .200, 71.4, 2774.1, 0.
3019 .300, 57.8, 2774.1, 0.
3020 .500, 49.9, 2774.1, 0.
3021 1.00, 45.3, 2774.1, 0.
3022 1.50, 43.1, 2774.1, 0.
3023 2.00, 41.4, 2774.1, 0.
3024 3.00, 36.8, 2774.1, 0.
6001 LEFT, 1, 2, 3, 1, 2, 2, 2, 1
6002 LEFT, 2, 2, 2, 1, 3, 4, 2, 1
6003 TOP, 3, 3, 5, 1, 4, 2, 2, 1
7001 TOP, 4, 2, 2, 1, 1.0

```

Fig. 65 Input card listing for Sample Problem 7.

```

*****THE REMAINING DATA CARDS ACTIVATE AND DESCRIBE*****
*****HEAT STRUCTURE MODEL*****
1000001      FT, BTU/HR, DEGR
1000002      -1 SEC 0.001
1000000      BTU/HR-FT-DEGF, BTU/FT3-DEGF, BTU/HR-FT2-DEGF
*            CONCRETE STEEL ALUMINUM
1000101      1.00 33.02 30.05 55.01 119.00 35.48
1010000      'ROOM 4 (MESH 3), LEFT CONCRETE'
1010001      6 1 0.0 0.0 100 0.01 0
1010002      MULTI 3 2 2 2 5 LUMPED 1 0 0 0 0
1010003      FT2, 415.7, FACES, NONE
1010009      11 11 11 11
1010200      0 2
1010201      .1667 5
1010301      1 5
1010401      0.0 5
1010601      286.35 6
1020000      'ROOM 4 (MESH 3), STEEL'
1020001      3 1 0.0 0.0 100 0.01 0
1020002      MULTI 3 3 3 3 5 DUMMY 0 0 0 0 0
1020003      FT2, 340.88, FACES, NONE
1020009      11 11 0 0
1020200      0 2
1020201      .007 2
1020301      2 2
1020401      0.0 2
1020601      286.35 3
1030000      'ROOM 4 (MESH 3), ALUMINUM'
1030001      3 1 0.0 0.0 100 0.01 0
1030002      SINGLE 3 3 2 0 0 DUMMY 0 0 0 0 0
1030003      FT2, 12.92, FACES, NONE
1030009      11 11 0 0
1030200      0 2
1030201      .009 2
1030301      3 2
1030401      0.0 2
1030601      286.35 3
1040000      'ROOM 6 (MESH 1), LOWER CONCRETE'
1040001      6 1 0.0 0.0 100 0.01 0
1040002      MULTI 1 2 2 7 2 LUMPED 1 0 0 0 0
1040003      FT2, 484.61, FACES, NONE
1040009      11 11 11 11
1040200      0 2
1040201      .1667 5
1040301      1 5
1040401      0.0 5
1040601      286.35 6
1050000      'ROOM 6 (MESH 1), STEEL'
1050001      3 1 0.0 0.0 100 0.01 0
1050002      MULTI 1 3 3 7 3 DUMMY 0 0 0 0 0
1050003      FT2, 450.84, FACES, NONE
1050009      11 11 0 0
1050200      0 2
1050201      .009 2
1050301      2 2
1050401      0.0 2
1050601      286.35 3
1060000      'ROOM 6 (MESH 1), ALUMINUM'
1060001      3 1 0.0 0.0 100 0.01 0
1060002      SINGLE 1 2 3 0 0 DUMMY 0 0 0 0 0
1060003      FT2, 102.22, FACES, NONE
1060009      11 11 0 0
1060200      0 2
1060201      .010 2
1060301      3 2
1060401      0.0 2
1060601      286.35 3

```

Fig. 65 (Cont'd)

```

1070000 'ROOM 9 (LPR 1), CONCRETE'
1070001 6 1 0.0 0.0 100 0.01 0
1070002 LUMPED 1 0 0 0 0 DUMMY 0 0 0 0 0
1070003 FT2, 9581.87, NONE, NONE
1070009 11 11 0 0
1070200 0 2
1070201 .1667 5
1070301 1 5
1070401 0.0 5
1070601 286.35 6
1080000 'ROOM 9 (LPR 1), STEEL'
1080001 3 1 0.0 0.0 100 0.01 0
1080002 LUMPED 1 0 0 0 0 DUMMY 0 0 0 0 0
1080003 FT2, 3432.66, NONE, NONE
1080009 11 11 0 0
1080200 0 2
1080201 .005 2
1080301 2 2
1080401 0.0 2
1080601 286.35 3
1090000 'ROOM 9 (LPR 1), ALUMINUM'
1090001 3 1 0.0 0.0 100 0.01 0
1090002 LUMPED 1 0 0 0 0 DUMMY 0 0 0 0 0
1090003 FT2, 218.44, NONE, NONE
1090009 11 11 0 0
1090200 0 2
1090201 .C09 2
1090301 3 2
1090401 0.0 2
1090601 286.35 3
1100000 'ROOM 6 (MESH 1), UPPER CONCRETE'
1100001 6 1 0.0 0.0 100 0.01 0
1100002 MULTI 1 2 4 7 4 LUMPED 1 0 0 0 0
1100003 FT2, 484.61, FACES, NONE
1100009 11 11 11 11
1100200 0 2
1100201 .1667 5
1100301 1 5
1100401 0.0 5
1100601 286.35 6
1110000 'ROOM 4 (MESH 3), RIGHT CONCRETE'
1110001 6 1 0.0 0.0 100 0.01 0
1110002 MULTI 3 4 2 4 5 LUMPED 1 0 0 0 0
1110003 FT2, 415.7, FACES, NONE
1110009 11 11 11 11
1110200 0 2
1110201 .1667 5
1110301 1 5
1110401 0.0 5
1110601 286.35 6

```

Fig. 65 (Cont'd)

Three variations of this problem were run to illustrate the effects of wall film and heat structures:

- (1) Configuration without heat structures and without wall film modeling (applicable input of Figure 65 deleted),
- (2) Configuration with heat structures but without wall film modeling (applicable input deleted).
- (3) Configuration with heat structures and with wall film modeling. The film in one-dimensional regions, being of only minor consequence, was turned off for computational efficiency. Also, film modeling in a lumped-parameter region is not allowed.

Each of these variations were executed to a problem time of 0.5 s. The effect of these variations on room pressure and temperature are compared in Figures 66 and 67. The results are as expected. Without heat structures and film modeling, the configuration is adiabatic and pressures and temperatures are expected to be highest. With the presence of heat structures, dropwise steam condensation occurs and heat is transferred to the walls causing pressures and temperatures to be lower. The formation of a liquid film on the walls, however, decreases the effective heat transfer to the walls. Therefore, the values are higher than those without film. Observation of Figure 66 shows that the rate at which the pressure rises in Room 6 is higher than that in Room 4 for the first 0.2 s. Beyond this time, the pressure curves in the two rooms start to converge as the fluid starts to accumulate in Room 4. Based on this pressure difference in the two rooms, the fluid velocity in Mesh 2 is observed to increase until it reaches a maximum value at 0.2 s, beyond which it monotonically decreases with time. A similar velocity peak, observed in Mesh 4, occurs later at 0.3 s, since the rate of pressure increase in Room 9 is much smaller due to its relatively large

Fig. 66 Effects of wall film and heat structures on pressures near the centers of rooms 4 and 6.

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Fig. 67 Effects of wall film and heat structures on pressures near the centers of rooms 4 and 6.

volume. Also, because of relatively small pressure in Room 9, the magnitude of maximum velocity observed in Mesh 4 is about 50% larger than the maximum velocity in Mesh 2 (381 m/s compared to 247 m/s).

Selected velocity vector and contour plots are shown in Figures 68 through 73 to illustrate the spatial dependence of these variables at a given time. Figure 68 shows the gas phase velocities at 0.08 s. Velocities in Room 9, which is modeled as a lumped-parameter region, are assumed zero. Hence Room 9 is not included in Figure 68. The velocities in Room 6 are generally higher than those in Room 4 as expected during an early part of the transient due to larger pressure differential between Rooms 6 and 4 as compared to that between Rooms 4 and 9. The velocity vectors in the top right corner of Room 6 are at a 45° angle due to a combined effect of the discharge from the source and a positive pressure gradient from left to right. Figures 69 and 70 show constant pressure and vapor temperature lines in Room 6 at 0.08 s. The maximum pressure and temperature are observed near the source, as expected. Figure 71 shows the contours of film mass. Since saturated steam was discharged by the source, highest film mass is observed near the source location due to large condensation rates. Also, the gravity tends to accumulate the liquid on the floor directly under the source. Spatial dependence of film velocities is presented in Figure 72 for all the meshes during the later part of the transient (0.5 s). Since film is not allowed in a lumped parameter region, Room 9 has not been shown in Figure 72. The film velocities are observed to be highest near the nozzles due to large fluid velocities. Since at this time, the fluid velocities are higher in Room 4 as compared to Room 6, as discussed earlier, higher film velocities are observed in Room 4. The large film velocity indicated at the bottom of Room 4 is physically unrealistic, and arises as a result of crude nodalization in which the large ambient fluid velocity is used for this film velocity calculation. Finally, Figure 73 shows constant film temperature lines for Room 6 at 0.5 s. The highest temperature is observed near the source, as expected.

SAMPLE PROBLEM 7 DRY CONTAINMENT MULTI-COMPARTMENT PROBLEM

VAPOR,
 TIME= 8.000-02 CYCLE= 173 MAXIMUM VELOCITY = 1.91513+02
 MESH= 3 GEOM= CARTSN JNH= JARTBXF

Fig. 68 Vapor velocity vectors at the time of maximum steam inflow for Sample Problem 7.

SAMPLE PROBLEM 7 DRY CONTAINMENT MULTI-COMPARTMENT PROBLEM

PRESSURE
TIME= 8.000-02 **CYCLE=** 173 **MESH=** 1 **GEOM=** CARTSN **JNM=** JARTBXF
MIN= 1.150+05 **MAX=** 1.339+05 **L=** 1.150+05 **H=** 1.320+05 **DQ=** 1.886+03

Fig. 69 Pressure contours in room 6 at the time of maximum steam inflow for Sample Problem 7.

SAMPLE PROBLEM 7 DRY CONTAINMENT MULTI-COMPARTMENT PROBLEM

TOAS						
TIME=	8.000-02	CYCLE=	173	MESH=	1	GEOM= CARTSN
MIN=	2.980+02	MAX=	4.289+02	L=	2.980+02	H= 4.158+02
						DQ= 1.309+01

Fig. 70 Gas temperature contours in room 6 at the time of maximum steam inflow for Sample Problem 7.

SAMPLE PROBLEM 7 DRY CONTAINMENT MULTI-COMPARTMENT PROBLEM

FMASS	MAX. 1-D FILM MASS = M =	1.732-06		
TIME= 8.000-02	CYCLE= 173	MESH= 1	GEOM= CARTSN	JNM= JARTB
MIN= 0.000	MAX= 4.471-03	L= 0.000	H= 4.024-03	OQ= 4.471-04

Fig. 71 Wall film mass contours in room 6 at the time of maximum steam inflow for Sample Problem 7.

SAMPLE PROBLEM 7 DRY CONTAINMENT MULTI-COMPARTMENT PROBLEM

WALL FILM
TIME= 5.000-01

CYCLE= 2577

MAXIMUM VELOCITY =
MESH= 1

4.56751+01
GEOM= CARTSN JNM= JARTBXF

Fig. 72 Wall film velocity vectors at 0.5s for Sample Problem 7.

SAMPLE PROBLEM 7 DRY CONTAINMENT MULTI-COMPARTMENT PROBLEM

FTEMP							
TIME=	5.000-01	CYCLE=	2577	MESH=	1	GEOM=	CARTSN
MIN=	2.865+02	MAX=	3.068+02	L=	2.865+02	H=	3.048+02
						DQ=	2.033+00
							JNH= JARTI

Fig. 73 Wall temperature contours in room 6 at 0.5s for Sample Problem 7.

Comparisons of CPU time required to run each of the three cases were also made. With no film or heat structures the CPU time was 259 seconds, with heat structures only it was 283 seconds, and with both film and heat structures it was 385 seconds.

VI. PROGRAM STRUCTURE

This section of the report contains general programming information for the BEACON/MOD2A code. It is directed to those who must implement the code on a computer, maintain the code capabilities, modify or extend it to meet specific users' needs, or convert the code to a different computer system or environment. A general overview of the BEACON code structure is given, subroutines are briefly described, supporting software requirements are defined, and, lastly, miscellaneous programming details are given.

1. GENERAL

The functional arrangement of the BEACON/MOD2A code is shown in Figure 74. The size of the BEACON code requires that overlay or segmentation be used for program execution. The segmentation structure is also shown in Figure 74. The code arrangement shown is designed to minimize memory usage during each major phase of program execution, and offers a good balance between memory usage and execution times for the present BEACON code capabilities. Subroutines that are unique to one execution phase only are generally forced to reside in the overlay segment for that phase. This is accomplished with the segmentation directives given in Figure 75. The maximum small core memory required is approximately 36000 decimal words excluding the dynamically allocated storage for heat structures. The largest root-plus-segment leg is in the fluid calculation phase.

The BEACON/MOD2A code was developed using a top-down modular programming approach, wherein the design, coding, and testing of the computer program is accomplished concurrently. As a result, the BEACON code is very modular, with over 190 subroutines in its source file. A more detailed code structure is presented in Figure 76, which shows the organization of first- and second-level subroutines. This is to

Fig. 74 BEACON/MOD2A code structure.

*****SEGLOAD DIRECTIVES

```

*          BEACON MOD24 SEGLOAD DIRECTIVES                                COL. 72!
BCNPGM    TREE          BEACON-(BCNINP-(KCHINP-(INP,MES,INP,LNKINP),HTINP),PLOTS,
,KFIXT,HTCNTL)
BEACON    INCLUDE      LOOP,HYDROCS,PACKZZ,IJLINK,RESET,INITAL,FLMTHK,STANTN
INP       INCLUDE      PGMINP,SOLINP,SETC,KASET1
MES,INP   INCLUDE      CELINP,CCINP,BDYINP,VELINP,POBINP,FLMINP
LNKINP    INCLUDE      ZDINP,SCINP,CELCHK,CELMAP,IJMAP
HTINP     INCLUDE      HTCOM,HTIINP
PLOTS     INCLUDE      SETSHG,MODESG,PAGEG,EXITG,PRINT,ZDPRNT,FBPRNT,FLMDBP
,HTOUT
KFIXT     INCLUDE      TILDE,BETAS,ITER,ICONV,ZEROD,SORE,ZDSORE,FLMDRV,IJNJZ
,MOVPAR,FLMSAV,WALTRN,FLMSURF
HTCNTL    INCLUDE      HTBCDN,HTISSI,HTITOP
          GLOBAL      STP,END,FCL,C,,Q8,IO.
          GLOBAL      KSC,PLTCOM,PPCOM,MMCOM,ZDCOM,MANDE,SCCOM,CNTLCOM
          GLOBAL      GLOBAL,CELCON,IJCON,TABCOM,EDSCOM,SCALAR,INPCOM
          GLOBAL      FTB,FLMCOM
          LEVEL
          TREE FTBNUL
FTBNUL    GLOBAL FAST,FTBLCM
          END

```

Fig. 75 Segmentation directives.

Fig. 76 BEACON/MOD2A subroutine organization.

assist the user in becoming familiar with the BEACON code and its general flow of computation. Descriptions of all BEACON subroutines are given in Section VI.3.

2. DYNAMIC STORAGE ALLOCATION

In the BEACON/MOD2A code, memory storage for the fluid region cell variables and for the heat structure variables are dynamically allocated. During program execution, the amount of data storage is reduced to that required by the problem being executed. A significant cost savings is realized in this mode of operation. The dynamic storage allocation is accomplished with the FTB package of the INEL Environmental Library, and is effected without resorting to pre-processing and recompilation procedures.

The fluid region cell variables are stored in large core memory (LCM) in a LEVEL 2, word-addressable mode. Each computational cell requires 66 words of storage. There is actually a total of 97 differently defined cell variables in the MOD2A code but 31 of these variables share storage with another variable. A staggered storage arrangement is used (Figure 77) wherein all the variables for a given cell are stored contiguously, followed by all the variables for the next cell, etc. Each defined variable is equivalenced to a general array AASC, which is dynamically managed to allocate the required storage for a problem. This method of storing data, as compared to using separate arrays for each variable, permits dynamic storage allocation to be involved in a very efficient manner. At the start of input processing, a fixed amount of LCM is requested (131071 decimal words). As each Eulerian region is processed, the cell storage space for that region is allocated contiguously to storage space of the region previously processed. Lumped-parameter regions are processed lastly and they are also stored in the same array contiguous to the Eulerian regions. After all regions have been processed, LCM is then reduced to the amount required for the problem.

Fig. 77 Staggered storage arrangement of cell variables.

In addition to simplifying dynamic storage allocation procedures, the use of LCM to store cell variables also permits a larger number of computational cells for problem modeling. The maximum size of any array is limited to 131071 decimal words, a CDC computer restriction. This permits up to 1985 computational cells to be used. By comparison, if small core memory (SCM) were used for cell variable storage, there would be room only for approximately 300 computational cells. The LEVEL 2 assignment permits a simple yet effective manner of using LCM. Problem execution times are increased about 6 to 7% over that required if the data were stored in SCM.

Storage for heat structures are also dynamically allocated. However, the dynamic allocation procedures are more complicated due to the different manner in which the storage space is partitioned and utilized. Storage for the heat structures is in SCM in the general array DSA of the common block FAST. The common block FAST is treated as a separate TREE segment, which places it at the end of the fluid transient calculations segment. This storage segment is not overlayed but remains in SCM during all phases of program execution.

The amount of heat structure storage used depends upon:

- (1) number of heat structures
- (2) heat structure nodalization
- (3) number and size of heat transfer characteristics tables
- (4) number of heat structure materials
- (5) number and size of material properties tables.

In addition to being used for heat structure storage, the common block FAST is also used to store the problem input data in its entirety. The input data is stored in a compressed, packed format and is saved

for subsequent case processing purposes. Thus, the total FAST storage includes the storage required for input data as well as for the heat structures. Table VII summarizes the utilization of the dynamic storage blocks in BEACON.

TABLE VII
DYNAMIC STORAGE ALLOCATION BLOCKS

<u>Common Block</u>	<u>Memory</u>	<u>Partition Number</u>	<u>Partition Usage</u>	<u>Partition Size</u>
CELCOM	LCM	-	Eulerian region and lumped-region cell variables	$66 \times \text{NCTOT}$
FAST	SCM	0.0	DSA bookkeeping area	200
FAST	SCM	1.0	Input data	Variable
FAST	SCM	2.0	Heat structure connection data	$26 \times \text{NHS}$
FAST	SCM	3.0	Heat structure computational arrays	$44 + \sum_{i=1}^{\text{NHS}} (13 \times \text{NCOLi})$
FAST	SCM	4.0	Heat structure tables	$11 \times \text{NHT} + \text{NTE}$
FAST	SCM	5.0	Scratch area	$2 \times \text{NCOLi}_{\text{max}} + 1$

NCTOT = Total number of cells
 NHS = Number of heat structures
 NCOLi = Number of nodes for heat structure i
 NHT = Number of heat tables
 NTE = Number of table entries

3. SUBROUTINE DESCRIPTIONS

A prime objective in the BEACON code development has been to provide adequate and up-to-date documentation in the source code. As such, all subroutines are fully commented. All variables in COMMON blocks are defined in a nonexecuting subroutine called COMDEF. Where required, variables local to a subroutine are also defined.

There are approximately 200 subroutines in the BEACON code. This section gives a brief description of each subroutine. The subroutine descriptions are arranged by functional order, beginning with the main entry and control subroutines and progressing through the input, output and transient computation groupings.

3.1 Main Program and Control Subroutines

BEACON	Main entry point: sequences execution of input data processing and transient computation of problem.
BCNINP	First-level input processor: reads report cards into packed storage for subsequent processing by second-level INP2 subroutines, controls dynamic storage allocation and tape restart.
HYDROCS	Controls the transient computations for Eulerian regions, lumped parameter regions, wall film modeling, and heat structures. Also controls the computational timestep and frequency of output.

3.2 Fluid Region Input Subroutines

KCHINP	Controls the INP2 input subroutines for setting up the basic program input and fluid region modeling of the problem.
--------	--

SETC	Initializes equation of state constants used by LASL in K-FIX code.
KASET1	INP2 input processor for basic input data common to all types of problems (processes input cards 100 through 180).
SOLINP	INP2 input processor for basic solution and physical parameter data common to most problems (processes input cards 200 through 250).
MESINP	INP2 input processor for mesh size, cell dimensions, geometry, and rigid boundary conditions (processes input cards M1000 through M1010).
MESSET	Initializes working variables and arrays that are related to geometry, mesh size, cell dimensions, and rigid boundary conditions.
CELINP	INP2 input processor for fluid region properties input data (processes input cards M1101 through M1199).
EOSIN	Equation of state initialization module, defines fluid thermodynamic properties given the type of fluid, type of state-point pair input, and state-point pair input values.
EOSINL	The same as EOSIN but for the equation of state model used by LASL in K-FIX code.
CELSET	Initializes the thermodynamic state conditions in each computational cell of the Eulerian computing mesh.

OCINP	INP2 input processor for obstacle cells, defines cell regions that are to be non-fluid obstacle regions, and set cell flags according to slip or no-slip conditions (processes input cards M1401 through M1499).
BDYINP	INP2 input processor for specified boundaries; inflow, outflow, or constant pressure (processes input cards M1701 through M1799).
BDYSET	Sets cell flags for specified boundaries, initializes state conditions where required.
VELINP	INP2 input processor for initial velocity input, allows initial velocities to be specified in fluid regions of computing mesh (processes input cards M1201 through M1299).
POBINP	INP2 input processor for partial flow cells (processes input cards M1301 through M1399).
FLMINP	INP2 input processor for wall film modeling option (processes input card M1050).
ZDINP	INP2 input processor for lumped-parameter regions and related coupling data. Defines volume, state conditions, and exchange functions (cards L2000 and L2010). Couples lumped-parameter regions to one-dimensional regions (cards 6001 through 6050).
VJOSET	Initializes current time level (n-time) arrays of thermodynamic state conditions for junctions between one-dimensional and lumped-parameter regions.

ZDJSET	Reflects the latest time level state conditions into exterior cells of junctions between one-dimensional and lumped-parameter regions.
LNKINP	INP2 input processor for Eulerian region coupling data. Finds the Eulerian regions and cells that are to be coupled and stores interfacing cell locations in exterior cells of opposite meshes (processes input cards 7001 through 7099).
SCSET	Sets the cell source flag indicator to point to location of source data.
CELMAP	Driver routine used in conjunction with MAPOUT to produce print map of cell flag values.
MAPOUT	Cell flag map output subroutine.
CELCHK	Checks the computing mesh to see that all cells have been defined.
IJMAP	Driver routine used in conjunction with IJOUT to print map of cell location values (the index variable IJ denoting the memory location of each cell).
IJOUT	Output routine for printing cell IJ values.
MASSUM	Computes initial mass and energy in the problem system before transient execution.

3.3 Heat Structure Input Subroutines

HTINP	Controls the input processing for heat structures, allocates storage and defines pointers.
HT1INP	Processes input for the HEAT1 Subcode (mesh noding, initial temperatures, material composition).
HTUNIT	Converts HEAT1 input data to SI units.
HTLOC	Prints storage locations of HEAT1 calculational arrays.
HTCOM	Processes material properties and miscellaneous heat transfer coefficients.
HTTAB	Processes tabular heat transfer coefficient data.
HTCON	Processes heat structure description data and heat structure connection data.
HTMISC	Processes heat transfer area multipliers and wall film orientation input.
HTAREA	Calculates heat structure areas connected to each cell.
HTAOUT	Prints heat structure areas connected to each cell.
HTBCIN	Loads heat transfer coefficient option switches.

3.4 Plot and Print Output Subroutines

PLOTS	Control subroutine for obtaining plot output at a given time.
PLOTS	Plots marker particles for vapor and liquid fields.
VLOTS	Plots velocity vectors for vapor and liquid fields.
CPLOTS	Plots contours of user-selected cell quantities.
FLMPLT	Plots velocity vectors of wall film.
FLMPLTB	Plots relative thickness of wall film mass along the side wall boundaries of mesh.
POBPLT	Plots boundaries of partial flow regions.
ADV	Advances film by a given number of frames.
OCPLT	Plots boundaries of obstacle regions.
FIXLBL	Puts labeling information on the plots. This includes time, cycle, job name, mode, mesh number and geometry.
FRAME	Draws a rectangular outline of mesh.
PLT	Plots a single character at a given point.
DRV	Draws a straight line from one point to another point.

PRINT	Control subroutine for obtaining print output.
CELPRNT	Prints cell variables of Eulerian regions.
SUMPRNT	Computes and prints summations of mass, momentum, and energy in a mesh.
ZDPRNT	Prints state conditions and lumped parameter regions.
HTOUT	Prints heat structure output data.
FBPRNT	Prints film mass, temperature, and velocities along side boundaries of mesh.
FLMDBP	Debug print for unsaved film variables.
VARMAP	Prints user-selected cell variables in map or matrix form (i.e., by rows and columns).

3.5 Fluid Dynamics Computations Subroutines

DTCALC	Computes maximum allowable timestep interval based on Courant-restricted flow.
KFIXT	Controls the sequence of K-FIX numerical flow computations.
SAVCQ	Saves current time level quantities of cell variables.
SORE	Table lookup for source addition of mass, energy, and momentum to Eulerian computing regions.

TILDE	Obtains advance estimates of momentum fluxes, velocities, mass fluxes, and exchange function values.
UGMOMF	Computes gas momentum flux in radial (abscissa) direction.
ULMOMF	Computes liquid momentum flux in radial (abscissa) directions.
VGMOMF	Computes gas momentum flux in axial (ordinate) direction.
VLMOMF	Computes liquid momentum flux in axial (ordinate) direction.
UGVS	Computes gas viscous stresses in radial (abscissa) direction.
ULVS	Computes liquid viscous stresses in radial (abscissa) direction.
VGVS	Computes gas viscous stresses in axial (ordinate) direction.
VLVS	Computes liquid viscous stresses in axial (ordinate) direction.
RHEATS	Computes interphasic heat transfer exchange parameter value.
KDRAGS	Computes interphasic momentum exchange parameter value.

BOIL	Computes interphasic evaporation rate.
COND	Computes interphasic condensation rate.
VELS	Computes gas and liquid velocities on all four sides of cell.
MASFG	Computes gas mass flux for all four sides of cell.
MASFL	Computes liquid mass flux for all four sides of cell.
RESETV	Resets velocities to n-time level values. Used in restarting a transient computation if the timestep interval taken is too large.
BETAS	Computes discrepancy derivatives for use in pressure iteration.
ITER	Pressure iteration, solves implicitly for pressure and velocities.
DVAP	Computes discrepancy in gas continuity.
DLIQ	Computes discrepancy in liquid continuity.
IGIL	Updates internal energies in pressure iteration to account for interphasic exchange of mass, momentum, and energy.
VRELS	Computes relative velocity vector between vapor and liquid fields.

EOSG	Linkage subroutine through which thermodynamic density, specific heat, and temperature for the vapor are returned to the K-FIX computations.
EOSL	Linkage subroutine through which thermodynamic density, specific heat, and temperature for the liquid are returned to the K-FIX computations.
SAT	Linkage subroutine through which saturation temperature and latent heat of vaporization are returned to the K-FIX computations.
NEWP	Calculates new pressure in pressure iteration using a constrained, two-sided secant method.
THGAS	Adjusts void fraction in pressure iteration to account for effects of convection and phase change.
ICONV	Updates internal energies explicitly to account for effects of convection, viscous and pressure work, and conduction.
THF	Computes void fraction flux terms on all four sides of cell.
SIEGF	Calculates the fluxes of specific internal energy for the gas.
SIELF	Calculates the fluxes of specific internal energy for the liquid.
HEATCG	Calculates the heat conduction fluxes for the gas.

HEATCL	Calculates the heat conduction fluxes for the liquid.
VWORKG	Calculates the viscous work for the gas.
IGVS	Calculates the viscous stresses used in the viscous work term for the gas.
VWORKL	Calculates the viscous work for the liquid.
ILVS	Calculates the viscous stresses used in the viscous work term for the liquid.
SETCQ	Computes new equation of state values and obtains new thermal conductivities and viscosities.
THERCON	Computes gas and liquid thermal conductivities.
VISC	Computes gas and liquid viscosities.
BDRY	Updates specified boundary conditions where required, sets exterior tangential velocities for free-slip or no-slip rigid walls.
INDEX	Obtains adjacent cell indices and sets reflective cell indices for rigid boundaries.
ZEROD	Lumped-parameter model, updates lumped-parameter regions for changes in mass and energy due to junction flow, source addition, and interphasic phase change and heat transfer.
ZDJSUM	Accumulates mass and energy flow for all one-dimensional junctions connecting to a given lumped-parameter region.

ZDSORE	Table lookup for source addition of mass, energy, and momentum to lumped-parameter regions.
PFLOW	Computes the volume and flow area multipliers and flow resistance forces for partial flow cells.
PFLOW2	Computes flow area multipliers for partial flow cells in the momentum calculations.

3.6 Mixed-Dimensional Coupling Subroutines

IJLINK	Provides for the computational coupling of inter-connected Eulerian regions. At an interface between coupled Eulerian regions, IJLINK defines the memory locations where computationally adjacent cell data may be accessed. IJLINK also computes for the sectional flow area multipliers for the modeling of unequal flow area coupling cases.
RESET	Resets cell indexing variables, working variables, and arrays pertinent to each Eulerian computing mesh.
ZETAX	Obtains flow area multipliers for unequal area coupling in the momentum flux computations.
ZDLINK	Provides computational coupling of lumped-parameter regions when in the Eulerian computational sweeps. At a junction between one-dimensional and lumped-parameter regions, certain Eulerian computations are required in the junction exterior cell. ZDLINK temporarily shifts cell indices to the exterior cell so that these computations may be performed therein.

IJRSET Resets cell indices to interior cell values after computations in the exterior cell have been performed in the exterior cell at a junction between one-dimensional and lumped-parameter regions.

IJNJZ Locates the one-dimensional region junction cell when in the lumped-parameter computations.

3.7 Wall Film Computations Subroutines

FLMDRV Main driver routine for film calculations.

FLMDEX Computes film orientation indicators and determines location of adjacent cell.

FLMTHK Computes film thickness from film mass and surface area.

FLMSURF Calculates heat and mass transfer rates at the film interface.

FLMTEM Computes new average film temperature.

STANTN Calculates the Stanton Number.

FLMVEL Calculates the film velocity.

FLMDP Calculates the pressure derivative for film velocity calculations.

FLMCNV Calculates the film convection terms.

FLMCOU' Calculates film cell indices for coupled mesh problems.

FLMFLO Calculates interfilm mass and energy flux.

FLMBAL Calculates film mass and energy balance.

3.8 Heat Structure Computations Subroutines

HTCNTL Main driver for heat structure initializing and transient calculations.

HTISST HEAT-1 steady state (initialization) solver.

HTITDP HEAT-1 transient solver.

MADATA HEAT-1 material properties routine.

HTBCDN Sets boundary conditions for use in HEAT-1 subcode.

HTHTC Retrieves user input heat transfer coefficients and bulk temperatures for use as boundary conditions.

HTINDX Calculates cell index for film layer adjacent to heat structure.

HTRATE Updates heat transfer rates.

HTCCORR Calculates a best estimate heat transfer coefficient based on local fluid conditions.

WALTRN Calculates the total heat and mass transfer rates between the wall and fluid cells.

WALUPD Updates fluid cell properties for wall heat and mass transfer.

3.9 Equation of State Subroutines

TLIQ(H,P)	Calculates temperature of water.
TV(H,P)	Calculates temperature of steam.
ROV(H,P)	Calculates the density of steam.
PRV(H,RO)	Calculates the pressure of steam.
POLY(N,A,X)	Calculates the value of the N-th degree polynomial having coefficients A at X.
PTOTAL	Calculates the total pressure of a vapor mixture given partial densities and internal energy.
S(X)	Algebraic fitting function used in evaluating points between two polynomial curve fits.
DENS(I,P)	Calculates steam density.
ROL(H,P)	Calculates density of water.
HLIQ(P,T)	Calculates enthalpy of water.
HVAP(P,T)	Calculates enthalpy of steam.
DIDTL(P,T)	Calculates the internal energy rate of change (dI/dt) for liquid water.
DIDTG(P,T)	Calculates dI/dt for steam.
SONIC2L(H,P)	Calculates sound speed squared for liquid water.

SONIC2M(P,U,XA)	Calculates sound speed squared for any mixture of air and steam.
SONIC2S(H,P)	Calculates sound speed squared for steam.
STOFPI(P,I)	Calculates steam temperature.
TROMIX	Calculates mixture temperature and mixture density for any air-steam mixture.
TSTEAM(H,P)	Calculates steam temperature and is used to correct TV(H,P).
WTOFPI	Calculates liquid water temperature and density.
HEV	Calculates heat at vaporization.
SATPRES	Calculates saturation pressure.

3.10 Auxiliary Subroutines

LOOP	Cell indexing subroutine. Initializes cell indices at start of computational mesh sweep and changes cell indices to move from one row of cells to the next row.
EOSUTS	Establishes state-point unit word values for type of state-point pair input.
UNITSI	Obtains SI units conversion factors for different physical quantities.
XINTRP	Linear interpolation routine for multiple number of dependent variables.

ENTRP	Linear interpolation routine for single dependent variable. Not presently used but provided for future use.
ERRMSG	General input error message routine.
TIMTST	Computes computing time remaining for job execution.
TLET	COMPASS routine for accessing job time limit and elapsed time.
JOBID	COMPASS routine for accessing job identification number used by computer system.
COMDEF	Nonexecuting routine which defines all common variables.

4. IMPLEMENTATION REQUIREMENTS

The BEACON code is written and developed on the CDC 7600 computer and operates in a SCOPE 2.1 system environment. CDC and INEL-supplied software facilities that are used include the following:

- (1) CDC Segmentation Loader. The BEACON code is a segmented loaded program as discussed in Section VI.1. Core memory required for the longest segment plus externals and fixed storage is approximately 36000 decimal words.
- (2) CDC UPDATE Utility. The BEACON code subroutine source file is in the CDC UPDATE format. This format utilizes *DECK and *COMDECK and other file directives to facilitate the updating and maintenance of the BEACON code.

(3) CDC FTN Compiler. With the exception of two COMPASS written subroutines (TLET and JOBID), the BEACON code is written in CDC Extended Fortran IV language. The BEACON code has been compiled at the highest optimization level of the FTN compiler (OPT=2) without encountering any difficulty in compilation or execution. Most of the Fortran language used is compatible with IBM Fortran IV. The primary differences are in Hollerith delimiters, multiple assignments, Hollerith variables, and masking expressions.

(4) INEL Environmental Library. This includes the INP package used for input processing, the FTB package used for memory management, and the IGS package used for plot output. This environmental library is also used on the RELAP4 and CONTEMPT codes.

In addition to the above, a proprietary graphics system DISSPLA, produced by Integrated Software System Corporation, is utilized in the BEACON plot file post-processor program (see Appendix B). Other required files include the Fortran mathematical library.

4.1 Job Control Statements

Job control cards will vary with installation and with file setup procedures. At INEL, it is convenient to create a single BEACON file consisting of four partitions:

<u>Partition</u>	<u>Contents</u>
1	Source file in CDC UPDATE format
2	SEGLOAD directives
3	BEACON reference test cases
4	Object file in library (referenceable) format

Figures 78, 79 and 80 illustrate typical job control statements for this file arrangement. An execute only job, a tape restart job, and an update, compile, execute job are shown, respectively. The INEL environmental library is assumed to be on a separate library file.

4.2 Execution Time Requirements

The computing time required for a problem depends upon a number of factors such as: problem time, nodalization, flow transient severity, modeling options invoked, etc. At present, only a gross estimate of the computing time required for a new problem can be obtained. To assist the user in estimating computing times for new problems, the computing times for several past test case runs have been correlated and are shown in Figure 81. A conservative estimate can be expressed by

$$\ln \left[\frac{\text{CPT}}{T (\text{NC})} \right] = -0.9 \ln (\overline{\delta t}) - 4.6$$

where

CPT = computing time, s

T = problem time, s

NC = number of fluid cells, including lumped parameter regions

$\overline{\delta t}$ = an estimated average timestep, s.

If the timestep is governed by the Courant flow restriction then

$$\overline{\delta t} = X_c \overline{\delta t}_c = X_c \frac{\overline{\delta x}}{V}$$

where

X_c = Courant timestep multiplier, a BEACON input parameter

JFLIBL, T377, P1, STMEZ.	JOB CARD
ACCOUNT, 2430, 432620000, TBL, LIME.	ACCOUNT CARD
ATTACH, BEACON, BEACON2A, ID=XXX.	BEACON MOD2A FILE
COPYP, BEACON, CLCPL.	PARTITION 1 = UPDATE SOURCE FILE
COPYP, BEACON, SEGCARD.	PARTITION 2 = SEGLOAD DIRECTIVES
COPYP, BEACON, INDATA.	PARTITION 3 = REF. TEST CASES
COPY, BEACON, OLDGBJ.	BEACON OBJECT CODE IN LIBRARY FORMAT
RETURN, BEACON, OLDPL.	RETURN UNNEEDED FILES
REWIND, SEGCARD, INDATA, OLDGBJ.	
ATTACH, ENVRL, ID=XXX.	INEL ENVIRONMENTAL SOFTWARE LIBRARY
DISPOSE, FILMPL, *FL=C02.	POST-DISPOSITION OF PLOT OUTPUT FILE
RFL(160000)	
LDSET(LIB=CLDGBJ/ENVRL/FORTRAN)	
SEGLOAD, I=SEGCARD.	
EXECUTE, BEACON, INDATA, PL=100000.	EXECUTE BEACON REF. TEST CASES
7/8/9 (END-OF-RECORD CARD)	

INPUT DATA FOR PROBLEMS NORMALLY GO HERE...

IF SO, THEN EXECUTE CARD SHOULD READ:

EXECUTE, BEACON, PL=100000.

6/7/8/9 (END-OF-FILE CARD)

Fig. 78 Job control statements: Execute only.

```

JFLTBL, T377, P1, STNFZ, JOB CARD
ACCOUNT, 2430, 432820000, TBL, LIME. ACCOUNT CARD
STAGE, TAPE3, VSN=123456, PE, E. REQUEST RESTART TAPE
STAGE, TAPE4, PE, E, POST. REQUEST POST-PROCESSING OF TAPE
ATTACH, BEACON, BEACON2A, ID=XXX. BEACON MOD2A FILE
COPYP, BEACON, OLDPL. PARTITION 1 = UPDATE SOURCE FILE
COPYP, BEACON, SEG CARD. PARTITION 2 = SEGLOAD DIRECTIVES
COPYP, BEACON, INDATA. PARTITION 3 = REF. TEST CASES
COPY, BEACON, OLD OBJ. BEACON OBJECT CODE IN LIBRARY FORMAT
RETURN, BEACON, OLDPL, INDATA. RETURN UNNEEDED FILES
REWIND, SEG CARD, OLD OBJ.
ATTACH, ENVRL. INEL ENVIRONMENTAL SOFTWARE LIBRARY
DISPOSE, FILMPL, *FL=CC2. POST-DISPOSITION OF PLOT OUTPUT FILE
RFL(160000)
LDSET(LIB=OLD OBJ/ENVRL/FORTRAN)
SEGLOAD, I=SEG CARD.
EXECUTE, BEACON, FL=100000. EXECUTE TAPE RESTART PROBLEM
7/8/9 (END-OF-RECORD CARD)

INPUT DATA FOR TAPE RESTART PROBLEM GOES HERE
6/7/8/9 (END-OF-FILE CARD)

```

Fig. 79 Job control statements: Tape restart and creation.

JFL TBL, T377, P1, STMFZ.	JOB CARD
ACCOUNT, 2430, 4326200CL, TBL, LIME.	ACCOUNT CARD
ATTACH, BEACON, BEACON2A, ID=XXX.	BEACON MOD2A FILE
COPYP, BEACON, OLDPL.	PARTITION 1 = UPDATE SOURCE FILE
COPYP, BEACON, SEG CARD.	PARTITION 2 = SEGLOAD DIRECTIVES
COPYP, BEACON, INDATA.	PARTITION 3 = REF. TEST CASES
COPY, BEACON, OLD OBJ.	BEACON OBJECT CODE IN LIBRARY FORMAT
RETURN, BEACON.	RETURN UNNEEDED FILES
REWIND, OLDPL, SEG CARD, INDATA, OLD OBJ.	
UPDATE.	UPDATE SOURCE CODING
RETURN, OLDPL.	
FTN(I=COMPILE, OPT=2, R=2, T, EL=F, A)	COMPILE
RETURN, COMPILE.	
ATTACH, ENVRL.	INEL ENVIRONMENTAL SOFTWARE LIBRARY
DISPOSE, FILMPL, *FL=CC2.	POST-DISPOSITION OF PLOT OUTPUT FILE
RFL(160000)	
LDSET(LIB=CLDOBJ/ENVRL/FORTRAN)	
SEGLOAD, 1=SEG CARD.	
LOAD(LGO)	
EXECUTE, BEACON, INDATA, PL=100000.	EXECUTE BEACON REF. TEST CASES
7/8/9	(END-OF-RECORD CARD)
UPDATES TO SOURCE FILE GO HERE	
7/8/9	(END-OF-RECORD CARD)
INPUT DATA FOR PROBLEMS NORMALLY GO HERE	
IF SO, THEN EXECUTE CARD SHOULD READ:	
EXECUTE, BEACON, PL=100000.	
6/7/8/9	(END-OF-FILE CARD)

Fig. 80 Job control statements: Update, compile and execute.

Fig. 81 Correlation of program computing time to timestep size.

$\overline{\delta t}_c$ = an estimated average Courant timestep, s

$\overline{\delta x}$ = an average cell dimension

$\overline{V}$ = an estimated average flow velocity.

Thus for a problem setup where

$$T = 1.0 \text{ s}$$

$$NC = 100 \text{ fluid cells}$$

$$\overline{V} = 50 \text{ ft/s}$$

$$\overline{\delta x} = 1 \text{ ft}$$

$$X_c = 0.1,$$

the required computing time is estimated to be

$$\ln \left[\frac{CPT}{1.0 (100)} \right] = -0.9 \ln \left[\frac{0.1 (1.0)}{50.0} \right] - 4.6$$

$$CPT = 270 \text{ s.}$$

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APPENDIX A

GOVERNING EQUATIONS
AND
NUMERICAL PROCEDURE

APPENDIX A

GOVERNING EQUATIONS AND NUMERICAL PROCEDURE

A.1 Introduction

The BEACON code primarily uses the LASL K-FIX numerical technique developed by Rivard and Torrey^[A-1]. The code simulates transient, two-dimensional, two-phase, two-component flow. The two phases, which are the liquid and the gas, have different densities velocities, and temperatures determined by separate mass, momentum, and energy equations. The two components in the gas phase, one of which is an inert gas, are assumed to have equal velocities. The resulting finite difference equations are fully implicit in the exchange of mass, momentum and energy, and are solved by a point relation technique, called implicit multifield technique (IMF)^[A-2], without linearization. The numerical technique permits all degrees of coupling between the phases and allows both phases to have all degrees of compressibility.

Section A.2 describes the solution technique in the Eulerian region, which includes the applicable governing equations, their finite difference form, and the numerical procedure. Section A.2 has been drawn heavily from the work of Rivard and Torrey^[A-1], with many of the details on numerical procedure omitted. The user may refer to the original manuscript by Rivard and Torrey for these details. The purpose of Section A.2 is to show the complete finite difference equations with latest modifications made to allow variable mesh and unequal area coupling capabilities for one-dimensional regions. Section A.3 delineates the lumped-parameter model employed in BEACON. Table A-I shows the nomenclature used in this appendix.

TABLE A-I

GOVERNING EQUATION NOMENCLATURE

Nomenclature

- a = adiabatic sound speed, m/s
- A = flow area, m^2
- C = $(\partial I / \partial T)_p$, specific heat at constant volume in an ideal gas, J/kg-K
- D = discrepancy in continuity equation
- $\underline{f}$ = body force vector per unit mass, N/kg
- g = acceleration due to gravity
- H = specific enthalpy, J/kg
- I = specific interval energy, J/kg
- J = condensation or evaporation rate per unit total volume, kg/m^3-s
- K = interfacial friction function for momentum exchange, $N-s/m^4$
- $\dot{m}$ = mass flow rate, kg/s
- p = pressure
- r = radial distance, m
- R = interfacial heat transfer function, J/m^3-s-K
- t = time, s
- T = temperature, K
- u = radial component of velocity, m/s
- $\underline{u}$ = velocity vector, m/s
- v = axial component of velocity
- V = volume, m^3
- x = mass fraction
- Xg = multiplier on gravity
- z = axial distance, m
- δ = defined in Table A-II
- θ = void fraction, volume of gas per unit total volume
- α = empirical constant
- κ = thermal conductivity, J/s-m-K
- λ = second coefficient of viscosity, kg/m-s

- μ = first coefficient of viscosity, kg/m-s
- ρ = microscopic density, mass of phase per unit volume of that phase, kg/m³
- ρ' = microscopic density, mass of phase per unit total volume, kg/m³
- $\underline{\sigma}$ = viscous stress tensor excluding pressure, N/m²
- ϕ = gravitational force orientation angle from the z-axis, measured clockwise, rad

Subscripts

- c = condensation
- e = evaporation
- g = gas phase
- i,j = cell designations
- J = junction between one-dimensional and lumped-parameter region
- l = liquid phase
- L = lumped-parameter region
- r = radial direction
- s = saturation
- S = source
- z = axial direction
- l = component l (vapor) in gas phase

Superscripts

- n = current value
- n+1 = new value after time step advancement
- = intermediate time level value
- = = intermediate time level value older than that given by a single bar (-)

A.2 Eulerian Region

An Eulerian Region may contain a one- or a two-dimensional mesh, or a combination of many one- and two-dimensional meshes. All Eulerian Regions are separated from each other by lumped-parameter regions. In

each Eulerian region, complete K-FIX equations are solved by the IMF technique in the Eulerian system of coordinates. The calculations are fully implicit in all the meshes composing an Eulerian Region.

A.2.1 Governing Equations

A separate set of equations for the gas and liquid phases, coupled through the condition of pressure equilibrium and through the exchange of mass, momentum, and energy, describes the problem in a given system. The governing continuity, momentum, energy, and state equations for the gas are

$$\frac{\partial \rho_g'}{\partial t} + \underline{\nabla} \cdot (\rho_g' \underline{u}_g) = J_e - J_c, \quad (A-1)$$

$$\frac{\partial \rho_{gl}'}{\partial t} + \underline{\nabla} \cdot (\rho_{gl}' \underline{u}_g) = J_e - J_c, \quad (A-2)$$

$$\begin{aligned} \frac{\partial \rho_g' \underline{u}_g}{\partial t} + \underline{\nabla} \cdot (\underline{u}_g \otimes \rho_g' \underline{u}_g) = & - \theta \underline{\nabla} p + K(\underline{u}_l - \underline{u}_g) + J_e \underline{u}_l - J_c \underline{u}_g \\ & + \underline{\nabla} \cdot (\theta \underline{\sigma}_g) + \rho_g' \underline{f}_g, \end{aligned} \quad (A-3)$$

$$\begin{aligned} \frac{\partial \rho_g' I_g}{\partial t} + \underline{\nabla} \cdot (\rho_g' I_g \underline{u}_g) = & - p \left[\frac{\partial \theta}{\partial t} + \underline{\nabla} \cdot (\theta \underline{u}_g) \right] \\ & + [K + (J_e + J_c)/2] (\underline{u}_g - \underline{u}_l)^2 \\ & + (J_e - J_c) H_g + R(T_l - T_g) + \theta \underline{\sigma}_g : (\underline{\nabla} \underline{u}_g) + \underline{\nabla} \cdot \kappa_g \theta \underline{\nabla} T_g, \end{aligned} \quad (A-4)$$

$$\rho_g = \rho_g(I_g, p), \text{ or } \rho_g' = \rho_g'(I_g, p, \theta), \quad (A-5)$$

and those for the liquid are

$$\frac{\partial \rho_l'}{\partial t} + \underline{\nabla} \cdot (\rho_l' \underline{u}_l) = J_c - J_e, \quad (A-6)$$

$$\frac{\partial \rho_l u_l}{\partial t} + \nabla \cdot (u_l \otimes \rho_l u_l) = - (1-\theta) \nabla p + K(u_g - u_l) + J_{c-g} u_g - J_{e-l} u_l$$

$$+ \nabla \cdot [(1-\theta) \underline{\sigma}_l] + \rho_l \underline{f}_l, \quad (A-7)$$

$$\frac{\partial \rho_l' I_l}{\partial t} + \nabla \cdot (\rho_l' I_l u_l) = - p \frac{\partial}{\partial t} \left\{ (1-\theta) \right.$$

$$\left. + \nabla \cdot [(1-\theta) u_l] \right\} - (J_e - J_c) H_g$$

$$+ R(T_g - T_l) + (1-\theta) \underline{\sigma}_l : (\nabla u_l) + \nabla \cdot \kappa_l (1-\theta) \nabla T_l, \quad (A-8)$$

$$\rho_l = \rho_l(I_l, p), \text{ or } \rho_l' = \rho_l'(I_l, p, \theta). \quad (A-9)$$

The above set of equations define the complete system. The equations to be solved are: three continuity (two for gas phase and one for liquid phase), four momentum (two for each phase), two energy, and two equations of state. The corresponding 11 unknowns are: p , u_g , v_g , u_l , v_l , ρ_l' , ρ_g' , ρ_{gl}' (or x_{gl}), ρ_l' , θ , I_g , and I_l .

A.2.2 Finite Difference Form

Equations (A-1) - (A-4) and (A-6) - (A-8) are cast in finite difference form in two dimensions for plane or axi-symmetric cylindrical geometries, and in one dimension for spherical geometry. Figure 1 shows a typical computation cell and the relative spatial locations of the variables that appear in the finite difference equations. The components of velocity for each phase are centered on the cell boundaries as indicated. The quantity $Q_{i,j}$ represents cell-centered quantities such as ρ_l , ρ_l' , ρ_g , ρ_g' , ρ_{gl}' , ρ_{gl}' , θ , J_e , J_c , p , K , λ_l , μ_l , λ_g , μ_g , I_l , I_g , κ_g , κ_l , and R .

Table A-II presents the definition of the unequal area coupling multipliers used and their computation in either axi-symmetric or Cartesian coordinates. The purpose of these multipliers is to modify the finite difference equations to enable one-dimensional regions of different cross-sectional flow area connections. These multipliers reflect the change in flow areas and control volumes across an unequal area coupling

TABLE A-II
UNEQUAL AREA COUPLING MULTIPLIERS

δl = Cell depth for
Cartesian coordinates

	<u>Axi-symmetric Coordinates</u>	<u>Cartesian Coordinates</u>
ζ_L Left edge area multiplier	$\frac{\delta z_{i-1,j}}{\delta z_{i,j}}$	$\frac{(\delta z \delta l)_{i-1,j}}{(\delta z \delta l)_{i,j}}$
ζ_R Right edge area multiplier	$\frac{\delta z_{i+1,j}}{\delta z_{i,j}}$	$\frac{(\delta z \delta l)_{i+1,j}}{(\delta z \delta l)_{i,j}}$
ζ_B Bottom edge area multiplier	$\frac{(r \delta r)_{i,j-1}}{(r \delta r)_{i,j}}$	$\frac{(\delta r \delta l)_{i,j-1}}{(\delta r \delta l)_{i,j}}$
ζ_T Top edge area multiplier	$\frac{(r \delta r)_{i,j+1}}{(r \delta r)_{i,j}}$	$\frac{(\delta r \delta l)_{i,j+1}}{(\delta r \delta l)_{i,j}}$

TABLE A-II (cont)

		<u>Axi-symmetric Coordinates</u>	<u>Cartesian Coordinates</u>
ζ_{L2}	Left edge area multiplier, cell _{i+1,j}	$\frac{\delta z_{i,j}}{\delta z_{i+1,j}}$	$\frac{(\delta z \delta l)_{i,j}}{(\delta z \delta l)_{i+1,j}}$
ζ_{R2}	Right edge area multiplier, cell _{i+1,j}	$\frac{\delta z_{i+2,j}}{\delta z_{i+1,j}}$	$\frac{(\delta z \delta l)_{i+2,j}}{(\delta z \delta l)_{i+1,j}}$
ζ_{B2}	Bottom edge area multiplier, cell _{i,j+1}	$\frac{(r\delta r)_{i,j}}{(r\delta r)_{i,j+1}}$	$\frac{(\delta r \delta l)_{i,j}}{(\delta r \delta l)_{i,j+1}}$
ζ_{T2}	Top edge area multiplier, cell _{i,j+1}	$\frac{(r\delta r)_{i,j+2}}{(r\delta r)_{i,j+1}}$	$\frac{(\delta r \delta l)_{i,j+2}}{(\delta r \delta l)_{i,j+1}}$
ζ_{RB}	Right boundary area multiplier of momentum control volume in radial direction	$\frac{\delta z_{i+1,j}}{\delta z_{i,j}}$	$\frac{(\delta z \delta l)_{i+1,j}}{(\delta z \delta l)_{i,j}}$
ζ_{TB}	Top boundary area multiplier of momentum control volume in axial direction	$\frac{(r\delta r)_{i,j+1}}{(r\delta r)_{i,j}}$	$\frac{(\delta r \delta l)_{i,j+1}}{(\delta r \delta l)_{i,j}}$

Note: In computations, area multipliers are restricted to values less than or equal to 1.0, except for ζ_{RB} and ζ_{TB} .

ζ_{VR} Momentum control volume multiplier in radial direction

$$= \begin{cases} \frac{1}{2} \left[1 + \frac{\delta z_{i+1,j}}{\delta z_{i,j}} \right] + \frac{\delta z_{i,j}}{8r_{i+\frac{1}{2}}} \left[\frac{\delta z_{i+1,j}}{\delta z_{i,j}} - 1 \right] & \text{Axi-symmetric Coordinates} \\ \frac{1}{2} \left[1 + \frac{(\delta z \delta l)_{i+1,j}}{(\delta z \delta l)_{i,j}} \right] & \text{Cartesian Coordinates} \end{cases}$$

TABLE A-II (cont)

ζ_{VZ} Momentum control volume multiplier in axial direction

$$= \begin{cases} \frac{1}{2} \left[1 + \frac{(r\delta r)_{i,j+1}}{(r\delta r)_{i,j}} \right] & \text{Axi-symmetric Coordinates} \\ \frac{1}{2} \left[1 + \frac{(\delta r \delta l)_{i,j+1}}{(\delta r \delta l)_{i,j}} \right] & \text{Cartesian Coordinates} \end{cases}$$

boundary, and are applied in a manner so as to decrease or increase a convective flux quantity across the control volume boundary of the computational cell. For computations of cell-centered variables, the computation control volume aligns with the cell edges and only the cell edge area multipliers (ζ_L , ζ_R , ζ_B , and ζ_T) need to be applied in the equations. However, for the flux quantities, the computation control volume is centered on a cell edge and extends into the next cell which necessitates a different set of area multipliers and introduces a control volume multiplier for each of the radial and axial flux computations. A total of 12 area and volume multipliers are required for the complete transient computation. For regular fluid cell computations and for equal area coupling, the multipliers have default values of 1.0.

The finite difference equations for the quantities at time $t = (n+1)\delta t$ form a system of coupled, nonlinear algebraic equations. The equations for an axi-symmetric cylindrical geometry, after some algebraic manipulations, are given below. Angle ϕ should be set equal to zero in these equations for this case. These equations can easily be modified for other geometries. For cartesian coordinates, r should be replaced by 1, whereas for one-dimensional spherical geometry, r should be replaced by r^2 and all z -dependent terms dropped with the body force terms set equal to zero.

$$D_g = (\rho'_g)_{i,j}^{n+1} - (\rho'_g)_{i,j}^n + \delta t \left[\langle (\rho'_g)^{n+1} u_g^{n+1} r \rangle_{i,j} / (r_i \delta r_i) + \langle (\rho'_g)^{n+1} v_g^{n+1} \rangle_{i,j} / \delta z_j - (\bar{J}_e)_{i,j} + (\bar{J}_c)_{i,j} \right], \quad (A-10)$$

$$(\rho'_{g1})_{i,j}^{n+1} = (\rho'_{g1})_{i,j}^n + \delta t \left[- \langle (\rho'_{g1})^{n+1} u_g^{n+1} r \rangle_{i,j} / (r_i \delta r_i) - \langle (\rho'_{g1})^{n+1} v_g^{n+1} \rangle_{i,j} / \delta z_j + (\bar{J}_e)_{i,j} - (\bar{J}_c)_{i,j} \right], \quad (A-11)$$

$$(u_g)_{i+1/2,j}^{n+1} = \left(\left[(\rho'_g \tilde{u}_g)_{i+1/2,j} - \Theta_{i+1/2,j}^{n+1} \delta t (p_{i+1,j}^{n+1} - p_{i,j}^{n+1}) / \delta r_{i+1/2} \right] \left[(\rho'_g)_{i+1/2,j}^{n+1} + \delta t \left[K_{i+1/2,j}^n + (\bar{J}_e)_{i+1/2,j} \right] \right] \right)$$

$$\begin{aligned}
& + \delta t \left[K_{i+1/2,j}^n + (\bar{J}_e)_{i+1/2,j} \right] \left[(\rho'_\ell \tilde{u}_\ell)_{i+1/2,j} \right. \\
& - \left. \delta t (1 - \theta_{i+1/2,j}^{n+1}) (p_{i+1,j}^{n+1} - p_{i,j}^{n+1}) / \delta r_{i+1/2} \right] \Bigg) / \left((\rho'_g)_{i+1/2,j}^{n+1} \left\{ (\rho'_\ell)_{i+1/2,j}^{n+1} \right. \right. \\
& + \left. \left. \delta t \left[K_{i+1/2,j}^n + (\bar{J}_e)_{i+1/2,j} \right] + \delta t \left[K_{i+1/2,j}^n + (\bar{J}_c)_{i+1/2,j} \right] (\rho'_\ell)_{i+1/2,j}^{n+1} \right\} \right), \\
& \hspace{15em} (A-12)
\end{aligned}$$

$$\begin{aligned}
(v_g)_{i,j+1/2}^{n+1} = & \left(\left[(\rho'_g \tilde{v}_g)_{i,j+1/2} - \theta_{i,j+1/2}^{n+1} \delta t (p_{i,j+1}^{n+1} - p_{i,j}^{n+1}) \right. \right. \\
& / \left. \delta z_{j+1/2} \right] \left\{ (\rho'_\ell)_{i,j+1/2}^{n+1} + \delta t \left[K_{i,j+1/2}^n + (\bar{J}_e)_{i,j+1/2} \right] \right\} \\
& + \delta t \left[K_{i,j+1/2}^n + (\bar{J}_e)_{i,j+1/2} \right] \left[(\rho'_\ell \tilde{v}_\ell)_{i,j+1/2} \right. \\
& - \left. (1 - \theta_{i,j+1/2}^{n+1}) \delta t (p_{i,j+1}^{n+1} - p_{i,j}^{n+1}) / \delta z_{j+1/2} \right] \Bigg) / \left((\rho'_g)_{i,j+1/2}^{n+1} \left\{ (\rho'_\ell)_{i,j+1/2}^{n+1} \right. \right. \\
& + \left. \left. \delta t \left[K_{i,j+1/2}^n + (\bar{J}_e)_{i,j+1/2} \right] + \delta t \left[K_{i,j+1/2}^n + (\bar{J}_c)_{i,j+1/2} \right] (\rho'_\ell)_{i,j+1/2}^{n+1} \right\} \right), \\
& \hspace{15em} (A-13)
\end{aligned}$$

$$\begin{aligned}
(I_g)_{i,j}^{n+1} = & (\bar{c}_g)_{i,j} \left[\left((\rho'_g)_{i,j}^{n+1} (\bar{T}_g)_{i,j} - (I_g)_{i,j}^n \left[(\rho'_g)_{i,j}^{n+1} - (\rho'_g)_{i,j}^n \right] \right. \right. \\
& - \left. \left. (\delta t / \delta z_j) \left\{ < (\rho'_g)^{n+1} I_g^n v_g^{n+1} >_{i,j} + p_{i,j}^{n+1} < \theta^{n+1} v_g^{n+1} >_{i,j} \right. \right. \right. \\
& - \left. \left. 1/4 \theta_{i,j}^{n+1} (\bar{\sigma}_{grz})_{i,j} \left[(u_g)_{i+1/2,j+1}^{n+1} + (u_g)_{i-1/2,j+1}^{n+1} - (u_g)_{i+1/2,j-1}^{n+1} \right. \right. \right. \\
& - \left. \left. (u_g)_{i-1/2,j-1}^{n+1} \right] - \theta_{i,j}^{n+1} (\bar{\sigma}_{gzz})_{i,j} \left[\zeta_T (v_g)_{i,j+1/2}^{n+1} - \zeta_B (v_g)_{i,j-1/2}^{n+1} \right] \right. \\
& - \left. \left. (\kappa_g)_{i,j+1/2}^n \theta_{i,j+1/2}^{n+1} \left[(\bar{T}_g)_{i,j+1} - (\bar{T}_g)_{i,j} \right] / \delta z_{j+1/2} \right. \right. \\
& + \left. \left. (\kappa_g)_{i,j-1/2}^n \theta_{i,j-1/2}^{n+1} \left[(\bar{T}_g)_{i,j} - (\bar{T}_g)_{i,j-1} \right] / \delta z_{j-1/2} \right\} \right. \\
& - \left. \left. (\delta t / \delta r_i) \left\{ < (\rho'_g)^{n+1} I_g^n u_g^{n+1} r >_{i,j} / r_i + p_{i,j}^{n+1} < \theta^{n+1} u_g^{n+1} r >_{i,j} / r_i \right. \right. \right.
\end{aligned}$$

$$\begin{aligned}
& - \theta_{i,j}^{n+1} (\bar{\sigma}_{grr})_{i,j} \left[\zeta_R (u_g)_{i+1/2,j}^{n+1} - \zeta_L (u_g)_{i-1/2,j}^{n+1} \right] \\
& - 1/4 \theta_{i,j}^{n+1} (\bar{\sigma}_{grz})_{i,j} \left[(v_g)_{i+1,j+1/2}^{n+1} + (v_g)_{i+1,j-1/2}^{n+1} - (v_g)_{i-1,j+1/2}^{n+1} \right. \\
& \left. - (v_g)_{i-1,j-1/2}^{n+1} \right] - r_{i+1/2} (\kappa_g)_{i+1/2,j}^n \theta_{i+1/2,j}^{n+1} \left[(\bar{T}_g)_{i+1,j} \right. \\
& \left. - (\bar{T}_g)_{i,j} \right] / (r_i \delta r_{i+1/2}) + r_{i-1/2} (\kappa_g)_{i-1/2,j}^n \theta_{i-1/2,j}^{n+1} \left[(\bar{T}_g)_{i,j} \right. \\
& \left. - (\bar{T}_g)_{i-1,j} \right] / (r_i \delta r_{i-1/2}) \left\{ + (\delta t / r_i) \theta_{i,j}^{n+1} (\bar{\sigma}_{g\phi\phi})_{i,j} \left[\zeta_R (u_g)_{i+1/2,j}^{n+1} \right. \right. \\
& \left. \left. + \zeta_L (u_g)_{i-1/2,j}^{n+1} \right] / 2 \right\} \left[2 (\bar{c}_\rho)_{i,j} (\rho'_\ell)_{i,j}^{n+1} + \delta t R_{i,j}^n \right] \\
& + \left\{ 1/2 \delta t R_{i,j}^n \left[(\bar{T}_\ell)_{i,j} - (\bar{T}_g)_{i,j} + (\bar{T}_g)_{i,j} / (\bar{c}_g)_{i,j} - (\bar{T}_\ell)_{i,j} \right. \right. \\
& \left. \left. / (\bar{c}_\ell)_{i,j} \right] - p_{i,j}^{n+1} (\theta_{i,j}^{n+1} - \theta_{i,j}^n) \right\} \left[2 (\bar{c}_\ell)_{i,j} (\rho'_\ell)_{i,j}^{n+1} \right] \\
& + \left((\rho'_\ell)_{i,j}^{n+1} (\bar{T}_\ell)_{i,j} - (I_\ell)_{i,j}^n \left[(\rho'_\ell)_{i,j}^{n+1} - (\rho'_\ell)_{i,j}^n \right] \right. \\
& \left. - (\delta t / \delta z_j) \left\{ < (\rho'_\ell)^{n+1} I_\ell^n v_\ell^{n+1} >_{i,j} + p_{i,j}^{n+1} < (1 - \theta^{n+1}) v_\ell^{n+1} >_{i,j} \right. \right. \\
& \left. \left. - 1/4 \theta (1 - \theta_{i,j}^{n+1}) (\bar{\sigma}_{\ell rz})_{i,j} \left[(u_\ell)_{i+1/2,j+1}^{n+1} + (u_\ell)_{i-1/2,j+1}^{n+1} - (u_\ell)_{i-1/2,j-1}^{n+1} \right. \right. \right. \\
& \left. \left. - (u_\ell)_{i-1/2,j-1}^{n+1} \right] - (1 - \theta_{i,j}^{n+1}) (\bar{\sigma}_{\ell zz})_{i,j} \left[\zeta_T (v_\ell)_{i,j+1/2}^{n+1} - \zeta_B (v_\ell)_{i,j-1/2}^{n+1} \right. \right. \\
& \left. \left. - (\kappa_\ell)_{i,j+1/2}^n (1 - \theta_{i,j+1/2}^{n+1}) \left[(\bar{T}_\ell)_{i,j+1} - (\bar{T}_\ell)_{i,j} \right] / \delta z_{j+1/2} \right. \right. \\
& \left. \left. + (\kappa_\ell)_{i,j-1/2}^n (1 - \theta_{i,j-1/2}^{n+1}) \left[(\bar{T}_\ell)_{i,j} - (\bar{T}_\ell)_{i,j-1} \right] / \delta z_{j-1/2} \right\} \right. \\
& \left. - (\delta t / \delta r_i) \left\{ < (\rho'_\ell)^{n+1} I_\ell^n u_\ell^{n+1} r >_{i,j} / r_i \right. \right. \\
& \left. \left. + p_{i,j}^{n+1} < (1 - \theta^{n+1}) u_\ell^{n+1} r >_{i,j} / r_i \right. \right.
\end{aligned}$$

$$\begin{aligned}
& - (1-\theta_{i,j}^{n+1}) (\bar{\sigma}_{\ell rr})_{i,j} \left[\zeta_R (u_\ell)_{i+1/2,j}^{n+1} - \zeta_L (u_\ell)_{i-1/2,j}^{n+1} \right. \\
& - 1/4 (1-\theta_{i,j}^{n+1}) (\bar{\sigma}_{\ell rz})_{i,j} \left[(v_\ell)_{i+1,j+1/2}^{n+1} + (v_\ell)_{i+1,j-1/2}^{n+1} - (v_\ell)_{i-1,j+1/2}^{n+1} \right. \\
& \left. - (v_\ell)_{i-1,j-1/2}^{n+1} \right] - r_{i+1/2} (\kappa_\ell)_{i+1/2,j}^n (1-\theta_{i+1/2,j}^{n+1}) \left[(\bar{T}_\ell)_{i+1,j} - (\bar{T}_\ell)_{i,j} \right] \\
& / (r_i \delta r_{i+1/2}) + r_{i-1/2} (\kappa_\ell)_{i-1/2,j}^n (1-\theta_{i-1/2,j}^{n+1}) \left[(\bar{T}_\ell)_{i,j} - (\bar{T}_\ell)_{i-1,j} \right] / (r_i \delta r_{i-1/2}) \Big\} \\
& + (\delta t / \delta r_i) (1-\theta_{i,j}^{n+1}) (\bar{\sigma}_{\ell \theta \theta})_{i,j} \left[\zeta_R (u_\ell)_{i+1/2,j}^{n+1} + \zeta_L (u_\ell)_{i-1/2,j}^{n+1} \right] \\
& / 2 \Big\} \delta t R_{i,j}^n \Big] / \left\{ (\bar{c}_g)_{i,j} (\rho'_g)_{i,j}^{n+1} \left[2 (\bar{c}_\ell)_{i,j} (\rho'_\ell)_{i,j}^{n+1} + \delta t R_{i,j}^n \right] \right. \\
& \left. + \delta t R_{i,j}^n (\bar{c}_\ell)_{i,j} (\rho'_\ell)_{i,j}^{n+1} \right\}, \tag{A-14}
\end{aligned}$$

$$\begin{aligned}
D_\ell = & (\rho'_\ell)_{i,j}^{n+1} - (\rho'_\ell)_{i,j}^n + \delta t \left[\langle (\rho'_\ell)^{n+1} u_\ell^{n+1} r \rangle_{i,j} / (r_i \delta r_i) \right. \\
& \left. + \langle (\rho'_\ell)^{n+1} v_\ell^{n+1} \rangle_{i,j} / \delta z_j + (\bar{J}_e)_{i,j} - (\bar{J}_c)_{i,j} \right], \tag{A-15}
\end{aligned}$$

$$\begin{aligned}
(u_\ell)_{i+1/2,j}^{n+1} = & \left(\left[(\rho'_\ell u_\ell)_{i+1/2,j} - \delta t (1-\theta_{i+1/2,j}^{n+1}) (p_{i+1,j}^{n+1} - p_{i,j}^{n+1}) \right. \right. \\
& \left. \left. + \delta r_{i+1/2} \right] \left\{ (\rho'_g)_{i+1/2,j}^{n+1} + \delta t \left[K_{i+1/2,j}^n \right. \right. \right. \\
& \left. \left. + (\bar{J}_c)_{i+1/2,j} \right] \right\} + \delta t \left[K_{i+1/2,j}^n + (\bar{J}_c)_{i+1/2,j} \right] \left[(\rho'_g u_g)_{i+1/2,j} \right. \\
& \left. - \theta_{i+1/2,j}^{n+1} \delta t (p_{i+1,j}^{n+1} - p_{i,j}^{n+1}) / \delta r_{i+1/2} \right] \Big) / \left((\rho'_g)_{i+1/2,j}^{n+1} \left\{ (\rho'_\ell)_{i+1/2,j}^{n+1} \right. \right. \\
& \left. \left. + \delta t \left[K_{i+1/2,j}^n + (\bar{J}_e)_{i+1/2,j} \right] \right\} + \delta t \left[K_{i+1/2,j}^n \right. \right. \\
& \left. \left. + (\bar{J}_c)_{i+1/2,j} \right] (\rho'_\ell)_{i+1/2,j}^{n+1} \right), \tag{A-16}
\end{aligned}$$

$$\begin{aligned}
(v_\ell)_{i,j+1/2}^{n+1} = & \left(\left[(\rho'_\ell v_\ell)_{i,j+1/2} - (1-\theta_{i,j+1/2}^{n+1}) \delta t (p_{i,j+1}^{n+1} - p_{i,j}^{n+1}) \right. \right. \\
& / \delta z_{j+1/2} \left. \left\{ (\rho'_g)_{i,j+1/2}^{n+1} + \delta t \left[K_{i,j+1/2}^n + (\bar{J}_c)_{i,j+1/2} \right] \right\} \right. \\
& + \delta t \left[K_{i,j+1/2}^n + (\bar{J}_c)_{i,j+1/2} \right] \left[(\rho'_g v_g)_{i,j+1/2} \right. \\
& - \theta_{i,j+1/2}^{n+1} \delta t (p_{i,j+1}^{n+1} - p_{i,j}^{n+1}) / \delta z_{j+1/2} \left. \left. \right] \right) / \left((\rho'_g)_{i,j+1/2}^{n+1} \left\{ (\rho'_\ell)_{i,j+1/2}^{n+1} \right. \right. \\
& + \delta t \left[K_{i,j+1/2}^n + (\bar{J}_e)_{i,j+1/2} \right] \left. \left. \right\} + \delta t \left[K_{i,j+1/2}^n \right. \right. \\
& + (\bar{J}_c)_{i,j+1/2} \left. \left. \right] (\rho'_\ell)_{i,j+1/2}^{n+1} \right), \quad (A-17)
\end{aligned}$$

$$\begin{aligned}
(I_\ell)_{i,j}^{n+1} = & (\bar{c}_\ell)_{i,j} \left\{ 2 \left[(\rho'_\ell)_{i,j}^{n+1} (\bar{T}_\ell)_{i,j} - (I_\ell)_{i,j}^n \left[(\rho'_\ell)_{k,j}^{n+1} - (\rho'_\ell)_{i,j}^n \right] \right. \right. \\
& - (\delta t / \delta z_j) \left\{ < (\rho'_\ell)^{n+1} I_\ell^n v_\ell^{n+1} >_{i,j} + p_{i,j}^{n+1} < (1-\theta^{n+1}) v_\ell^{n+1} >_{i,j} \right. \\
& - 1/4 (1-\theta_{i,j}^{n+1}) (\bar{\sigma}_{\ell rz})_{i,j} \left[(u_\ell)_{i+1/2,j+1}^{n+1} + (u_\ell)_{i-1/2,j+1}^{n+1} - (u_\ell)_{i+1/2,j-1}^{n+1} \right. \\
& - (u_\ell)_{i-1/2,j-1}^{n+1} \left. \right] - (1-\theta_{i,j}^{n+1}) (\bar{\sigma}_{\ell zz})_{i,j} \left[\zeta_T (v_\ell)_{i,j+1/2}^{n+1} - \zeta_B (v_\ell)_{i,j-1/2}^{n+1} \right] \\
& - (\kappa_\ell)_{i,j+1/2}^n (1-\theta_{i,j+1/2}^{n+1}) \left[(\bar{T}_\ell)_{i,j+1} - (\bar{T}_\ell)_{i,j} \right] / \delta z_{j+1/2} \\
& + (\kappa_\ell)_{i,j-1/2}^n (1-\theta_{i,j-1/2}^{n+1}) \left[(\bar{T}_\ell)_{i,j} - (\bar{T}_\ell)_{i,j-1} \right] / \delta z_{j-1/2} \left. \right\} \\
& - (\delta t / \delta r_i) \left\{ < (\rho'_\ell)^{n+1} I_\ell^n u_\ell^{n+1} r >_{i,j/r_i} \right. \\
& + p_{i,j}^{n+1} < (1-\theta_{i,j}^{n+1}) u_\ell^{n+1} r >_{i,j/r_i} - (1-\theta_{i,j}^{n+1}) (\bar{\sigma}_{\ell rr})_{i,j} \left[\zeta_R (u_\ell)_{i+1/2,j}^{n+1} \right. \\
& - \zeta_L (u_\ell)_{i-1/2,j}^{n+1} \left. \right] - 1/4 (1-\theta_{i,j}^{n+1}) (\bar{\sigma}_{\ell rz})_{i,j} \left[(v_\ell)_{i+1,j+1/2}^{n+1} + (v_\ell)_{i+1,j-1/2}^{n+1} \right. \\
& - (v_\ell)_{i-1,j+1/2}^{n+1} - (v_\ell)_{i-1,j-1/2}^{n+1} \left. \right] - r_{i+1/2} (\kappa_\ell)_{i+1/2,j}^n (1-\theta_{i+1/2,j}^{n+1}) \left[(\bar{T}_\ell)_{i+1,j} \right.
\end{aligned}$$

$$\begin{aligned}
& - (\bar{T}_\ell)_{i,j} \Big] / (r_i \delta r_{i+1/2}) + r_{i-1/2} (\kappa_\ell)_{i-1/2,j}^{(n)} (1-\theta_{i-1/2,j}^{n+1}) \Big[(\bar{T}_\ell)_{i,j} \\
& - (\bar{T}_\ell)_{i-1,j} \Big] / (r_i \delta r_{i-1/2}) \Big\} + (\delta t / r_i) (1-\theta_{i,j}^{n+1}) (\bar{\sigma}_{\ell\phi\phi})_{i,j} \Big[\zeta_R (u_\ell)_{i+1/2,j}^{n+1} \\
& + \zeta_L (u_\ell)_{i-1/2,j}^{n+1} \Big] / 2 \\
& + p_{i,j}^{n+1} (\theta_{i,j}^{n+1} - \theta_{i,j}^n) \Big) - \delta t R_{i,j}^n \Big[(\bar{T}_\ell)_{i,j} - (\bar{T}_g)_{i,j} \\
& + (\bar{T}_g)_{i,j} / (\bar{c}_g)_{i,j} - (\bar{T}_\ell)_{i,j} / (\bar{c}_\ell)_{i,j} \Big] + \delta t R_{i,j}^n (I_g)_{i,j}^{n+1} \\
& / (\bar{c}_g)_{i,j} \Big] / \Big[2 (\bar{c}_\ell)_{i,j} (\rho'_\ell)_{i,j}^{n+1} + \delta t R_{i,j}^n \Big]. \quad (A-18)
\end{aligned}$$

The quantities denoted by a super bar in equations (A-10)-(A-18), refer to a value of the quantity at a time intermediate between $n(\delta t)$ and $(n+1)\delta t$. The effects of interfacial heat transfer in equations (A-14) and (A-18) have been treated implicitly by writing T_g^{n+1} and T_ℓ^{n+1} as

$$T_g^{n+1} = \bar{T}_g + \left[I_g^{n+1} - \bar{T}_g \right] / \bar{c}_g, \quad (A-19)$$

and

$$T_\ell^{n+1} = \bar{T}_\ell + \left[I_\ell^{n+1} - \bar{T}_\ell \right] / \bar{c}_\ell, \quad (A-20)$$

where $\bar{T}_g$ and $\bar{T}_\ell$ are given by, $\bar{T}_g = T_g [p^{n+1}, I_g^n]$ and $\bar{T}_\ell = T_\ell [p^{n+1}, (I_\ell)^n]$, with $\bar{c}_g$ and $\bar{c}_\ell$ treated similarly. The effects of interfacial heat transfer are divided equally between the calculations of I_g^{n+1} and I_ℓ^{n+1} .

The momentum density quantities denoted by a superscript tilde ($\sim$) account for the effects of momentum convection, gravity, and viscous stress through the following relations:

$$(\rho'_g \tilde{u}_g)_{i+1/2,j} = (\rho'_g u_g)_{i+1/2,j}^n + \frac{\delta t}{\varepsilon_{VR}} \left\{ - \langle (\rho'_g)^n u_g^n u_g^n r \rangle_{i+1/2,j} \right.$$

$$\begin{aligned}
& / (r_{i+1/2} \delta r_{i+1/2}) - < (\rho'_g)^n u_g^n v_g^n >_{i+1/2,j} / \delta z_j \\
& + \left[r_{i+1} \theta_{i+1,j}^n (\sigma_{grr})_{i+1,j}^n \zeta_{RB} - r_i \theta_{i,j}^n (\sigma_{grr})_{i,j}^n \right] / (r_{i+1/2} \delta r_{i+1/2}) \\
& + \left[\theta_{i+1/2,j+1/2}^n (\sigma_{grz})_{i+1/2,j+1/2}^n \right. \\
& \quad \left. - \theta_{i+1/2,j-1/2}^n (\sigma_{grz})_{i+1/2,j-1/2}^n \right] / \delta z_j \Big\} \\
& - \delta t \theta_{i+1/2,j}^n (\sigma_{g\theta\theta})_{i+1/2,j}^n / r_{i+1/2} + \delta t (\rho'_g)^n_{i+1/2,j} \chi_g g \sin \phi, \\
& \hspace{15em} (A-21)
\end{aligned}$$

$$\begin{aligned}
(\rho'_g \tilde{v}_g)_{i,j+1/2} &= (\rho'_g v_g)_{i,j+1/2}^n + \frac{\delta t}{\zeta_{VZ}} \left\{ - < (\rho'_g)^n v_g^n u_g^n r >_{i,j+1/2} \right. \\
& / (r_i \delta r_i) - < (\rho'_g)^n v_g^n v_g^n >_{i,j+1/2} / \delta z_{j+1/2} \\
& + r_{i+1/2} \theta_{i+1/2,j+1/2}^n (\sigma_{grz})_{i+1/2,j+1/2}^n \\
& - r_{i-1/2} \theta_{i-1/2,j+1/2}^n (\sigma_{grz})_{i-1/2,j+1/2}^n \\
& / (r_i \delta r_i) + \left[\theta_{i,j+1}^n (\sigma_{gzz})_{i,j+1}^n \zeta_{TB} - \theta_{i,j}^n (\sigma_{gzz})_{i,j}^n \right] \\
& \left. / \delta z_{j+1/2} \right\} + \delta t (\rho'_g)^n_{i,j+1/2} \chi_g g \cos \phi, \\
& \hspace{15em} (A-22)
\end{aligned}$$

$$\begin{aligned}
(\rho'_\ell \tilde{u}_\ell)_{i+1/2,j} &= (\rho'_\ell u_\ell)_{i+1/2,j}^n + \frac{\delta t}{\zeta_{VR}} \left\{ - < (\rho'_\ell)^n u_\ell^n u_\ell^n r >_{i+1/2,j} \right. \\
& / (r_{i+1/2} \delta r_{i+1/2}) - < (\rho'_\ell)^n u_\ell^n v_\ell^n >_{i+1/2,j} / \delta z_j \\
& + \left[r_{i+1} (1-\theta_{i+1,j}^n) (\sigma_{\ell rr})_{i+1,j}^n \zeta_{RB} - r_i (1-\theta_{i,j}^n) (\sigma_{\ell rr})_{i,j}^n \right] \\
& / (r_{i+1/2} \delta r_{i+1/2}) + \left[(1-\theta_{i+1/2,j+1/2}^n) (\sigma_{\ell rz})_{i+1/2,j+1/2}^n \right. \\
& \quad \left. - (1-\theta_{i+1/2,j-1/2}^n) (\sigma_{\ell rz})_{i+1/2,j-1/2}^n \right] / \delta z_j \Big\} \\
& - \delta t (1-\theta_{i+1/2,j}^n) (\sigma_{\ell\theta\theta})_{i+1/2,j}^n / r_{i+1/2} + \delta t (\rho'_\ell)^n_{i+1/2,j} \chi_g g \sin \phi, \\
& \hspace{15em} (A-23)
\end{aligned}$$

$$\begin{aligned}
(\rho'_\ell v_\ell)_{i,j+1/2} &= (\rho'_\ell v_\ell)_{i,j+1/2}^n + \frac{\delta t}{\delta V Z} \left\{ - \langle (\rho'_\ell)^n v_\ell^n u_\ell^n r \rangle_{i,j+1/2} \right. \\
&\quad / (r_i \delta r_i) - \langle (\rho'_\ell)^n v_\ell^n v_\ell^n \rangle_{i,j+1/2} / \delta z_{j+1/2} \\
&\quad + \left[r_{i+1/2} (1-\theta_{i+1/2,j+1/2}^n) (\sigma_{\ell r z})_{i+1/2,j+1/2}^n \right. \\
&\quad \left. - r_{i-1/2} (1-\theta_{i-1/2,j+1/2}^n) (\sigma_{\ell r z})_{i-1/2,j+1/2}^n \right] / (r_i \delta r_i) \\
&\quad + \left[(1-\theta_{i,j+1}^n) (\sigma_{\ell z z})_{i,j+1}^n \zeta_{TB} - (1-\theta_{i,j}^n) (\sigma_{\ell z z})_{i,j}^n \right] / \delta z_{j+1/2} \\
&\quad + \delta t (\rho'_\ell)_{i,j+1/2}^n x_g g \cos \emptyset .
\end{aligned} \tag{A-24}$$

The flux quantities in equations (A-10)-(A-18) denoted symbolically by $\langle Q_{ur} \rangle$ and $\langle Q_v \rangle$ are calculated using donor-cell differencing, where Q refers to θ , $(1-\theta)$, ρ'_g , ρ'_{g1} , ρ'_ℓ , $(\rho'_g u_g)$, $(\rho'_g v_g)$, $(\rho'_\ell u_\ell)$, $(\rho'_\ell v_\ell)$, $(\rho'_g I_g)$, or $(\rho'_\ell I_\ell)$. The quantities $\langle Q_{ur} \rangle_{i,j}$ and $\langle Q_v \rangle_{i,j}$ that appear in equations (A-10), (A-11), (A-14), (A-15), and (A-18) are thus given by

$$\begin{aligned}
\langle Q_{ur} \rangle_{i,j} &= \zeta_R (u r)_{i+1/2,j} \begin{cases} Q_{i,j} & \text{if } u_{i+1/2,j} > 0 \\ Q_{i+1,j} & \text{if } u_{i+1/2,j} \leq 0 \end{cases} \\
&\quad - \zeta_L (u r)_{i-1/2,j} \begin{cases} Q_{i-1,j} & \text{if } u_{i-1/2,j} > 0 \\ Q_{i,j} & \text{if } u_{i-1/2,j} \leq 0 \end{cases} ,
\end{aligned} \tag{A-25}$$

and

$$\begin{aligned} \langle Q_v \rangle_{i,j} = \zeta_T v_{i,j+1/2} & \begin{cases} Q_{i,j} & \text{if } v_{i,j+1/2} > 0 \\ Q_{i,j+1} & \text{if } v_{i,j+1/2} \leq 0 \end{cases} \\ - \zeta_B v_{i,j-1/2} & \begin{cases} Q_{i,j-1} & \text{if } v_{i,j-1/2} > 0 \\ Q_{i,j} & \text{if } v_{i,j-1/2} \leq 0 \end{cases} \end{aligned} \quad (A-26)$$

The remaining flux quantities that appear in equations (A-21)-(A-24) in the form $\langle Q_{ur} \rangle_{i+1/2,j}$, $\langle Q_v \rangle_{i+1/2,j}$, $\langle Q_{ur} \rangle_{i,j+1/2}$, and $\langle Q_v \rangle_{i,j+1/2}$ are given by

$$\begin{aligned} \langle Q_{ur} \rangle_{i+1/2,j} = \zeta_{RB} (u_r)_{i+1,j} & \begin{cases} Q_{i+1/2,j} & \text{if } u_{i+1,j} > 0 \\ Q_{i+3/2,j} & \text{if } u_{i+1,j} \leq 0 \end{cases} \\ - (u_r)_{i,j} & \begin{cases} Q_{i-1/2,j} & \text{if } u_{i,j} > 0 \\ Q_{i+1/2,j} & \text{if } u_{i,j} \leq 0 \end{cases} \end{aligned} \quad (A-27)$$

$$\begin{aligned} \langle Q_v \rangle_{i+1/2,j} = v_{i+1/2,j+1/2} & \begin{cases} Q_{i+1/2,j} & \text{if } v_{i+1/2,j+1/2} > 0 \\ Q_{i+1/2,j+1} & \text{if } v_{i+1/2,j+1/2} \leq 0 \end{cases} \\ - v_{i+1/2,j-1/2} & \begin{cases} Q_{i+1/2,j-1} & \text{if } v_{i+1/2,j-1/2} > 0 \\ Q_{i+1/2,j} & \text{if } v_{i+1/2,j-1/2} \leq 0 \end{cases} \end{aligned} \quad (A-28)$$

$$\begin{aligned}
\langle Q_{ur} \rangle_{i,j+1/2} = (u_r)_{i+1/2,j+1/2} & \begin{cases} Q_{i,j+1/2} & \text{if } u_{i+1/2,j+1/2} > 0 \\ Q_{i+1,j+1/2} & \text{if } u_{i+1/2,j+1/2} \leq 0 \end{cases} \\
- (u_r)_{i-1/2,j+1/2} & \begin{cases} Q_{i-1,j+1/2} & \text{if } u_{i-1/2,j+1/2} > 0 \\ Q_{i,j+1/2} & \text{if } u_{i-1/2,j+1/2} \leq 0 \end{cases} ,
\end{aligned}
\tag{A-29}$$

and

$$\begin{aligned}
\langle Q_v \rangle_{i,j+1/2} = \zeta_{TB} v_{i,j+1} & \begin{cases} Q_{i,j+1/2} & \text{if } v_{i,j+1} > 0 \\ Q_{i,j+3/2} & \text{if } v_{i,j+1} \leq 0 \end{cases} \\
- v_{i,j} & \begin{cases} Q_{i,j-1/2} & \text{if } v_{i,j} > 0 \\ Q_{i,j+1/2} & \text{if } v_{i,j} \leq 0 \end{cases} ,
\end{aligned}
\tag{A-30}$$

where the momentum transport velocities are calculated as

$$u_{i+1,j} = (\zeta_{R2} u_{i+3/2,j} + \zeta_{L2} u_{i+1/2,j}) / 2$$

$$u_{i,j} = (\zeta_R u_{i+1/2,j} + \zeta_L u_{i-1/2,j}) / 2$$

$$v_{i+1/2,j+1/2} = \zeta_T (v_{i+1,j+1/2} + v_{i,j+1/2}) / 2$$

$$v_{i+1/2,j-1/2} = \zeta_B (v_{i+1,j-1/2} + v_{i,j-1/2}) / 2$$

$$u_{i+1/2,j+1/2} = \zeta_R (u_{i+1/2,j+1} + u_{i+1/2,j}) / 2$$

$$u_{i-1/2,j+1/2} = \zeta_L (u_{i-1/2,j+1} + u_{i-1/2,j}) / 2$$

$$v_{i,j+1} = (\zeta_{T2} v_{i,j+3/2} + \zeta_{B2} v_{i,j+1/2}) / 2$$

$$v_{i,j} = (\zeta_T v_{i,j+1/2} + \zeta_B v_{i,j-1/2}) / 2$$

The viscous stress components in momentum and energy equations are calculated with the standard central differencing technique. These components, denoted by σ , are evaluated using the time level (n) quantities in the momentum equations. However, for the energy equations, where they are denoted by $\bar{\sigma}$, the calculation is partially implicit with the time level (n+1) velocities and the time level (n) viscosities.

A.2.3 Numerical Procedure

The finite difference equations are solved by an implicit point relaxation technique. The calculation sequence is given below.

1. Subroutine TILDE calculates explicitly the convection, gravity, and viscous stress terms for all cells for the momentum equations (A-12), (A-13), (A-16), and (A-17) using equations (A-21)-(A-24). The mass fluxes are also estimated using the time level (n) densities and the estimated advanced time velocities from equations (A-12), (A-13), (A-16), and (A-17). In addition, J_e^n , J_c^n , K^n , and R^n are also computed.
2. Subroutine ITER controls the iterative part of the solution. The pressure is adjusted in the cells until D_g or D_ℓ in equations (A-10) or (A-15), depending on whether $\theta \geq \theta^*$ or $\theta < \theta^*$, where $\theta^* = 0.5$, is less than a specified small quantity, ϵ . The value of ϵ used in the code is $10^5 (\rho')_{i,j}$. The calculation sequence of the pressure iteration is as follows:
 - (a) Calculate D_ℓ from equation (A-15) if $\theta_{i,j}^n < \theta^*$, or calculate D_g from equation (A-10) if $\theta_{i,j}^n > \theta^*$. If D_g or $D_\ell < \epsilon$, go to step (h).

- (b) Since $|D_\ell|$ or $|D_g| > \epsilon$, adjust $p_{i,j}^{n+1}$. This is done by using a constrained two-sided secant method^[A-1]. This method requires knowledge of two pressures that bracket the desired pressure.

Before these two pressures are obtained, the pressure is adjusted according to the recurrence relation

$$p_{i,j} \leftarrow p_{i,j} - D_\ell / (dD_\ell / dp),$$

or

$$p_{i,j} \leftarrow p_{i,j} - D_g / (dD_g / dp), \quad (A-31)$$

where

$$\begin{aligned} dD_\ell / dp = & (1 - \theta_{i,j}^n) / a_\ell^2 + (\rho_\ell)_i^n \theta_{i,j}^n / [(\rho_g)_i^n a_g^2] \\ & + (\delta t / \delta z_j)^2 \left\{ \zeta_T + \zeta_B + \theta_{i,j}^n (\rho_\ell)_i^n \right\} \zeta_T \theta_{i,j+1/2}^n \\ & / [(\rho_g')_{i,j+1/2}^n + \delta t K_{i,j+1/2}] + \zeta_B \theta_{i,j-1/2}^n / [(\rho_g')_{i,j-1/2}^n \\ & + \delta t K_{i,j-1/2}] \Big\} + (\delta t / \delta r_i)^2 \left\{ \zeta_R r_{i+1/2} + \zeta_L r_{i-1/2} \right. \\ & + \theta_{i,j}^n (\rho_\ell)_i^n \left\{ \zeta_R r_{i+1/2} \theta_{i+1/2,j}^n / [(\rho_g')_{i+1/2,j}^n + \delta t K_{i+1/2,j}] \right. \\ & + \zeta_L r_{i-1/2} \theta_{i-1/2,j}^n / [(\rho_g')_{i-1/2,j}^n + \delta t K_{i-1/2,j}] \Big\} \Big\} \\ & / r_i, \text{ for } \theta_{i,j}^n < \theta^*, \end{aligned} \quad (A-32)$$

and

$$dD_g / dp = \theta_{i,j}^n / a_g^2 + 1/2 \left\{ (\delta t / \delta r_i)^2 \left[\zeta_R r_{i+1/2} (\theta_{i,j}^n + \theta_{i+1,j}^n) \right. \right.$$

$$+ \zeta_L r_{i-1/2} (\theta_{i,j}^n + \theta_{i-1,j}^n) \Big] / r_i + (\delta t / \delta z_j)^2 \left[\zeta_T (\theta_{i,j}^n + \theta_{i,j+1}^n) + \zeta_B (\theta_{i,j}^n + \theta_{i,j-1}^n) \right] \Big\} , \text{ for } \theta_{i,j}^n \geq \theta^* . \quad (\text{A-33})$$

(c) Calculate $(\bar{I}_g)_{i,j}$ and $(\bar{I}_\ell)_{i,j}$ from the energy equations omitting temporarily the effects of convection, work, and single-phase conduction. The finite difference form of the equations solved is

$$\begin{aligned} (\bar{I}_g)_{i,j} = (\bar{c}_g)_{i,j} \Big\{ & \left((I_g)_{i,j}^n (\rho'_g)_{i,j}^{n+1} + \delta t \left[(\bar{J}_e)_{i,j} - (\bar{J}_c)_{i,j} \right] \right) \left[p_{i,j}^{n+1} / (\bar{\rho}_g)_{i,j} \right] + (I_g)_{i,j}^n + \delta t \left\{ K_{i,j}^n + \left[(\bar{J}_e)_{i,j} + (\bar{J}_c)_{i,j} \right] \right. \\ & / 2 \Big\} \left\{ \left[\zeta_R (u_g)_{i+1/2,j}^{n+1} + \zeta_L (u_g)_{i-1/2,j}^{n+1} - \zeta_R (u_\ell)_{i+1/2,j}^{n+1} - \zeta_L (u_\ell)_{i-1/2,j}^{n+1} \right]^2 \right. \\ & + \left[\zeta_T (v_g)_{i,j+1/2}^{n+1} + \zeta_B (v_g)_{i,j-1/2}^{n+1} - \zeta_T (v_\ell)_{i,j+1/2}^{n+1} - \zeta_B (v_\ell)_{i,j-1/2}^{n+1} \right]^2 \Big\} + \delta t R_{i,j}^n \left[(\bar{T}_\ell)_{i,j} \right. \\ & - (I_\ell)_{i,j}^n / (\bar{c}_\ell)_{i,j} - (\bar{T}_g)_{i,j} + (I_g)_{i,j}^n / (\bar{c}_g)_{i,j} \\ & / 2 \Big\} + 2 (\bar{c}_\ell)_{i,j} (\rho'_\ell)_{i,j}^{n+1} + \delta t R_{i,j}^n \left(\delta t \left\{ K_{i,j}^n + \left[(\bar{J}_e)_{i,j} + (\bar{J}_c)_{i,j} \right] \right. \right. \\ & / 2 \Big\} \left\{ \left[\zeta_R (u_g)_{i+1/2,j}^{n+1} + \zeta_L (u_g)_{i-1/2,j}^{n+1} - \zeta_R (u_\ell)_{i+1/2,j}^{n+1} - \zeta_L (u_\ell)_{i-1/2,j}^{n+1} \right]^2 \right. \\ & + \left[\zeta_T (v_g)_{i,j+1/2}^{n+1} + \zeta_B (v_g)_{i,j-1/2}^{n+1} - \zeta_T (v_\ell)_{i,j+1/2}^{n+1} - \zeta_B (v_\ell)_{i,j-1/2}^{n+1} \right]^2 \Big\} + (I_\ell)_{i,j}^n (\rho'_\ell)_{i,j}^{n+1} + (I_g)_{i,j}^n (\rho'_g)_{i,j}^{n+1} \Big) \\ & / \left\{ (\bar{c}_g)_{i,j} (\rho'_g)_{i,j}^{n+1} \left[2 (\bar{c}_\ell)_{i,j} (\rho'_\ell)_{i,j}^{n+1} + \delta t R_{i,j}^n \right] \right. \\ & \left. + \delta t R_{i,j}^n (\bar{c}_\ell)_{i,j} (\rho'_\ell)_{i,j}^{n+1} \right\} , \quad (\text{A-34}) \end{aligned}$$

and

$$\begin{aligned}
 (\bar{I}_\ell)_{i,j} = & (\bar{c}_\ell)_{i,j} \left(2 \left\{ (I_\ell)_{i,j}^n (\rho'_\ell)_{i,j}^{n+1} \right. \right. \\
 & - \delta t \left[(\bar{J}_e)_{i,j} - (\bar{J}_c)_{i,j} \right] \left[p_{i,j}^{n+1} / (\bar{\rho}_g)_{i,j} \right. \\
 & + (I_g)_{i,j}^n \left. \right] - \delta t R_{i,j}^n \left[(\bar{T}_\ell)_{i,j} - (I_\ell)_{i,j}^n / (\bar{c}_\ell)_{i,j} - (\bar{T}_g)_{i,j} \right. \\
 & + (I_g)_{i,j}^n / (\bar{c}_g)_{i,j} \left. \right] / 2 \left. \right\} + \delta t R_{i,j}^n (\bar{T}_g)_{i,j} / (\bar{c}_g)_{i,j} \left. \right) \\
 & / \left[2 (\bar{c}_\ell)_{i,j} (\rho'_\ell)_{i,j}^{n+1} + \delta t R_{i,j}^n \right],
 \end{aligned}
 \tag{A-35}$$

where $\bar{T}_g$ and $\bar{T}_\ell$ are given by $\bar{T}_g = T_g[p^{n+1}, I_g^n]$ and $\bar{T}_\ell = T_\ell[p^{n+1}, I_\ell^n]$, and arise as a result of implicit treatment of the interfacial heat transfer coefficient and the specific heats, as $\bar{T}_g$ and $\bar{T}_\ell$ arise in equations (A-14) and (A-18).

- (d) Calculate $(\bar{\rho}_g)_{i,j}$, $(\bar{T}_g)_{i,j}$, $(\bar{\rho}_\ell)_{i,j}$, $(\bar{T}_\ell)_{i,j}$ from the gas phase mass fractions, pressure, and internal energies using the two equations of state. Calculate $(T_s)_{i,j}^{n+1}$, $(\bar{J}_e)_{i,j}$, and $(\bar{J}_c)_{i,j}$.
- (e) If $\theta_{i,j}^n < \theta^*$: Calculate $(\rho'_g)_{i,j}^{n+1}$ from an implicit solution (in terms of convection and phase change effects) of equation (A-10), with $D_g=0$. Similarly calculate $(\rho'_{gl})_{i,j}^{n+1}$ from equation (A-11), which gives $(x_{gl})_{i,j}^{n+1} = (\rho'_{gl})_{i,j}^{n+1} / (\rho'_g)_{i,j}^{n+1}$. Estimate $\theta_{i,j}^{n+1} = (\rho'_g)_{i,j}^{n+1} / (\bar{\rho}_g)_{i,j}$.
- If $\theta_{i,j}^n \geq \theta^*$: Use the previous iteration value of $\theta_{i,j}^{n+1}$. Calculate $(x_{gl})_{i,j}^{n+1} = (\rho'_g)_{i,j}^{n+1} / [\theta_{i,j}^{n+1} (\bar{\rho}_g)_{i,j}]$, where $(\rho'_{gl})_{i,j}^{n+1}$ is obtained from the solution of equation (A-11).

(f) Calculate $(u_g)_{i+1/2,j}^{n+1}$, $(v_g)_{i,j+1/2}^{n+1}$, $(u_\ell)_{i+1/2,j}^{n+1}$, and $(v_\ell)_{i,j+1/2}^{n+1}$ using equations (A-12), (A-13), (A-16), and (A-17) respectively.

(g) Calculate new gas or liquid mass fluxes depending on whether $\theta_{i,j}^n < \theta^*$ or $\theta_{i,j}^n \geq \theta^*$.

(h) Case (i), $\theta_{i,j}^n < \theta^*$: Explicitly solve equation (A-10) for $(\rho'_g)_{i,j}^{n+1}$ by putting $D_g=0$. Solve equation (A-11) for $(\rho'_{gl})_{i,j}^{n+1}$ and calculate $(x_{gl})_{i,j}^{n+1} = (\rho'_{gl})_{i,j}^{n+1} / (\rho'_g)_{i,j}^{n+1}$. Calculate $\theta_{i,j}^{n+1} = (\rho'_g)_{i,j}^{n+1} / (\bar{\rho}_g)_{i,j}$. Then calculate $(\rho'_\ell)_{i,j}^{n+1} = (1 - \theta_{i,j}^{n+1})(\bar{\rho}_\ell)_{i,j}$. If $D_\ell \leq \epsilon$, go to the next cell, otherwise compute new liquid mass fluxes using latest ρ'_ℓ and velocities, and repeat steps (b) through (g).

Case (ii), $\theta_{i,j}^n \geq \theta^*$: Explicitly solve equation (A-13) for $(\rho'_\ell)_{i,j}^{n+1}$ by putting $D_\ell=0$. Calculate $\theta_{i,j}^{n+1} = 1 = (\bar{\rho}_\ell)_{i,j}^{n+1} / (\bar{\rho}_\ell)_{i,j}$. Then calculate $(x_{gl})_{i,j}^{n+1} = (\rho'_{gl})_{i,j}^{n+1} / [\theta_{i,j}^{n+1} (\bar{\rho}_g)_{i,j}]$, where $(\rho'_{gl})_{i,j}^{n+1}$ is obtained from the solution of equation (A-11). Also compute $(\rho'_g)_{i,j}^{n+1} = \theta_{i,j}^{n+1} (\bar{\rho}_g)_{i,j}$. If $D_g \leq \epsilon$, go to the next cell, otherwise compute new gas mass fluxes using latest ρ'_g and velocities, and repeat steps (b) through (g).

3. The pressure iteration (Step 2) is complete when $|D_\ell|$ or $|D_g| \leq \epsilon$ simultaneously in all the cells. When this is achieved, complete solution to the continuity and momentum

equations, along with the partial solution of the energy equations has been obtained. Final complete solution to the energy equations (A-12) and (A-16) is obtained in subroutine ICØNV.

4. By using the values of I_g^{n+1} , I_ℓ^{n+1} , and p^{n+1} , final values of T_s , ρ_g , T_g , c_g , ρ_ℓ , T_ℓ , c_ℓ , κ_g , κ_ℓ , μ_g , and μ_ℓ , are calculated through the equation of state and transport property routines. This completes a computational cycle.

A.3 Lumped-Parameter Region

A lumped-parameter model of a large volume in a containment system has been developed and added as an option in the BEACON code. The assumption is made that velocities in the volume are negligible and that conditions in the volume can be characterized by a single set of stagnation properties. Therefore, only the mass and energy equations need be written for the volume. These equations are solved explicitly for all lumped-parameter regions. The time step size in this case is several times larger than that for the Eulerian regions. Lumped-parameter volumes or regions are connected only to one-dimensional (1-D) Eulerian regions as shown in Figure A-2. Any number of 1-D regions may be connected to a given lumped-parameter region, the maximum number being limited by array dimensions in the code.

A.3.1 Governing Equations

The mass conservation equations for the lumped-parameter region are

$$(\rho'_g)_L^{n+1} = (\rho'_g)_L^n + \frac{\delta t_L}{V_L} \left[\sum (\overline{\rho'_g u_g})_J + \sum \bar{\dot{m}}_{gS} \right] + \delta t_L (J_e^n - J_c^n)_L, \quad (A-36)$$

$$(\rho'_{g1})_L^{n+1} = (\rho'_{g1})_L^n + \frac{\delta t_L}{V_L} \left[\sum (\overline{\rho'_{g1} u_g})_J + \sum \bar{\dot{m}}_{g1S} \right] + \delta t_L (J_e^n - J_c^n)_L, \quad (A-37)$$

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Fig. A-2 1-D Region Coupled to Lumped Parameter Region

$$(\rho'_\ell)_L^{n+1} = (\rho'_\ell)_L^n + \frac{\delta t_L}{V_L} \left[\sum (\overline{\rho'_\ell v_\ell A})_J + \sum \overline{\dot{m}_\ell S} \right] - \delta t_L (J_e^n - J_c^n)_L, \quad (A-38)$$

and the energy conservation equations are

$$\begin{aligned} (I_g)_L^{n+1} = & \frac{1}{(\rho'_g)_L^{n+1}} \left((\rho'_g I_g)_L^n + \frac{\delta t_L}{V_L} \left\{ \sum \left[\left(H_g + \frac{u_g^2}{2} \right) (\rho'_g u_g A) \right]_J \right. \right. \\ & + \left. \left. \sum \left[\overline{\dot{m}_g \left(H_g + \frac{u_g^2}{2} \right)} \right]_S \right\} + \delta t_L \left\{ R_L^n (T_\ell^n - T_g^n)_L \right. \right. \\ & \left. \left. + (J_e^n - J_c^n)_L (H_{g1})_L^n \right\} \right) \quad , \end{aligned} \quad (A-39)$$

$$\begin{aligned} (I_\ell)_L^{n+1} = & \frac{1}{(\rho'_\ell)_L^{n+1}} \left((\rho'_\ell I_\ell)_L^n + \frac{\delta t_L}{V_L} \left\{ \sum \left[\left(H_\ell + \frac{u_\ell^2}{2} \right) (\rho'_\ell u_\ell A) \right]_J \right. \right. \\ & + \left. \left. \sum \left[\overline{\dot{m}_\ell \left(H_\ell + \frac{u_\ell^2}{2} \right)} \right]_S \right\} - \delta t_L \left\{ R_L^n (T_\ell^n - T_g^n)_L \right. \right. \\ & \left. \left. + (J_e^n - J_c^n)_L (H_{g1})_L^n \right\} \right) \quad . \end{aligned} \quad (A-40)$$

A.3.2 Numerical Procedure

The computations for the time advancement of lumped-parameter regions proceed in the following manner:

1. The new partial densities of the vapor and liquid fields are computed from equations (A-36)-(A-38). New mass fraction of component 1 is then computed from the new gas densities.
2. The new internal energies are computed from equations (A-39) and (A-40)

3. New thermodynamic liquid density is calculated from the liquid equation of state using the old pressure

$$(\rho_l)^{n+1} = \rho_l \left[(I_l)^{n+1}, p^n \right]$$

4. New void fraction is calculated as

$$\theta^{n+1} = 1 - (\rho'_l)^{n+1} / (\rho_l)^n.$$

If $\theta^{n+1} < 0$, θ^{n+1} is set equal to zero with $(\rho'_l)^{n+1} = (\rho_l)^n$ and $(\rho'_l)^{n+1} = 0$. If $\theta^{n+1} > 1$, θ^{n+1} is set equal to unity with $(\rho'_l)^{n+1} = 0$. In either case, the internal energies and the junction flow rates are readjusted to satisfy the appropriate condition.

5. If the new void fraction is nonzero, the new pressure is calculated from the gas equation of state

$$p^{n+1} = p \left[(\rho'_g)^{n+1}, (x_{g1})^{n+1}, \theta^{n+1}, I_g^{n+1} \right]$$

6. Other thermodynamic quantities such as temperatures, specific heats, thermal conductivities, and thermodynamic densities are brought up to the new time levels. The equation-of-state and interphasic exchange function computations used are the same as those used for the K-FIX numerical scheme.

After the time advancement of the lumped-parameter region is completed, the properties of the exterior 1-D cell (cell $i+1$ of Figure A-2) are updated. The exterior cell properties are related to the lumped-parameter state conditions in the following form:

$$P_{i+1} = \alpha_p P_L, \quad I_{i+1} = \alpha_I I_L, \quad \text{and} \quad \rho_{i+1} = \alpha_\rho \rho_L,$$

where α_p , α_I and α_ρ are empirical constants or are calculated from relationships appropriate to the modeled geometry and flow. For the initial checkout runs $\alpha_p = \alpha_I = \alpha_\rho = 1.0$ is being used in BEACON.

The conditions in the exterior cell are then held invariant as the 1-D region is advanced to the next time level. The flow velocities at the 1-D junction are determined in the Eulerian region computations.

The entrance and exit form losses presently reflected in the 1-D/lumped-parameter coupling are:

- (1) For flow leaving the lumped-parameter region, form losses are zero (Bellmouth entrance).
- (2) For flow entering the lumped-parameter region, $1/2$ of the velocity head is recovered.

The form losses result from the above assumptions and method of coupling the two regions. Future BEACON code development will provide a number of form loss modeling options.

References

- A-1 W. C. Rivard, and M. D. Torrey, K-FIX: A Computer Program for Transient, Two-Dimensional, Two-Fluid Flow, Report No. LA-NUREG-6623, NRC-4, Los Alamos Scientific Laboratory, Los Alamos, Apr. 1977
- A-2 F. H. Harlow, and A. A. Amsden, "Numerical Calculation of Multiphase Fluid Flow," J. Comp. Phys., Vol. 17, No. 19, 1975.

APPENDIX B

TIME HISTORY PLOT FILE PROGRAM

APPENDIX B

TIME HISTORY PLOT FILE PROGRAM

The BEACON/MOD2A code plot capability is supplemented by a separate plot package named PLTBCN. PLTBCN requires a data tape generated by BEACON for use with a systems graphics output program named DISSPLA. This appendix describes PLTBCN and provides instructions for its use.

1. GENERAL DESCRIPTION

The BEACON/MOD2A program has the capability to generate contour plots, particle plots and velocity vector plots. These are spatially oriented plots at a given problem time. To augment this capability, a time plot program was developed and is available for use with BEACON/MOD2A. This program, called PLTBCN, is used to plot BEACON fundamental output variables against time. A data tape generated by the BEACON code is used by PLTBCN along with a graphics program called DISSPLA to provide plots of output variable versus time.

PLTBCN also provides an overlay capability for the plotting of from two to five variables on one axis against one independent variable, (normally time), on the other axis. The independent coordinate may also be any fundamental variable, providing plots of output variable versus output variable. The difference between two specified BEACON variables may also be plotted against time or against an independent variable.

The plotting options mentioned above use a plot data restart tape created during a BEACON run. PLTBCN can also provide similar plots using arbitrary input data independent of the restart tape. In this case the coordinate values are input to PLTBCN on punched cards. A

useful application of this option is in verification studies where the user may choose to overlay experimental data (entered by cards) with corresponding BEACON output data (entered by tape).

This section describes the subroutines unique to the plot file program.

PLTBCN - main routine for BEACON/MOD2A time plots

AXISDV - divides a plotting axis into a specified number of divisions

DEFAULT - sets the default values of input variables

DOLLAR - appends a dollar sign (\$) onto the right end of a given word to allow easier use of DISSPLA labeling routines

INPERR - prints error messages detected at input processing time

INPUTO - reads the input cards and processes them

PLTKOM - primary interface routine with the DISSPLA software

RONOFF - rounds a real number to a specified number of significant figures

RTAPE2 - reads the BEACON restart tape and extracts values of variables that are to be plotted

SELCOM - Finds location of variable to plot and transfers data from tape to plotting array

2. INPUT

As with the BEACON code, PLTBCN also utilizes the INEL INP input processing package to process input data. General information on the required input format, rules and conventions are presented in the BEACON users manual.

- (1) Card 100 A variable to plot and its location.
(Required)

W1-A VARIBL

The variable names are the same as in the CELCOM common block in BEACON. Presently the following variables may be plotted:

CRATE	TG
ERATE	TH
KDRAG	TL
P	TS
RGP	UG
RGP1	UL
RL	VG
RLP	VL
ROG	
XMG1	
SIEG	
SIEL	

W2-I LOC

This location is the IJ value found at the beginning of the output on a BEACON run.

Example:

100 TG 501

- (2) Card 101 Plot Title
(Optional)

W1,W6-A TITLEP

A six word array is allowed for plot titles. Note that single quotes are required. Up to 59 characters may be used including blanks.

Example:

101 'SAMPLE TEMPERATURE PLOT'

- (3) Card 105 X-AXIS Title
(Optional)

W1-W6,A XTITLE

A six word array, up to 59 characters, for labeling the X-axis.

Example:

105 'TIME-SEC'

- (4) Card 110 Y-AXIS TITLE
(Optional)

W1,W6-A YTITLE

A six word array, up to 59 characters, for labeling Y-AXIS

Example:

110 'TEMPERATURE OF VAPOR-CELL 2,2'

(5) Cards 115, 116, 117 Main heading (Optional)

W1,W6-A HEADER Up to 3 cards, 59 characters each, to
produce up to 3 lines of heading infor-
mation on each plot.

Example:

115 'BATTELLE-FRANKFURT TEST-1'
116 'ANALYSIS WITH BEACON2M'
117 'USING NEW DRAG MODEL'

(6) Card 125 User specified Xmin, Xmax, Ymin, Ymax
(Optional)

W1-R	XMIN	Minimum X-coordinate
W2-R	XMAX	Maximum X-coordinate
W3-R	YMIN	Minimum Y-coordinate
W4-R	YMAX	Maximum Y-coordinate

Example

125 0.0 1.0 1.E5 2.E5

(7) Card 130 User specified details of the plot
(Optional)

W1-I IDARK Number of times the curve will be
retraced. Retracing is useful to darken
lines.

W2-I	LSTYLE	<p>Lettering style.</p> <p>= 0, default/DISSPLA</p> <p>= 1, Leroy or duplex lettering</p> <p>= 2, complex lettering</p>
W3-I	IGRIDP	<p>Specific grid type.</p> <p>= 1, dots for grid</p> <p>= 0, no grid</p> <p>= +1, solid grid</p>
W4-I	IXGRID	<p>Number of grid lines per division on X-axis; suggest at least 2.</p>
W5-I	IYGRID	<p>Number of grid lines per division on Y-axis; suggest at least 2.</p>
W6-I	NDIVX	<p>Number of divisions on X-axis; suggest at least 5.</p>
W7-I	NDIVY	<p>Number of divisions on Y-axis; suggest at least 5.</p>
W8-I	LINSET	<p>Type of line for the curve</p> <p>= 0, solid line</p> <p>= 1, dotted line</p> <p>= 2, dashed line</p> <p>= 3, chain dot</p> <p>= 4, chain dash</p>
W9-I	IDRAW	<p>Used in conjunction with W8 above, for connecting the points on the curve.</p> <p>= + I, points are connected and there is a symbol every Ith point.</p>

= - 1, points are not connected and
there is a symbol every 1th point.
= 0, points connected with a solid line
and no symbol.

W10-I NSPLIN

Spline fit.

= 0, no spline fit

= 1, spline fit

Example:

130 3 0 0 2 2 5 5 0 +1 0

- (8) Card 140 Difference plots.
(Optional)

W1-A VARIBL2

The difference between this variable and
the one on card 100, is plotted. See
Card 100 for possible variables.

W2-I LOC2

The IJ location of this variable. Need
not be the same location as on
Card 100.

Example:

140 TL 1129

- (9) Card 150 Change of independent variable (from the default of
(Optional) "TIME").

W1-A XVARB

New independent variable. Must be one
in the same group as on Card 100.

W2-I IXLOC IJ location of new independent variable.

Example:

150 KDRAG 501

- (10) Card 160-163 Overlay variable (two to five dependent
(Optional) variables).

W1-A OVARIB Variable name.

W2-I LOCOV Location (IJ-value) of node.

- (11) Cards 200-249 Arbitrary data to be plotted; any
(Optional) (x,y).

W1-R X Any arbitrary abscissa.

W2-R Y Any arbitrary ordinate.

Examples:

200 1.2 1.E5

201 3.0 10.33

3. OUTPUT

Sample plots depicting the five basic PLTBCN features described in Section B.1 are presented as Figures B-1 through B-5. These figures are:

	<u>Figure</u>
(a) Variable versus time	B-1
(b) Variable 1 versus Variable 2	B-2
(c) Overlay of two variables	B-3
(d) Difference of two variables	B-4
(e) Plot of arbitrary data	B-5

Fig. B-1 PLTBCN plot of variable vs. time.

Fig. 3-2 PLTBCN plot of variable vs. variable.

Fig. B-3 PLTBCN overlay plot.

Fig. B-4 PLTBCN difference plot.

Fig. B-5 PLTBCN plot of arbitrary data.

4. SAMPLE JOB REQUEST

This section presents typical input with the resultant plot obtained using PLTBCN. The input (Figure B-6) includes job control statements as well as the specific PLTBCN input cards used to generate the graph (Figure B-7).

SWJTBL,T37,P1,STMFZ,SI.
 ACCOUNT,2430,432820000,TBL.
 COMMENT.
 STAGE,TAPE2,PE,L,VSU=A3E535.
 ATTACH,BEACON,BEACCN2T,ID=SKJ.
 COPYP,BEACCN,CLOPL.
 COPYP,BEACCN,SECCARL.
 COPYP,BEACCN,TSTCAS.
 COPY,BEACCN,OLDDBJ.
 RETURN,OLDPL,SECCARL,TSTCAS.
 ATTACH,ENVRL,ID=KJW.
 ATTACH,DISSPLA.
 RFL(160000)
 LDSET(LIB=DISSPLA/OLDDBJ/ENVRL/FORTRAN)
 LIBLOAD(DISSPLA,FRAME)
 LIBLOAD(OLDDBJ,PLTBCN)
 EXECUTE,PLTBCN.
 REWIND,PLFILE.
 ATTACH,FR&CPLP.
 FR&OPOP.
 7/8/9

TAPE2 IS THE INPUT TAPE FOR PLTBCN.
 ACCESS COMPLETE BEACON PACKAGE.

PLTBCN IN OLDOBJ.
 DON'T NEED THESE FOR PLTBCN.
 ENVIRONMENTAL PACKAGE.
 DISSPLA GRAPHICS PACKAGE.
 REQUEST 160K FIELD LENGTH.
 SPECIFY ORDER FOR LIBRARIES.
 TAKE FRAME FROM DISSPLA ONLY.
 LOAD PLTBCN FROM OLDOBJ.

PLFILE FOR POST PROCESSOR.
 ATTACH POST PROCESSOR.
 EXECUTE POST PROCESSOR.

* THE FOLLOWING CARD MEANS PLTBCN WILL PLOT PRESSURE AT IJ = 3763.

100 P 3763

* THE ABOVE IS THE ONLY INPUT NEEDED TO MAKE THIS PLOT.
 * DEFAULT QUANTITIES EXIST FOR EVERYTHING OTHER THAN VARIABLE TO
 * PLOT AND ITS IJ LOCATION.

7/8/9
 6/7/8/9

Fig. B-6 PLTBCN Job Control and Input

BEACON MOD2 ADVANCED CONTAINMENT ANALYSIS CODE

Fig. B-7 Typical plot when using the PLTBLN input data cards shown in Figure 6.

APPENDIX C

FLOW CHARTS

APPENDIX C

FLOW CHARTS

Certain flow charts have been found to be helpful in the development of the BEACON/MOD2A program, namely those relating to the K-FIX numerical technique as installed in the BEACON code. These charts are presented herein for documentary purposes:

- (1) KFIXT - Sequence of subroutine calls for each phase of the Eulerian fluid computations.
- (2) ITER - Pressure-velocity iteration subroutine.
- (3) INDEX - Cell index setting subroutine.
- (4) BDRY - Boundary reflecting subroutine.

Other charts of interest including the BEACON general code organization are presented in elsewhere this report. The timestep advancement and output control logic charts are shown in the main body of this report.

Fig. C-1 Sequence of subroutine calls for K-FIX.

310

Fig. C-2 Pressure-velocity iteration subroutine.

ITER

Pg. 2 of 5

(From Pg. 1)

" $\theta \geq \theta^*$
SIDE

Obtains DG, gas
continuity
discrepancy

$$CONV = \epsilon_g n'_g$$

DVAP

CONVRG=EPSG*RPNG(IJ)
TARGET=(1.0-OMEGA)*DG
DGORIG=DG

NIT .GT. 1
.AND.
|DG-TARGET| > CONVRG

.T.
Converged
path

78
(Pg. 4)

MUSTIT=1
D3=DG
P3=P(IJ)

NIT

SET D2, P2

D2=D3
P2=P3
IF (KROS.EQ.-1) KROS=1
IF (KROS.EQ.0) KROS=2

55 (Pg. 3)

SAVE $\tilde{\rho}_g$ for
USE IN THGAS

" $\theta < \theta^*$
SIDE

Obtains DL, liquid
continuity discrepancy

$$CONV = \epsilon_L n'_L$$

DLIQ

RGP1T=RGPI(IJ)
CONVRG=EPSL*RLPN(IJ)
TARGET=(1.0-OMEGA)*DL
DLORIG=DL

NIT .GT. 1
.AND.
|DL-TARGET| > CONVRG

.T.
Converged
path

90
(Pg. 4)

MUSTIT=1
D3=DL
P3=P(IJ)

NIT

SET D1, P1

D1=D3
P1=P3
IF (KROS.EQ.-1) KROS=0
IF (KROS.EQ.1) KROS=2

55 (Pg. 3)

Pressure guess
start point

10

12
(Pg. 3)

Subsequent passes

Subsequent passes

First pass

First pass

$\geq \theta^*$

$< \theta^*$

> 1

> 1

D3 > TARGET

(Pg. 3)

$\langle \rho_g' V_g \rangle$

ITER Pg. 5 of 6

315

Fig. C-3 Cell index setting subroutine.

MULTI-MESH
sequencing loop

DO 300 MESHNO=MESHI,MESHF

HMTOT >1

RESET(7)

Resets computations
for selected MESH

DO 200 J=2,JU1
DO 200 I=1,I1
IJ=IJ11+(I-1)*NQ+(J-1)*NOI

FL(IJ) #1

200

NOT A FLUID CELL,
SKIP TO NEXT CELL

INDEX

LOCALIZE CELL FLAG VARIABLES

NFLB = FL(IJM)
NFLR = FL(IPJ)
NFLL = FL(IMJ)
NFLT = FL(IJP)
NFLBR = FL(IPJM)
NFLTR = FL(IPJP)
NFLTL = FL(IMJP)

Right
boundary
outflow

=4

NFLR

#4 .A. #7

Not a specified
flow boundary

=7

Shift cell-centered
variables to exterior
cell, except cell
flag

L=IJ-1
LX=IPJ-1
DO 35 N=1,NVAR

NINFL

AASC(LX+N)=AASC(L+N)
CONTINUE

35

Extrapolate
velocities
and KDRAG

Right
boundary
Const.
Press.

VG(IPJ)=VG(IJ)
UG(IPJ)=[(R(I+1)+R(I))*RB(I)+UG(IJ)-
R(I+1)*RB(I-1)+UG(IMJ)]*RRB(I+1)*RRI(I)
[SAME AS ABOVE FOR VL(IPJ) AND UL(IPJ)]
KDRAG(IPJ) = KDRAG(IJ)

50
(PG=2)

Fig. C-4 Boundary reflecting subroutine.