Basics of TRACE Computer Code and Analysis Methods

Information Systems Laboratories, Inc.

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Nuclear Regulatory Commission
TRACE/SNAP User Workshop
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Objective

Provide basic information about the TRACE code and system modeling for workshop attendees:

- With little or no TRACE background, or
- Desiring a refresher in TRACE methods

This presentation and the one that follows on basic SNAP methods will provide attendees with the TRACE and SNAP background needed for the training exercises conducted during the remainder of the workshop.

Outline

- Basic TRACE code theory and governing equations
- Closure relationships
- Flow regimes
- Code numerical solution scheme
- Special process models
- TRACE input and output
- Introduction to hydrodynamic and heat structure components
- Introduction to control system models
- Status of ongoing TRACE code development activities

TRACE Code documentation

TRACE V5.0 Theory Manual, Field Equations, Solution Methods and Physical Models

TRACE V5.0 Assessment Manual

- Fundamental Validation Cases (Appendix A)
- Separate Effects Test Assessments (Appendix B)
- Integral Effects Test Assessments (Appendix C)

TRACE V5.0 User’s Manual

- Input Specification (Volume 1 – available on the workshop PCs)
- Modeling Guidelines (Volume 2)

Basic TRACE Code Theory and Governing Equations

Six field-equation model for two-phase flow:

1. Conservation of mass, liquid phase
2. Conservation of mass, vapor phase
3. Conservation of momentum, liquid phase
4. Conservation of momentum, vapor phase
5. Conservation of energy, liquid phase
6. Conservation of energy, vapor phase

Additional equations are solved for non-condensible gases (tracked with the vapor phase) and dissolved boron (tracked with the liquid phase) when they are present in the fluid.

TRACE primary solution variables: void fraction, steam and non-condensible gas pressures, liquid and vapor velocities, liquid and vapor temperatures, boron concentration, heat structure temperatures.

Closure Relationships

Closure relationships are needed to form a complete set of equations to solve.

These relationships are semi-empirical correlations and equations, not first-principle representations of the physical properties and processes:

- Equations of State
  Vapor and liquid phase pressures, temperatures and densities
- Wall Drag
  Irrecoverable pressure loss caused by friction of vapor and liquid phases flowing adjacent to a wall (additional losses may be specified for flow through bends, area changes, etc.)
- Interfacial Drag
  Body force between vapor and liquid flowing at different velocities
- Wall Heat Transfer
  Energy flow between a structure and the vapor and liquid phases
- Interfacial Heat Transfer
  Energy exchange between vapor and liquid phases, with mass transfer resulting from boiling/evaporation of liquid and condensation of steam

Flow Regimes

The TRACE hydraulic and heat transfer models are selected based upon the flow regime present in each hydrodynamic fluid cell.

TRACE has static flow regime maps for “normal” fluid conditions in vertical and horizontal configurations, and for “reflood” fluid conditions in vertical configurations.

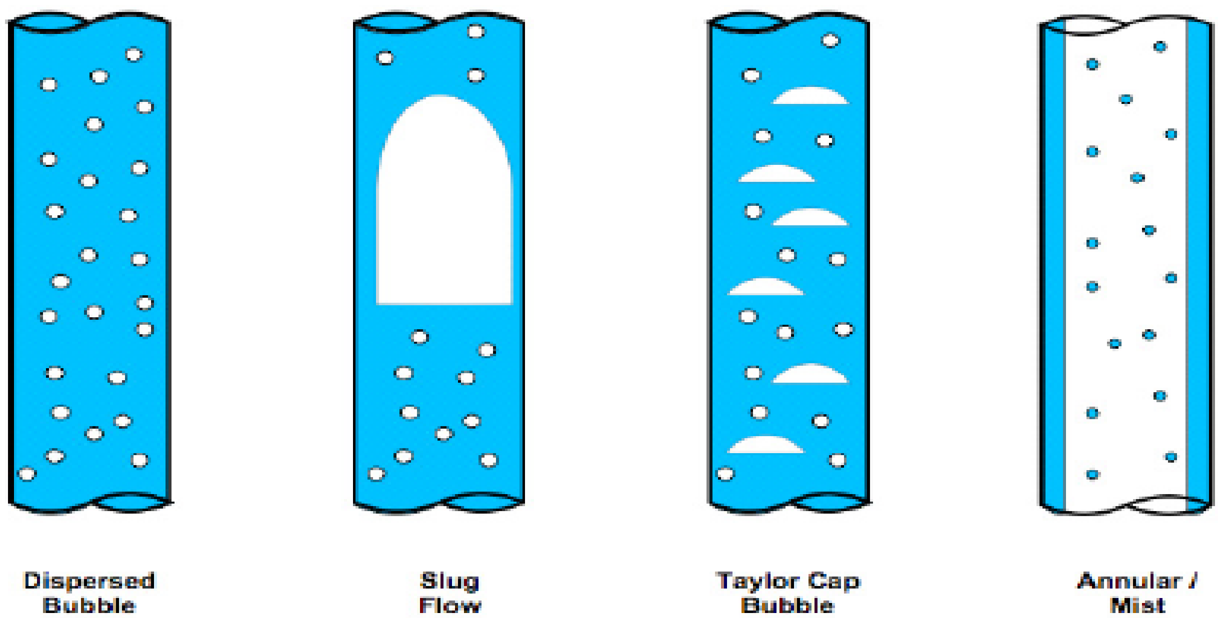
The flow regime map selection considers the fluid conditions (void fraction, velocities, etc.) and the wall-to-fluid heat transfer processes (based on a comparison with the critical heat flux, CHF):

- Pre-CHF heat transfer
  - Wall is wet – convection to liquid, subcooled and nucleate boiling
- Post-CHF heat transfer
  - Wall is dry – transition and film boiling, convection to vapor

Normal Vertical Flow Map

Pre-CHF vertical flow regimes:

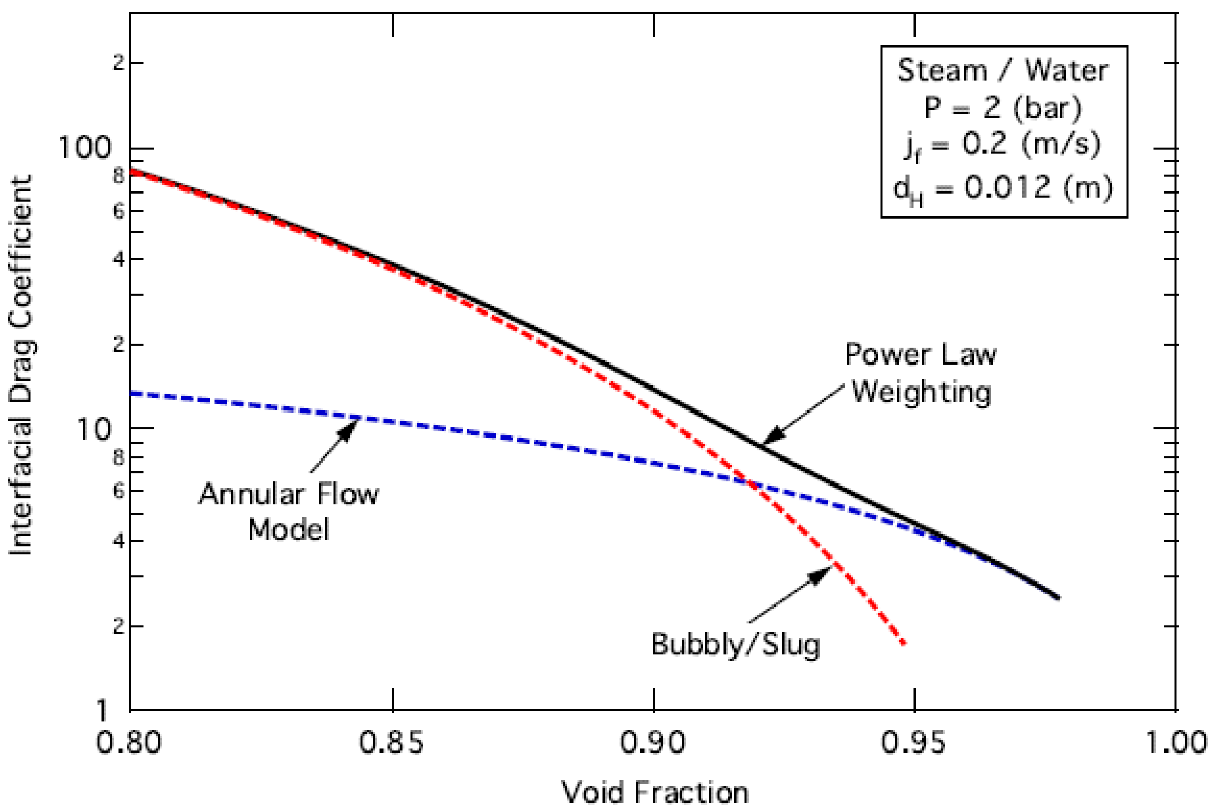
- Dispersed Bubble
- Slug
- Taylor Cap Bubble
- Annular / Mist



Normal Vertical Flow Map

Pre-CHF flow map for interfacial drag is very simple:

- Calculate bubbly-slug (BS) drag (drift-flux based)
- Calculate annular-mist (AM) drag
- Total drag = (BSn + AMn)**1/n, where n = 2

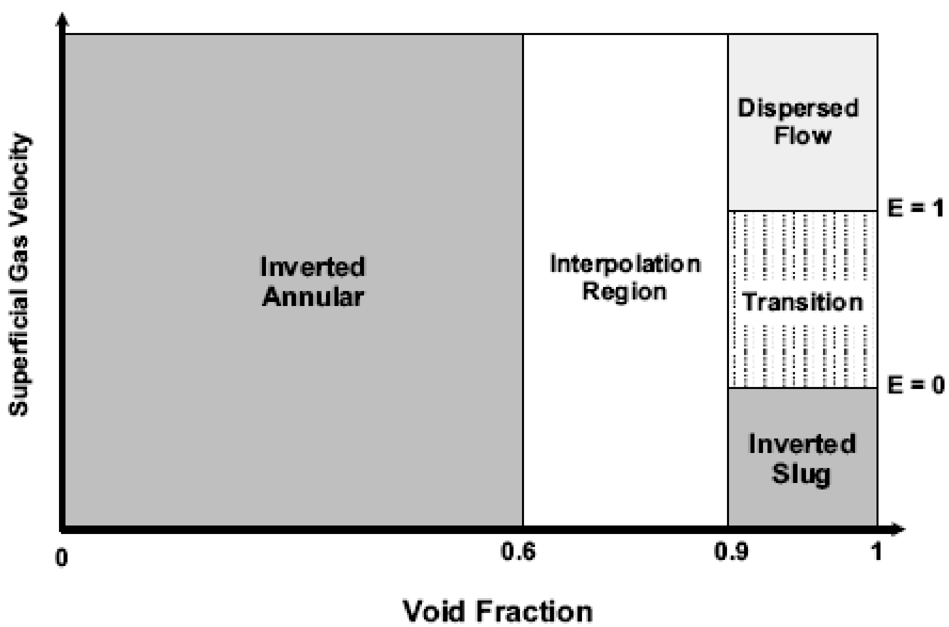


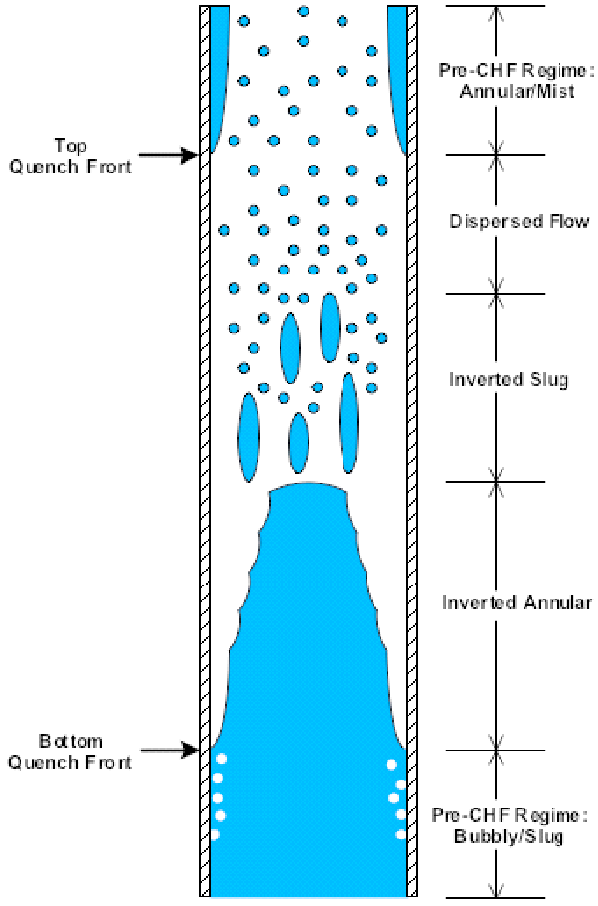
Reflood Vertical Flow Map

Post-CHF vertical flow regimes:

- Inverted Annular
- Inverted Slug
- Dispersed Flow

E = entrainment fraction





Horizontal Flow Map

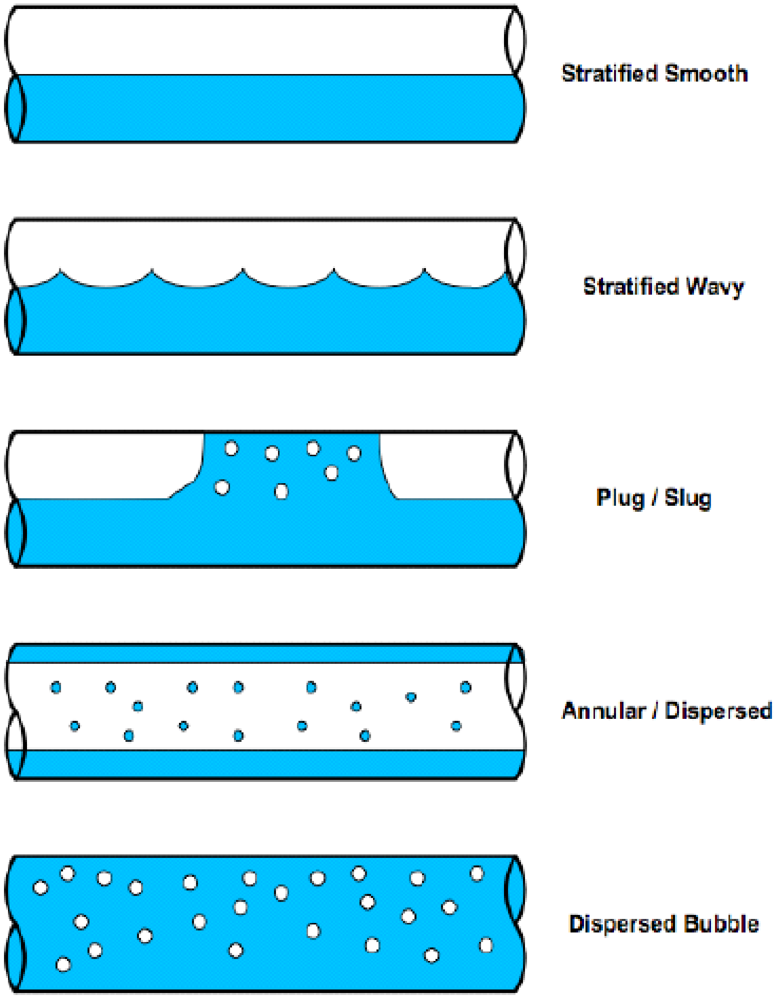
Horizontal flow regimes:

Dispersed Bubble

Annular / Dispersed

Stratified Smooth

The Stratified Wavy and Plug/Slug regimes shown in the diagram are not modeled explicitly but are treated as transitions among the other regimes

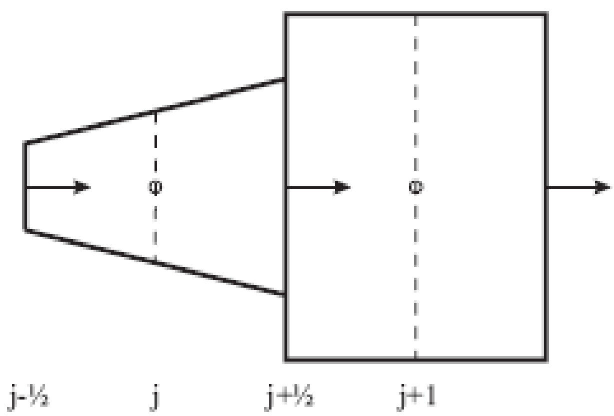


TRACE Solution Uses a Staggered-Mesh Modeling Approach

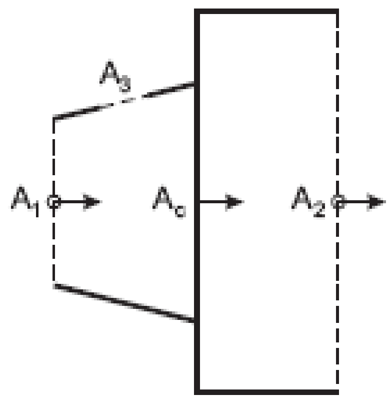
A discrete approximation of the fluid volumes and flow paths of the physical system is specified through input. This represents development of a facility input model.

Thermodynamic fluid state variables (pressure, temperature, etc.) for mass and energy conservation are evaluated as hydrodynamic volume properties.

Momentum equation variables (velocities) are evaluated at the faces between the hydrodynamic volumes.



Two Mass and Energy Conservation Volumes



Corresponding Momentum Conservation Faces

TRACE Numerical Solution Schemes

Two TRACE numerical solution methods are available:

- Semi-Implicit
- Stability Enhancing Two-Step (SETS)

SETS, which offers improved run-time performance for LOCAs and transients, is recommended for most reactor safety applications.

Semi-Implicit (with time step selected to keep Courant number near 1.0 in the region of interest) is recommended if continuity or kinematic waves need to be tracked and errors caused by numerical diffusion effects are significant:

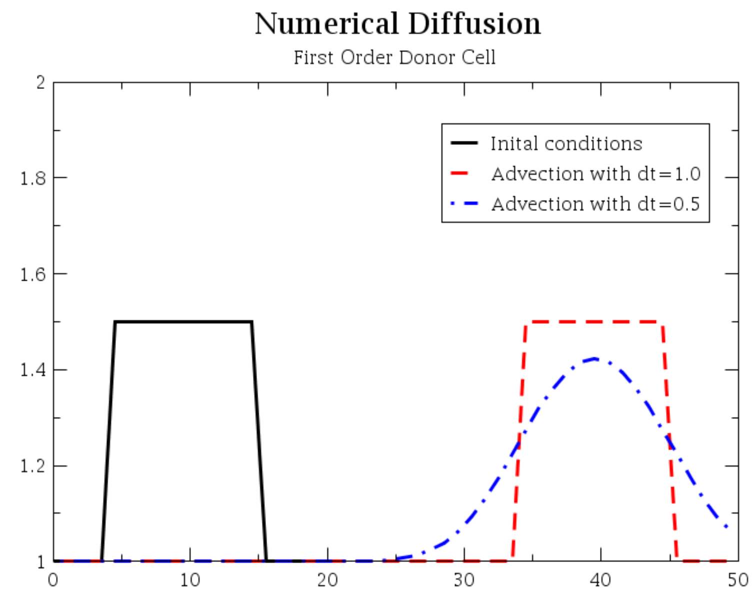
- Density wave propagation
- Progression of boron concentration or thermal fronts

SETS and Semi-implicit are first-order methods and both are diffusive, but SETS is more so.

TRACE numerical discretization in time and space are first-order accurate and must be small enough to resolve the time scales and profiles of interest for the applications. Beyond hydrodynamics, appropriate time scales of interest may also be limited by heat transfer within and to structures, and variations in responses of control systems or boundary conditions.

Numerical Diffusion

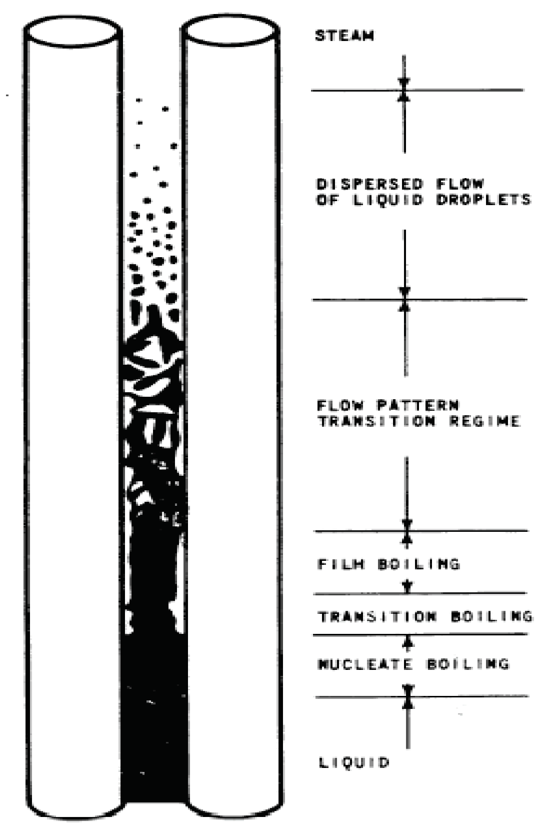
- Advection numerical methods diffuse steep fronts.
- Peaks are reduced and fronts arrive too early.
- No numerical diffusion for Courant number of 1
- Can't maintain Courant number of 1 everywhere
- Effect can be minimized by increasing nodalization in region of interest.



A TRACE Energy Equation Limitation

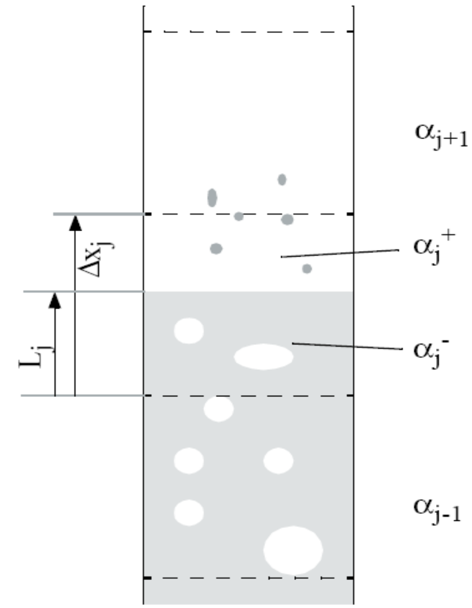
- TRACE does not accurately calculate the flow of energy across cell faces with large pressure differences between adjacent cells
  - Not an issue for choked flow at cell faces connecting “normal” TRACE components (such as PIPEs, VALVEs and VESSELs) to TRACE CONTAN components (that are used to model containments)
  - The problem is for choked flow at cell faces internal to (or between) the “normal” TRACE component types
    - In this situation, TRACE will underpredict the flow of energy into the cell downstream of the choking location
    - As a workaround for this problem, one can calculate the magnitude of the error with a control system and compensate by using a FLPOWER component that deposits the additional heat into the downstream cell

Special Process Models



Level Tracking

Model modifications for interfacial drag, wall drag, interfacial heat transfer and gravity head to better track void discontinuities.



Reflood Model

Characteristic lengths of important phenomena are less than the hydrodynamic cell length. Uses heat structure fine-mesh rezoning to resolve axial temperature and heat flux profiles and to track a quench front within cells.

Special Process Models

Critical Flow

Velocities at a cell face are limited to the sound speed to simulate choked flow conditions. Subcooled liquid, two-phase fluid and single-phase vapor coefficients are used. Default coefficients available, or user may specify them as desired. Typically used for modeling flows through pipe breaks and relief valves.

Countercurrent Flow Limiting

Interfacial drag model for vertical configurations modified to simulate limitation of downward liquid flow by upward vapor flow. Correlations for standard simple geometries are included, along with flexibility to specify configuration-dependent correlation data if available. Typically used to simulate liquid hold-up in PWR SG tubes or above PWR and BWR upper core plates.

Special Process Models

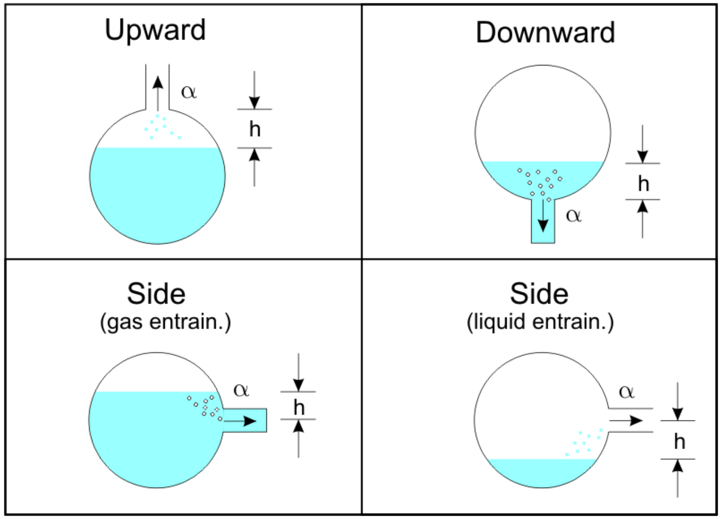
Offtake Model for Connections to Horizontal Pipes

Mainly used for SBLOCAs. The formulation contains a critical entrainment height:

$$h_b = \frac{C_1 W_k^{0.4}}{(g\rho_k \Delta\rho)^{0.2}}$$

W_k = major-phase mass-flow rate

ρ_k = major-phase density.



Offtake Geometry	Correlation Constant, C_1
Upward	1.67
Downward	1.50
Side (gas entrain.)	0.75
Side (liquid entrain.)	0.69

Special Process Models

Abrupt Area Change

Model calculates flow losses for expansions and contractions based on geometry and the fluid conditions. If active, the flow loss from this model is added to wall friction and user-specified flow loss.

TRACE Input and Output

Two naming conventions for input and output files

Default naming convention: “trc + suffix” (“tracin” is an exception)

Prefix naming convention: <user-defined prefix> + “.” + “suffix”, engaged with “–prefix” command line option

File suffixes:

.inp	input file
.out	output file
.xtv	graphics file
.msg	message file
.rst	restart file
.echo	input echo file
.dif	difference file
.tpr	thermal-hydraulic portable restart file

Converting a .xtv graphics file to .dmx (demux) format significantly reduces the file size and facilitates plotting of output.

Philosophy for Developing a TRACE Facility Input Model

- Think in terms of the physical objects within the facility

- Model the geometry of a single object

- Use TRACE built-in multipliers to indicate the numbers of objects
  - npipes, nchans, njetp, nseps, nrods

Example: SG tubes

Model a single tube with PIPE and HTSTR components. Use npipes and nrods to specify the number of tubes. This reduces the potential for input errors due to faulty calculations and, in this example, makes the model easy to modify for performing tube plugging studies.

Introduction to TRACE Components

BREAK Component

Single hydrodynamic cell with user-specified or controlled fluid state and a face connecting the BREAK to another TRACE component.

Example application: sink pressure boundary condition, representing the containment into which a ruptured pipe discharges.

FILL Component

User-specified or controlled fluid state, and the flow condition at a face connecting the FILL to another TRACE component.

Example application: flow boundary condition for pumped ECC injection into a PWR as a function of cold leg pressure.

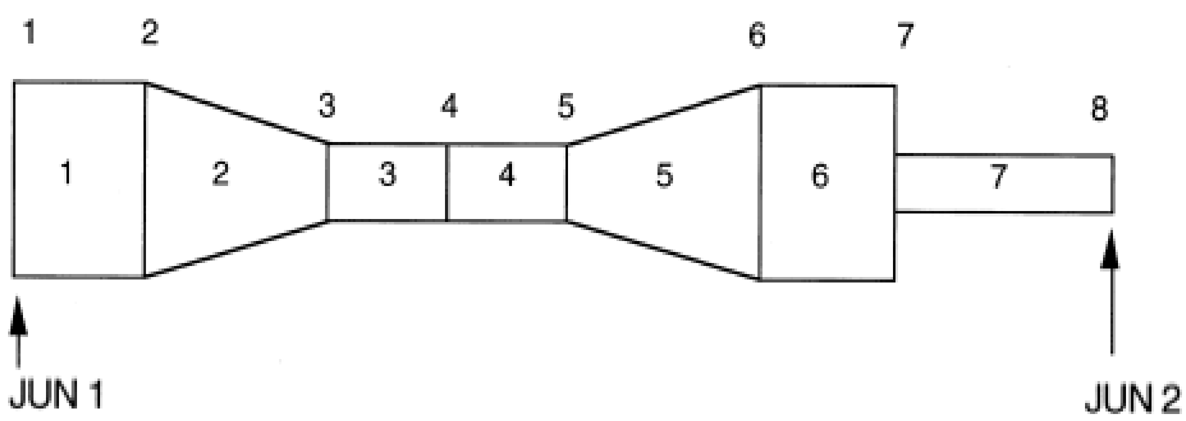
Introduction to TRACE Components

PIPE Component

Features fluid cells and internal flow faces, specification of junction numbers that connect the PIPE to other TRACE components, and piping wall heat structures. Side connections to PIPE components are also permitted.

Example application: PWR coolant loop piping.

Accumulators are modeled using a PIPE component with the “PIPETYPE” flag set to 1, 2 or 3. This invokes a gas/liquid interface sharpener and an optional model preventing gas outflow. Other “PIPETYPE” options are also available (see the manual).



Introduction to TRACE Components

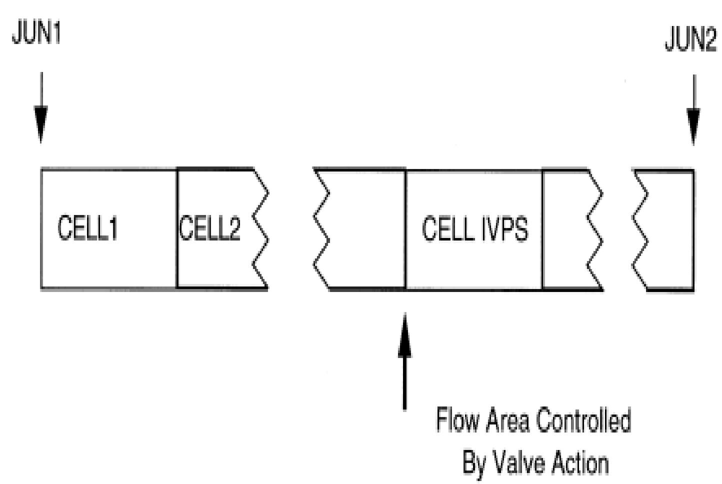
VALVE Component

Includes fluid cells and internal flow faces, variable control over one internal cell face (the valve location), specification of junction numbers for connections to other TRACE components, and piping wall heat structures. A VALVE component may consist of only a single junction if desired.

Flexibility for modeling a wide variety of valve-face control schemes.

Except for the control over the valve face, the TRACE VALVE Component features are similar to those of a TRACE PIPE Component.

Example application: check valve in an ECC injection line.



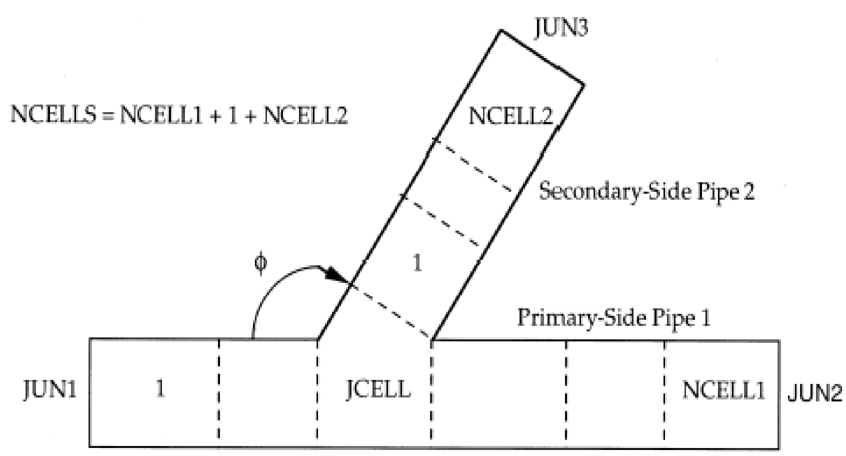
Introduction to TRACE Components

TEE Component

Includes fluid cells and internal faces for a main flow path and a connecting side flow path, and piping wall heat structures for both the main and side paths. Consider using PIPE component with side connections as a more flexible approach for flow branch modeling.

Junctions to other TRACE components are specified at the two end faces of the main path and at the free end of the side path. The angle between the main and side paths is specified and the momentum solution at the TEE is dependent upon the angle.

Example application: PWR hot leg to pressurizer surge line connection.



Introduction to TRACE Components

PUMP Component

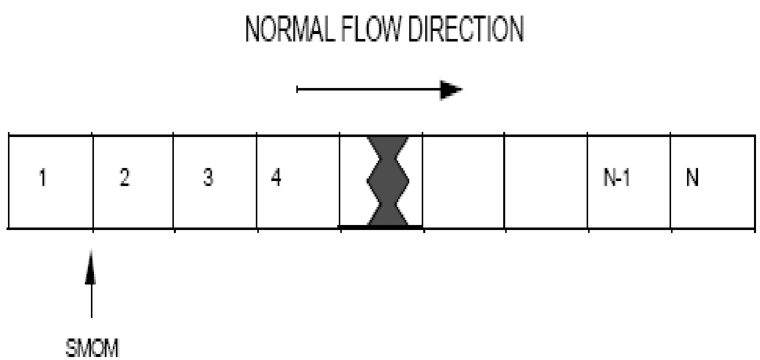
Includes fluid cells and internal flow faces, piping wall heat structures, a momentum source at one face, and models for speed control (user-specified speed or inertial coast-down).

Momentum source term at Face 2 based on pump homologous curves.

Except for the face with the momentum source, the TRACE PUMP Component features are similar to those of a TRACE PIPE Component.

PUMP may be modeled using only a single junction (SJC-type component) at which the momentum is added (see IPMPTY 10 and 11 in the manual).

Example application: PWR reactor coolant pump.



Introduction to TRACE Components

PUMP Component (continued)

The PUMP component describes the momentum interaction between the rotor and the coolant in a centrifugal pump. The basic TRACE PUMP models are the same as used in the TRAC, RELAP5 and RETRAN pump models.

The model uses a non-dimensional homologous-curve formulation for the relations between:

- pump head, speed and flow
- pump torque, speed and flow

The user may input homologous curve data for a specific pump or use TRACE built-in homologous curve data for:

Semiscale Mod-1 pump
LOFT pump
PWR Bingham-Wilamette pump
PWR Westinghouse pump

Data is also input describing control of the pump speed

Pump heat (resulting from the work performed on the fluid) is included in the model (except currently for the SJC-type pump configuration)

Introduction to TRACE Components

SEPD Component

Specialized version of the TEE component. Separates an incoming steam/water mixture into two streams, one that is vapor-enriched and one that is liquid-enriched.

Option available allowing user to represent different physical separation efficiencies.

Liquid carryover and vapor carryunder fractions specified as a function of void fraction of the incoming steam/liquid mixture.

Example applications: BWR steam separators, PWR SG steam separators.

Introduction to TRACE Components

JETP Component

Component model representing BWR jet pumps. Includes primary (main flow) and side arm (driver flow) fluid cells and piping heat structures.

Models the pumping action achieved by transferring the momentum of the driver flow (from BWR recirculation pumps) into the reactor pressure vessel downcomer flow.

CHAN Component

Component model representing BWR fuel assemblies. Includes multiple axial fluid cells and connecting faces, junction connections at the bottom and top faces, fuel rod heat structures, water rod heat structures, channel box wall heat structure, and leakage paths from the channel box into the core bypass region.

Introduction to TRACE Components

HTSTR Component

Models heat conduction within structures and heat transfer to the adjacent fluids.

Example applications: core fuel rods, piping walls.

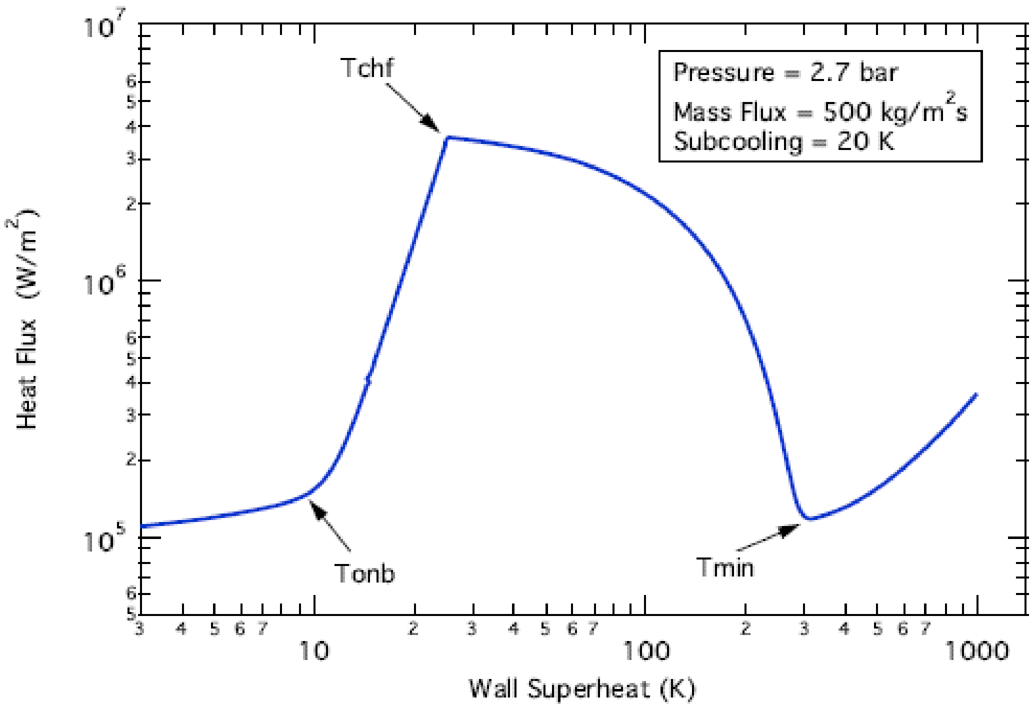
Generic model building block that may be made as specific as needed in order to represent the physical structures.

This structure modeling capability is in addition to existing pipe-wall modeling feature included in many of the TRACE components.

May be coupled with POWER component to represent structures with internal heating.

HTSTR Component

Heat flux from wall to fluid is calculated using the wall, fluid and saturation temperatures and correlations representing the various regions of the "boiling curve": single phase convection, subcooled nucleate boiling, saturated nucleate boiling, critical heat flux, transition boiling and film boiling.



Introduction to TRACE Components

POWER Component

User specification or TRACE calculation of total power (based on current conditions elsewhere in the model). Identifies the HTSTR components into which power is deposited and the distribution of the power among them.

Example application: core power calculation based on table lookup (power as a function of time) or reactor kinetics calculation.

CONTAN Component

Models multiple compartments of a reactor containment, heat structures for containment walls, internals and containment coolers, passive junctions between compartments, forced junctions between compartments.

Example application: BWR containment (drywell, horizontal vents, wetwell suppression pool and vapor spaces).

Introduction to TRACE Components

VESSEL Component

Models fluid cells laid out using a level, ring and azimuth sector grid arrangement. Connecting junctions (termed vessel source connections) to other TRACE components are specified. Heat structures (such as internals and PWR core fuel rods) are modeled using separate HTSTR components.

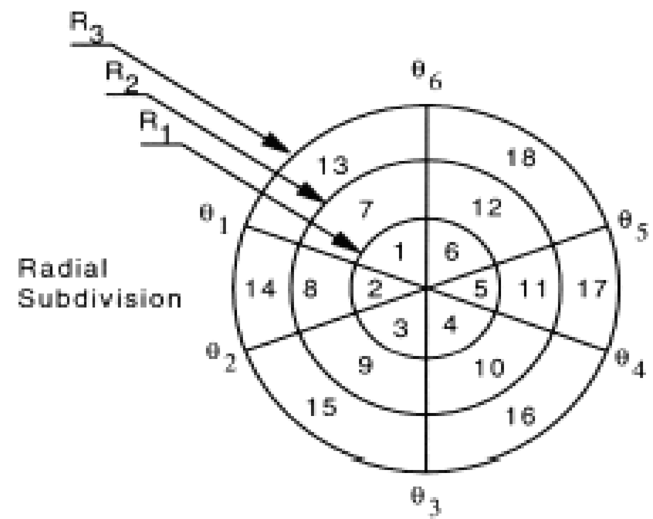
The dimensional grid that is input for the VESSEL defines both the locations of the fluid cells and their dimensions. A Cartesian (X, Y, Z) grid structure is available in addition to a right-circular cylinder (R, Ɵ, Z) grid structure.

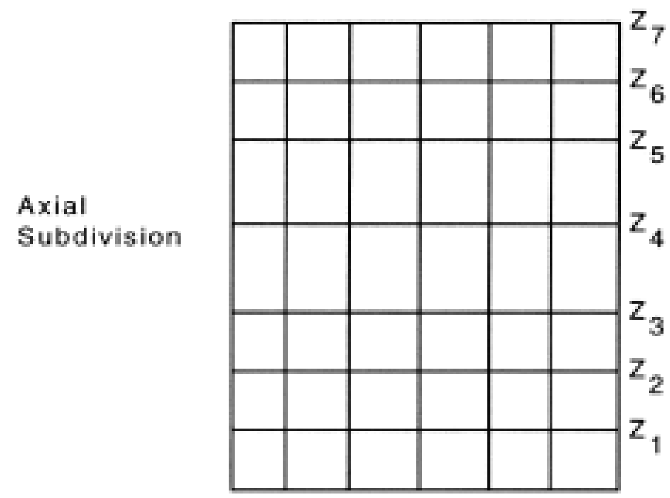
The cell and cell-face input data (fluid volume, flow area, etc.) are entered as fractions of the full cell or cell-face values.

The volume and flow area fractions typically are the same for regular geometries and typically are different when modeling irregular geometries.

VESSEL Component

Typical Nodalization Layout





Introduction to TRACE Components

VESSEL Component Special Models

- Core Region
  - Bestion correlation is used for interfacial drag
  - Core reflood models
- Downcomer
  - Axial direction interfacial drag is 1/8th of normal interfacial drag. The multiplier was selected based on comparisons to ECC penetration in the UPTF Test 6 series
- Orifice Model
  - Used to suppress transverse momentum from being carried across an orifice (e.g., core support plates)
  - Engage this model by setting a negative value for the axial hydraulic diameter

Summary of Less-Frequently Used TRACE Components

EXTERIOR	Connects TRACE calculations to other parallel-running codes
FLPOWER	Direct heating of fluid, for example due to gamma heating
HEATR	Comprehensive combination of models for representing heat exchangers
PLENUM	Fluid cell with velocity heads from connections converted to pressure (this component is currently not recommended for use)
PRIZER	Comprehensive combination of models for representing a pressurizer system
RADENC	Connects HTSTR components together into a common thermal radiation heat transfer enclosure
TURB	Specialized version of TEE component representing energy removed from fluid due to turbine work and resulting fluid momentum, energy, and turbine speed

Introduction to TRACE Control System Models

- Used to control behavior of thermal and hydraulic components
  - VALVE flow areas, FILL flow rates, HTSTR powers
- Used to calculate convenience output variables
  - Pressure drops, collapsed levels, component masses
- Three subsets of control system model features
  - Signal variables
  - Control blocks
  - Trips

Introduction to TRACE Control System Models

Signal Variables

Signal Variables are fundamental objects in the TRACE control system.

The user specifies signal variables, which then become usable elsewhere in the model.

123 types of signal variables are available.

Most common usage of signal variables is to retrieve calculated parameters (pressures, void fractions, densities, etc.) for use in trips and control blocks.

A signal variable might be set up, for example, to represent the pressure in the TRACE hydrodynamic cell at the top of a PWR pressurizer. That signal variable could then be used in a trip to test if the pressure exceeds the relief valve opening setpoint (with the trip then used to control the VALVE model).

No equivalent feature is used in RELAP5 code and this can be a source of confusion

Introduction to TRACE Control System Models

Control Blocks

A Control Block is a mathematical function that operates on zero or more inputs defined by signal variables or other control blocks

The output of a control block may be used as

1) input to another control block or signal variable,

2) a trip parameter,

3) an independent variable for component-action tables:

Parameters that can be Controlled	Component
Pressure and fluid-state boundary condition	BREAK
Velocity or mass-flow and fluid-state boundary cond.	FILL
Reactor-core programmed reactivity or neutronic power	POWER
Reactor-core axial-power shape	POWER
Energy deposition directly in the coolant	PIPE,TEE,TURB,FLPOWER
Energy generation in the hydro-component wall	PIPE,TEE,PUMP,VALVE
Pump-impeller rotational speed	PUMP
Turbine power demand	TURB
Valve flow-area fraction or relative stem position	VALVE

Trips

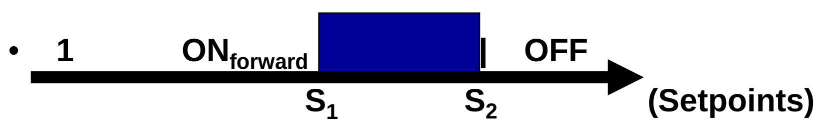
A Trip is a logical operator with an output status that is specified as $ON_{forward}$, OFF or $ON_{reverse}$, with corresponding numerical values of 1.0, 0.0 and -1.0.

Trips test the current value of an independent variable against a set of criteria (involving user-input setpoints and time delays) to determine a current value for the trip status.

The test criteria is specified according to trip type (11 trip types are available). For example, the two most commonly-used trips are Types 1 and 2, which have a status of $ON_{forward}$ or OFF.

In the deadband between S1 and S2, the status of the trip does not change value from when it entered the deadband.

Concepts covering more the complex types of trips are included in subsequent workshop sessions.



Example use : trip reactor if the loop flow rate falls below 12,000 kg/s

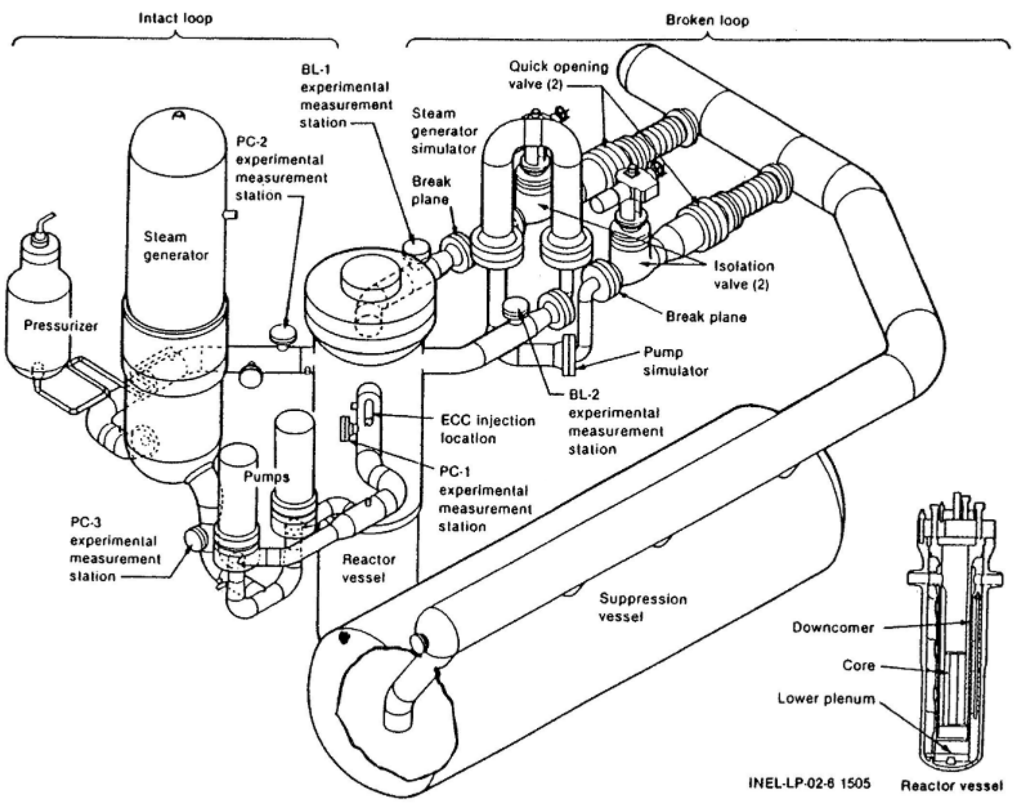
Example use: open a relief valve if the pressure exceeds 16 MPa and reclose the valve if the pressure subsequently falls below 15 MPa

Putting it All Together

- TRACE is made up of many physical models that are shown to work at local and component levels.
  - See TRACE Assessment Manual Appendix B
- Need to demonstrate that everything works together and accurately predicts system response when these models interact in a full reactor plant model.
  - Integral test assessments
- Integral tests try to capture plant phenomena and behavior for different transient and accident types
  - See TRACE Assessment Manual Appendix C
    - PWR – CCTF, SCTF, LOFT
    - BWR – FIST, TLTA, SSTF

Example Integral Effects Assessment - LOFT Large Break LOCA Test L2-5

- LOFT was a 50 MW nuclear reactor.
- Small break, large break, and transient tests were run in LOFT



Example Integral Effects Assessment - LOFT Large Break LOCA Test L2-5

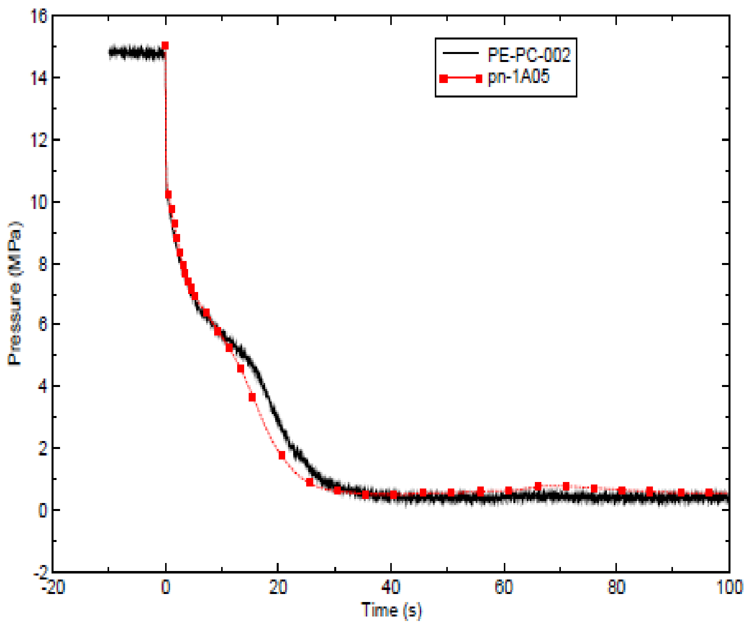


Figure C.1-37. L2-5 Intact Loop Hot Leg Pressure.

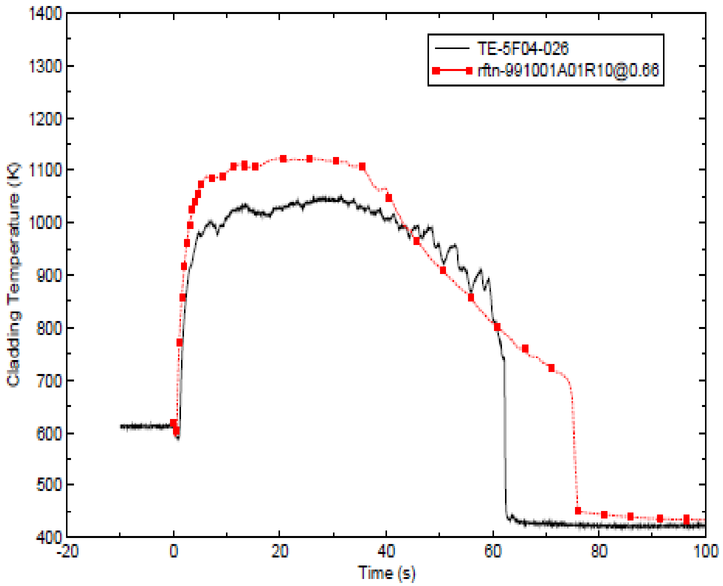


Figure C.1-53. L2-5 Cladding Temperature at 0.66 m.

Planned Improvements to TRACE

- Physical Models
  - Improve 3D interfacial heat transfer
  - Improve transition boiling models
  - Droplet field to improve reflood and spray modeling (partially done)
  - Mechanistic flashing model to give predictions of nucleation delay during flashing
  - Improve the fuel rod models
- Numerical methods improvements
  - Implicit interfacial heat transfer (coding completed, not assessed)
  - Implicit interfacial drag
  - Implicit TRACE/PARCS coupling
  - Improve boron tracking capabilities (add density effects of liquid solute)
  - Conservative formulation of the energy equation
- Validation of TRACE for new applications
  - Small modular reactors (SMRs)

Questions?

Any questions on TRACE components, features, basic capabilities and limitations before moving on to the introduction to SNAP?