Exceptional service in the national interest

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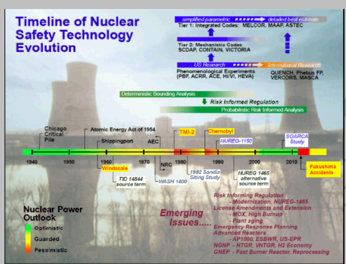

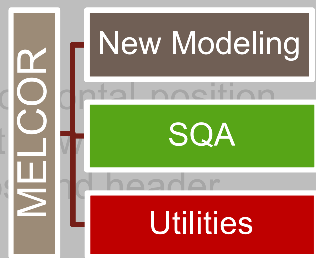

MELCOR Overview

Workshop on Operational Experience and Advances in MELCOR Modeling

Shenzhen, China, November 19-23, 2012

Presented by Larry Humphries (llhumph@sandia.gov)

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

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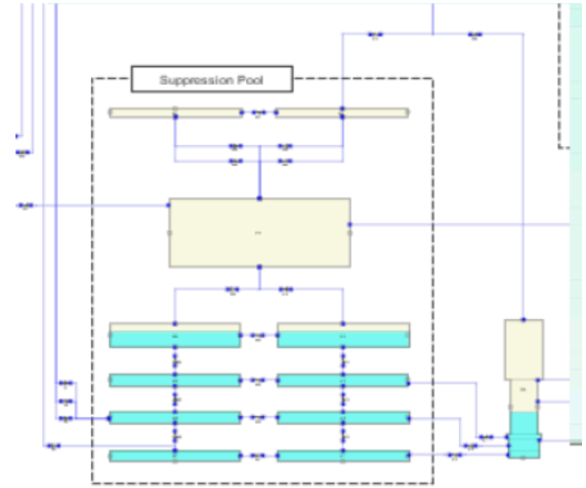
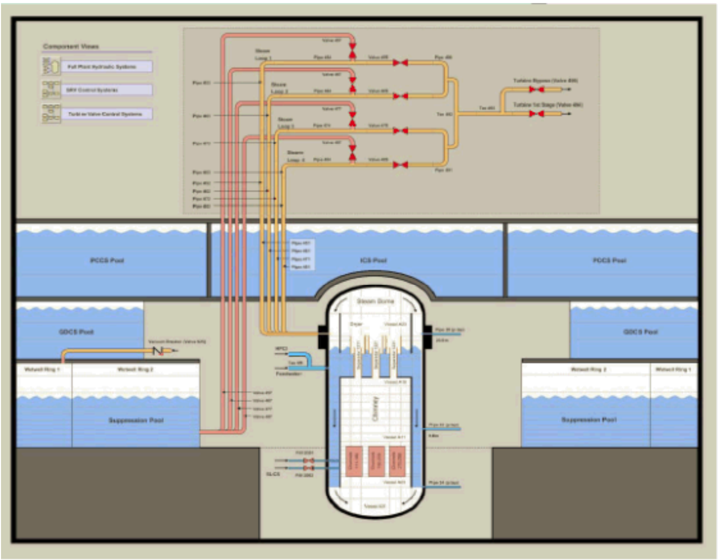
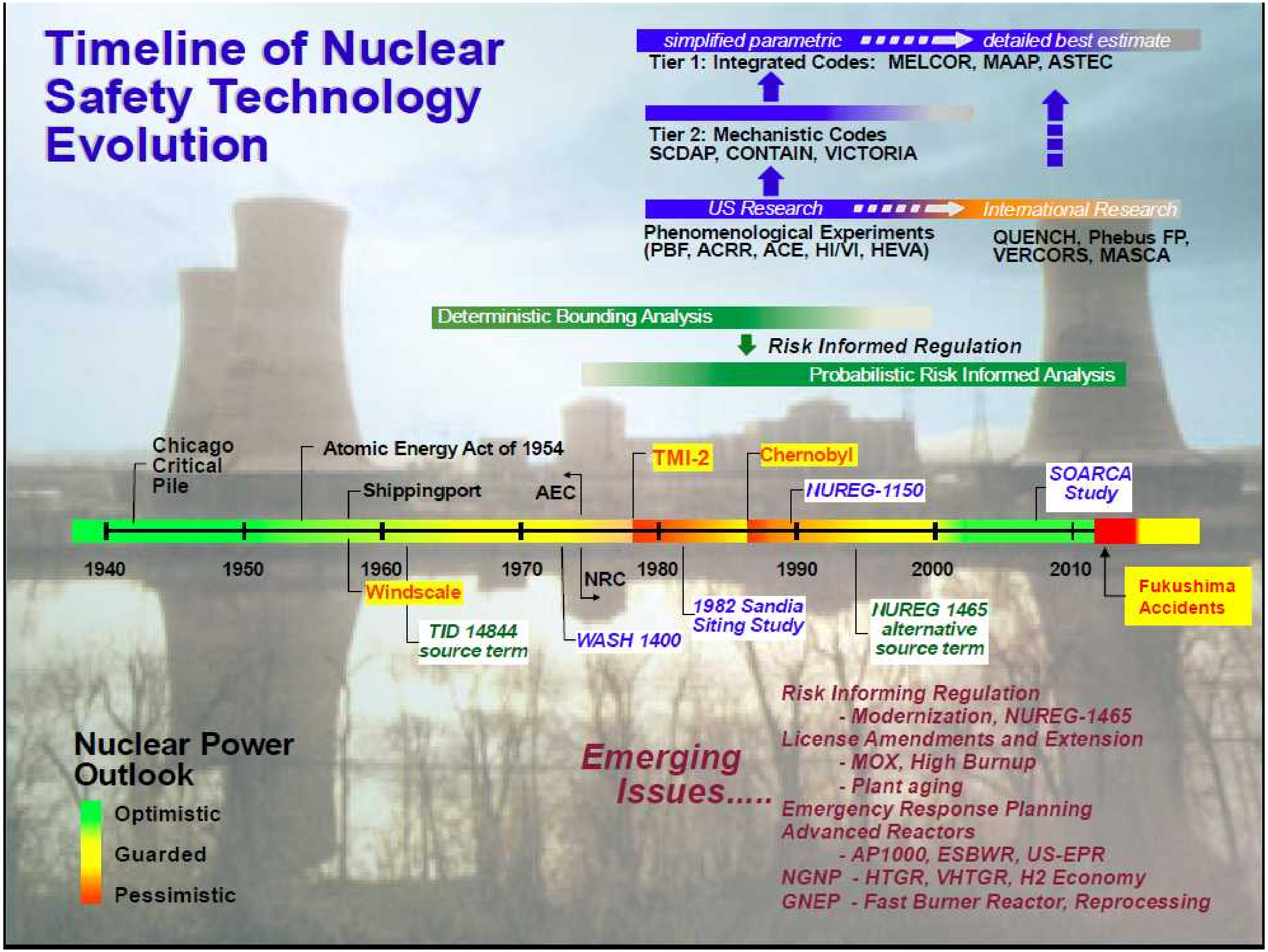
What is the MELCOR Code

- NRC sponsored simulation code for analysis of accidents in nuclear power plants
  - Also applied to containment DBA simulation
  - PWR, BWR, HTGR, PWR-SFP, BWR-SFP
- Fully Integrated, engineering-level code
  - Thermal-hydraulic response in the reactor coolant system, reactor cavity, containment, and confinement buildings;
  - Core heat-up, degradation, and relocation;
  - Core-concrete attack;
  - Hydrogen production, transport, and combustion;
  - Fission product release and transport behavior
- Desk-top application
  - Windows/Linux versions
  - Relatively fast-running
    - One or two days common
    - One or two weeks possible
    - Project to improve code performance
  - SNAP for post-processing, visualization, and GUI





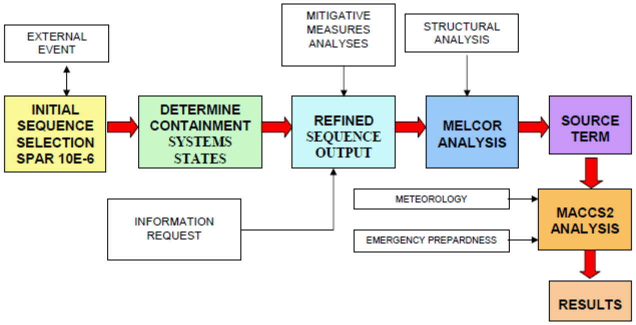


Timeline of Nuclear Safety Technology Evolution
simplified parametric
detailed best estimate
Tier 1: Integrated Codes: MELCOR, MAAP, ASTEC
Tier 2: Mechanistic Codes
SCDAP, CONTAIN, VICTORIA
US Research
International Research
Phenomenological Experiments
(PBF, ACRR, ACE, HI/VI, HEVA)
QUENCH, Phebus FP,
VERCORS, MASCA
Deterministic Bounding Analysis
Risk Informed Regulation
Probabilistic Risk Informed Analysis
Chicago Critical Pile
Atomic Energy Act of 1954
Shippingport
AEC
TMI-2
Chernobyl
NUREG-1150
SOARCA Study
1940
1950
1960
1970
1980
1990
2000
2010
Windscale
TID 14844 source term
NRC
WASH 1400
1982 Sandia Siting Study
NUREG 1465 alternative source term
Fukushima Accidents
Nuclear Power Outlook
Optimistic
Guarded
Pessimistic
Emerging Issues.....
Risk Informing Regulation
- Modernization, NUREG-1465
License Amendments and Extension
- MOX, High Burnup
- Plant aging
Emergency Response Planning
Advanced Reactors
- AP1000, ESBWR, US-EPR
NGNP - HTGR, VHTGR, H2 Economy
GNEP - Fast Burner Reactor, Reprocessing

MELCOR Applications

- Forensic analysis of accidents – Fukushima, TMI
- State-of-the-art Reactor Consequence Analysis- SOARCA
- License Amendments
- Risk informed regulation
- Design Certification
- Preliminary Analysis of new designs
- Support of International Regulatory Bodies
- Non-reactor applications
  - Leak Path Factor Analysis
  - DOE Safety Software "Toolbox" code

SOARCA PROCESS



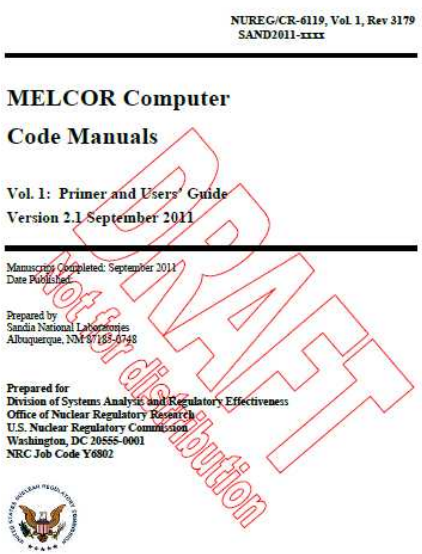
MELCOR Users Worldwide

- Argentina
- Belgium
- Bulgaria
- Canada
- China
- Czech Republic
- Finland
- France
- Germany
- India
- Italy
- Japan
- Mexico
- Netherlands
- Poland
- Russia
- S.Korea
- Slovak Republic
- South Africa
- Spain
- Sweden
- Switzerland
- Turkey
- UAE
- UK
- USA

MELCOR User Workshops and Meetings

- MELCOR Workshop
  - September 12-15, 2011
    - More than 70 participants
    - Use of SNAP
  - September 10, 2012
    - More than 90 registered
- MELCOR Code Assessment Program (MCAP)
  - September 22-23, 2011
  - September 13-14, 2012
- European MELCOR User Group (EMUG)
  - ENEA: April 11-12, 2011
  - GRS : April 16-17, 2012

MELCOR Documentation


NUREG/CR-6119, Vol. 1, Rev 3179
SAND2011-xxxx

MELCOR Computer Code Manuals

Vol. 1: Primer and Users' Guide
Version 2.1 September 2011

Manuscript Completed: September 2011
Date Published:

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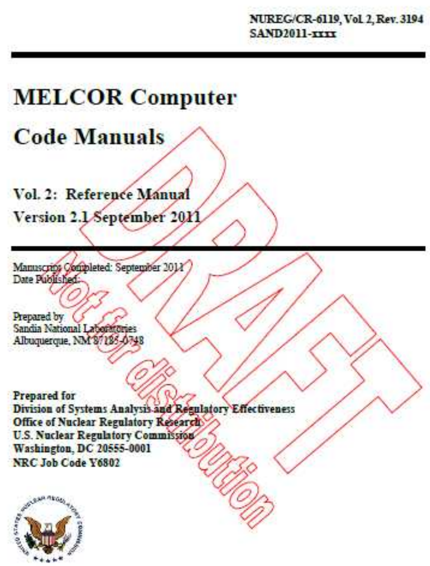
Albuquerque, NM 87185-0748

Prepared for
Division of Systems Analysis and Regulatory Effectiveness
Office of Nuclear Regulatory Research
U.S. Nuclear Regulatory Commission
Washington, DC 20555-0001
NRC Job Code Y6802

Volume I: User Guide


NUREG/CR-6119, Vol. 2, Rev. 3194
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Version 2.1 September 2011

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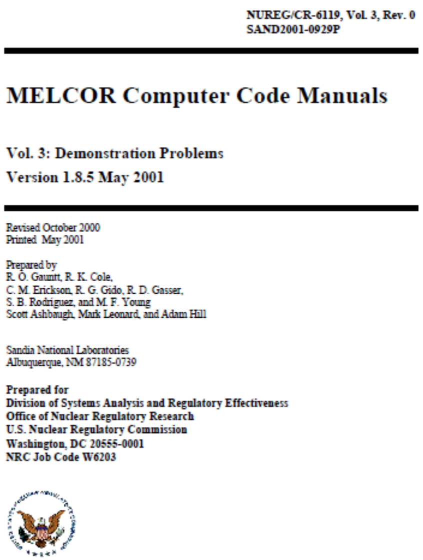
Volume II: Reference Manual


NUREG/CR-6119, Vol. 3, Rev. 0
SAND2001-0929P

MELCOR Computer Code Manuals

Vol. 3: Demonstration Problems
Version 1.8.5 May 2001

Revised October 2000
Printed May 2001

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Volume III: Assessments

Phenomena Modeled by MELCOR

- Goal of modeling "all" relevant phenomena is quite ambitious
- Main phenomena modeled include
  - Two-phase hydrodynamics, from RCS (Reactor Coolant System) to environment
  - Heat conduction in solid structures
  - Reactor core heatup and degradation
  - Ex-vessel behavior of core debris
  - Fission product release and transport
  - Aerosol and vapor physics
- Others will be mentioned in presentation
- There is no detailed neutronics model
  - Fission power history can be user-specified
  - Point kinetics model available

MELCOR Modeling Approach

- Modeling is as mechanistic as possible, consistent with a reasonable run time
  - “Reasonable” is up to the user, depends on level of detail
    - Original thought was “a few hours”
    - Some applications now run many days
- Some parametric models, where appropriate
- Uses general, flexible models
  - Relatively easy to model novel designs
  - Puts greater burden on analyst to develop input deck
- Allows sensitivity analyses
  - Many parameters accessible to user from input
    - Properties of materials, coefficients in correlations, numerical controls and tolerances, etc.

MELCOR Packages

- Major pieces of MELCOR called "Packages"
  - Each handles a set of closely-related modeling functions
  - Do *not* correspond to ancestral codes
- Three general types of packages in MELCOR
  - Basic physical phenomena
    - Hydrodynamics, heat and mass transfer to structures, gas combustion, aerosol and vapor physics, etc.
  - Reactor-specific phenomena
    - Core degradation, ex-vessel phenomena, sprays and other ESFs (Engineered Safety Features)
  - Support data and functions for general use
    - Thermodynamic equations of state, other material properties, decay heat generation data
    - Data-handling utilities, equation solvers

MELCOR Code Structure

- Code structure reflects basic phenomena more than reactor design
  - Same general control-volume/flow-path hydrodynamics used in reactor cooling system and containment
  - There is NO single package that deals with the vessel and all its contents or with a steam generator
- Time advancement for each package is largely independent
  - Reduces need for simultaneous solutions of many equations
    - Solution strategy for each can be appropriately chosen
  - Possible through carefully designed package interfaces
    - Restricted information exchange between packages
    - Use of partially-implicit “predictor/corrector-like” methods to deal with stiffness of equations

MELCOR Top-Level Control (1)

- Executive level coordinates other modules
  - Manages input, output, time step definition, etc.
    - Each package has its own i/o routines, called in turn
    - Time step chosen subject to various constraints
      - Executive input defines maximum and minimum timesteps
      - Any package can request a limit on timestep for next advancement
      - Executive considers all requests and reconciles with bounds
        - » Calculation will be terminated if no acceptable timestep
  - Controls time advancement of each package's data, in turn
    - Package coupling numerically explicit
      - Each package uses start-of-step data from other packages (with a very few exceptions, where end-of-step data are used)
      - Pass changes (e.g. heat and mass transfers) to other packages
      - Order of advancement chosen to facilitate this

MELCOR Top-Level Control (2)

- Executive deals with advancement problems
  - Any package can force a “fallback”
    - Problems in advancement of package itself
      - Convergence problem or other failure of solution algorithm
      - Change in properties too large (excesive rate of change)
    - Problems with end-of-step data from *another* package
      - Change too large (e.g. advection far overshoots ignition limit for combustion)
    - Requests repeat of advancement attempt with a reduced timestep
  - Executive provides graceful termination with final text edit and restart dump if advancement fails
    - Timestep less than minimum
    - Error in any package where reduced step wouldn’t help
    - “Logic Error”, meaning occurrence of a situation that the code developer considered impossible

More about MELCOR Packages

- Packages conventionally referred to by 2- or 3-letter names, mnemonic of functions, e.g.
  - Used extensively in input record identifiers
  - CVH (Control Volume Hydrodynamics) and FL (FLow path) treat the control volume and flow path portions of the hydrodynamic modeling
  - HS (Heat Structures) treats conduction in, heat and mass transfer to/from structures such as walls, floors, pipes
  - COR (CORe) treats reactor core response and degradation phenomena
  - MP (Material Properties) provides various properties
  - TF (Tabular Function) is a general table utility
- In general, no duplication of function
  - No in-line materials properties; (should) use MP package
  - All input data tables (should be) processed and stored by TF package

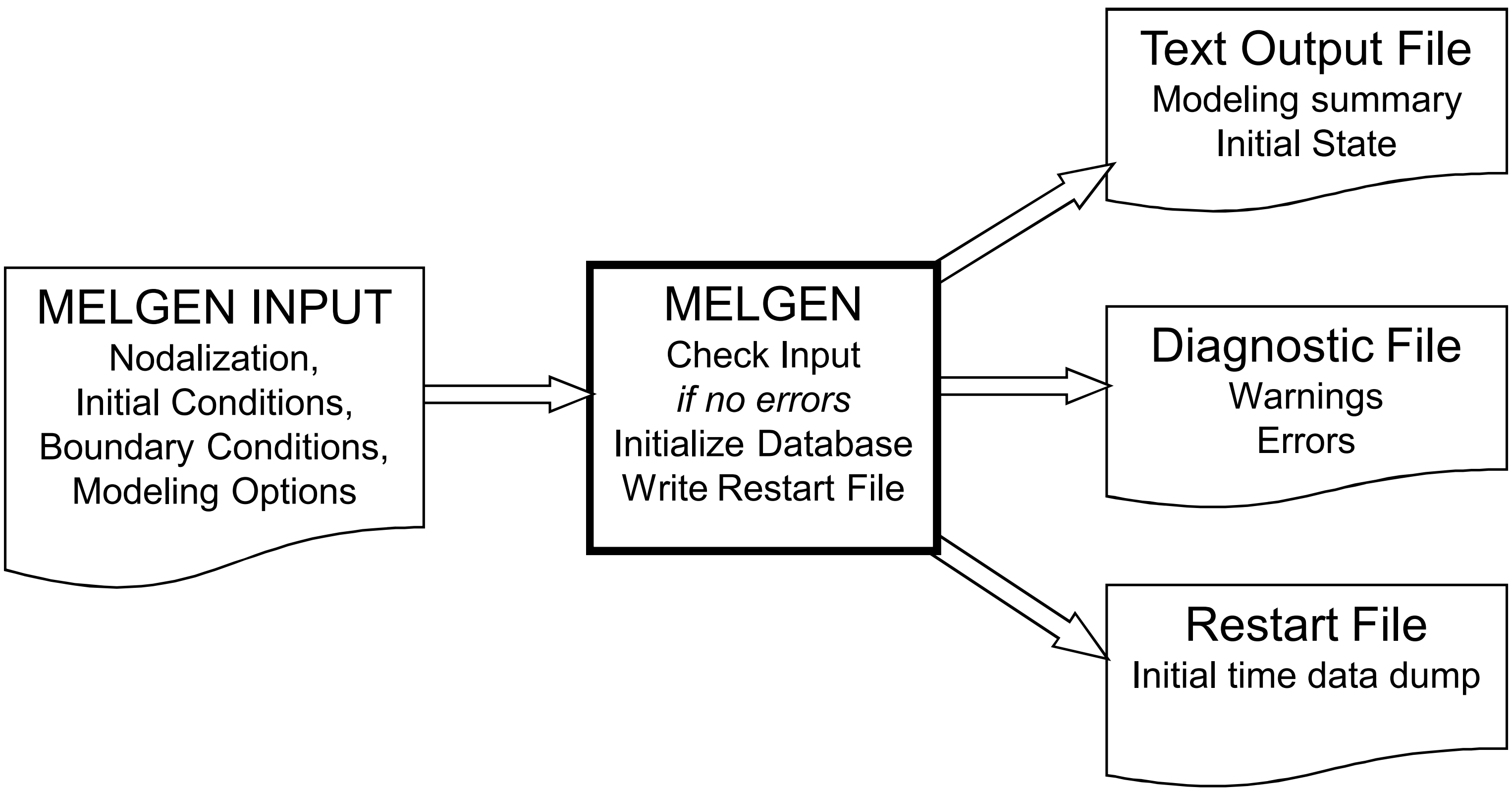
MELGEN and MELCOR

- "MELCOR" is actually two executables that perform different parts of the simulation
- MELGEN is run first
  - Its basic task is to set up the desired calculation
    - Problem definition, initial and boundary conditions
  - Has no time-advancement capability
- MELCOR is run next
  - Its basic task is to advance the simulation in time
  - Reads complete problem description from a file
  - Has limited ability to modify that description before starting the time advancement
- Two codes share many subroutines
  - I/O, properties, etc.

MELGEN

- MELGEN execution
  - Basic task is to set up the desired calculation
  - Input focuses on problem definition
    - Reads description of system to be simulated as provided through user input, including:
      - Nodalization to be used
      - Initial and boundary conditions
      - Modeling options
    - Checks input for completeness and consistency
    - Issues diagnostic warnings and/or error messages when appropriate
  - If (and *only* if) input contains no errors
    - Initializes all time-dependent data
    - Writes full text edit with model and state description
    - Writes restart file dump with complete database

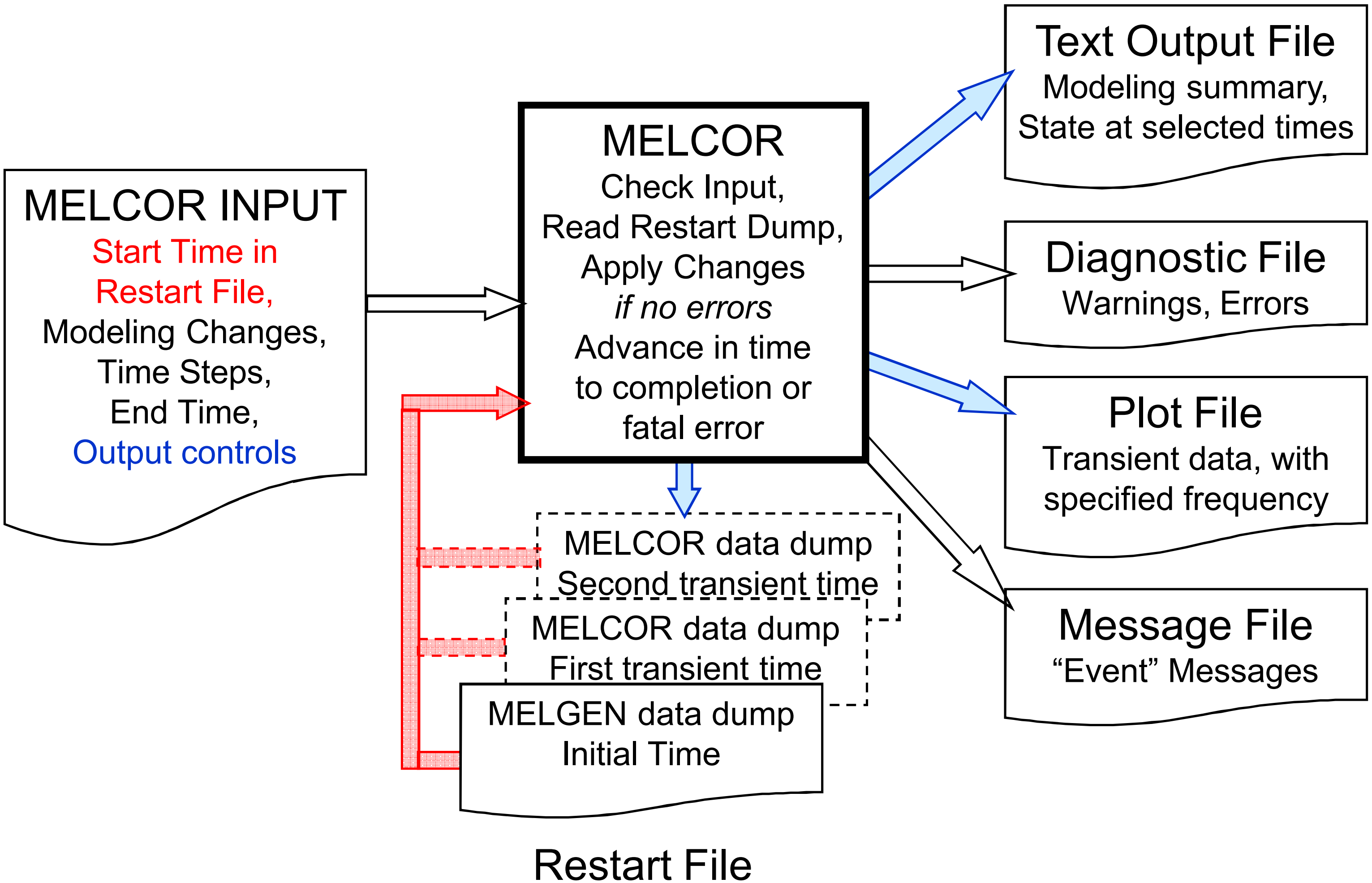
MELGEN Files and Information Flow



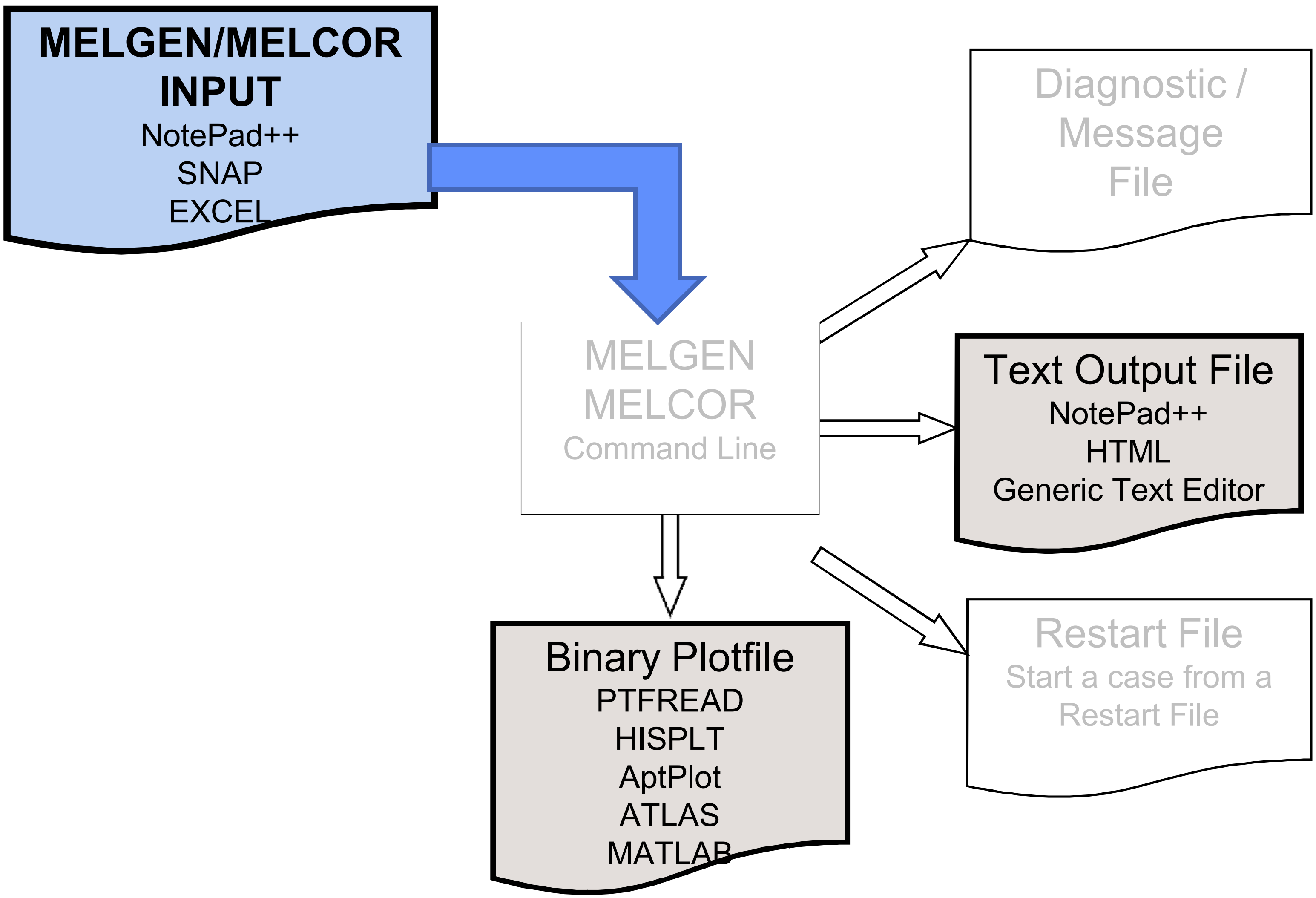
MELCOR

- MELCOR execution
  - Basic task is to advance simulation in time
  - Always run in "restart" mode
    - Reads time-independent and initial time-dependent data from a restart file "dump"
      - First restart written by MELGEN
      - Successive restart dumps from previous MELCOR run
    - Advances time-dependent data through time
  - Input focuses on control of advancement
    - Start time, end time, time steps, output frequency
    - Limited capability to modify problem description
      - Useful for sensitivity studies, treatment of branches in event trees
      - Recently added 'Smart' restart capability for modifying control functions
    - Writes text edits, restart, and plot files as requested
      - Any point in the restart file can be used as the initial state for a subsequent MELCOR execution

MELCOR Files and Information Flow

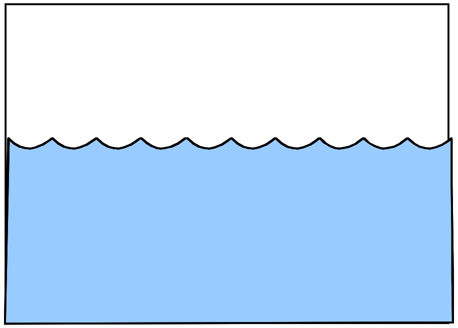


MELCOR I/O Tools

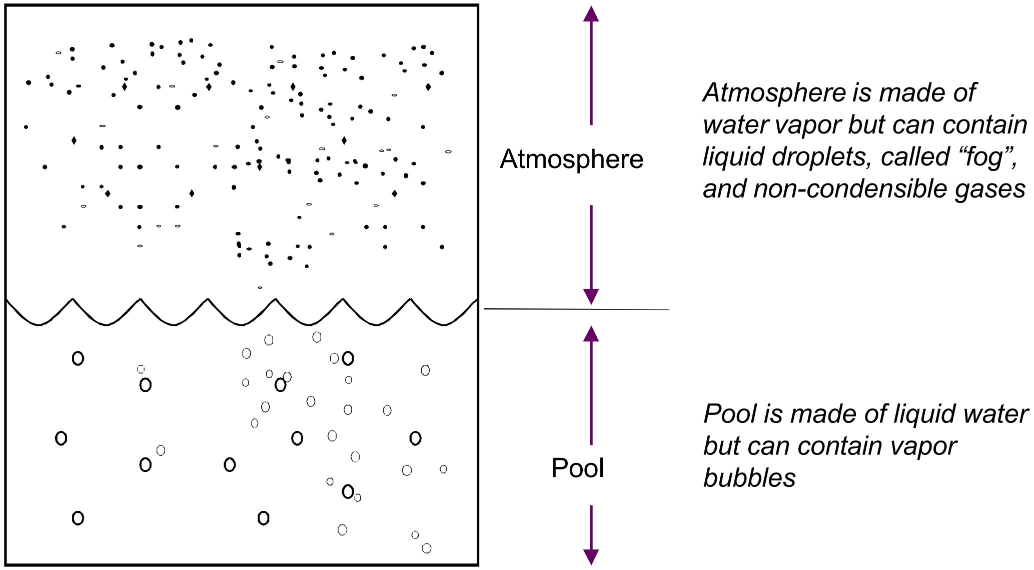


Control Volume Hydrodynamics (CVH) Package

- Definition of control volume
  - A region of space that contains hydrodynamic materials
    - User defines geometry from volume-altitude tables (no pre-defined shapes)
  - Thermodynamic states
    - Pressure and temperature
    - Equilibrium, non-equilibrium
  - Multi-Materials
    - Water, steam,
    - 14 noncondensible gases in atmosphere (H_2, N_2, O_2, etc.)
  - Sources and Sinks
    - Mass and Energy
- Interfaces to almost everything else in MELCOR
  - Provides boundary conditions to other packages
  - “Sees” most other packages only as sources and sinks of mass, energy, and volume available to fluids
    - Zircaloy oxidation in core is a sink of H_2O with source of H_2 and/or sink of O_2
    - Movement of core debris changes volume available to fluids in CVH
  - Changes in core geometry can change flow resistance
    - Not default, requires optional user input to relate nodalizations



CVH Package (2)

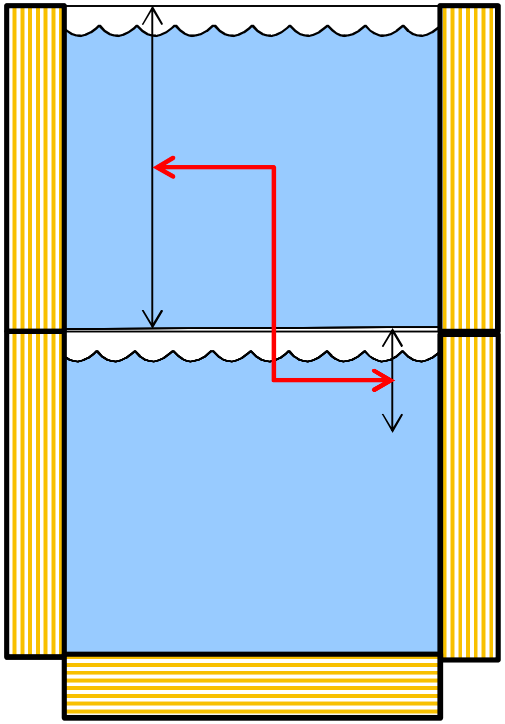


Pool and atmosphere are coupled. They exchange mass and energy due to condensation or evaporation

- CV contents partitioned into two fields:
  - Fields are called "pool" and "atmosphere"
  - Each is in complete internal thermodynamic equilibrium. Equal pressures, $P_{pool}=P_{atm}$

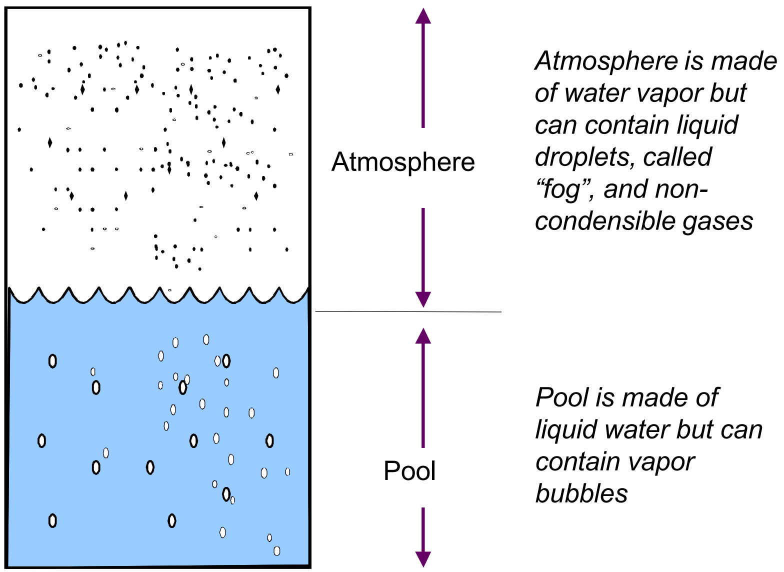
Flow Path (FL) Package

- All flow of hydro materials is through flow paths
- Each flow path connects two control volumes
  - One volume is referred to as the 'from' volume and the other as the 'to' volume thus defining positive flow
  - User specifies junction elevations and opening heights
- No volume, mass, or energy is associated with a flow path itself
- Each flow path is characterized by a nominal area and length.
  - The area may be modified by controlling the open fraction (e.g., to model valves)
- Wall Friction & Form Losses



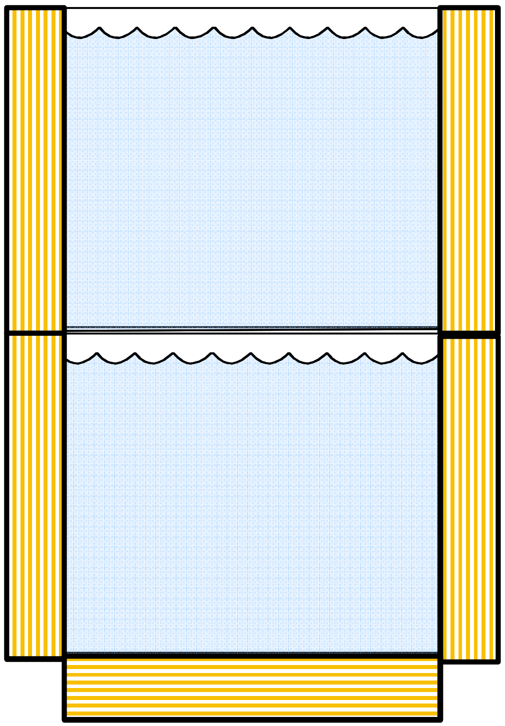
CVH/FL Package (2)

- Formulation of Equations
  - Four-field formulation
    - Continuous liquid (pool)
    - Continuous vapor (atmosphere)
    - Dispersed liquid (fog)
    - Dispersed vapor (bubbles)
  - Homogeneous equilibrium model (HEM) reduces 12 equations (mass, momentum & energy) to 6
    - Pool: Continuous liquid & dispersed vapor in equilibrium
      - Total Mass, total energy, same velocity
    - Atm: Continuous vapor & dispersed liquid in equilibrium
      - Total mass, total energy, same velocity
- Implicit Continuous-fluid Eulerian (ICE)
  - Substitute mass equation into momentum equation
  - Solve a matrix for velocity
  - Back solve for density
  - Pressure from linearized EOS
  - Iterate to get pressure correct



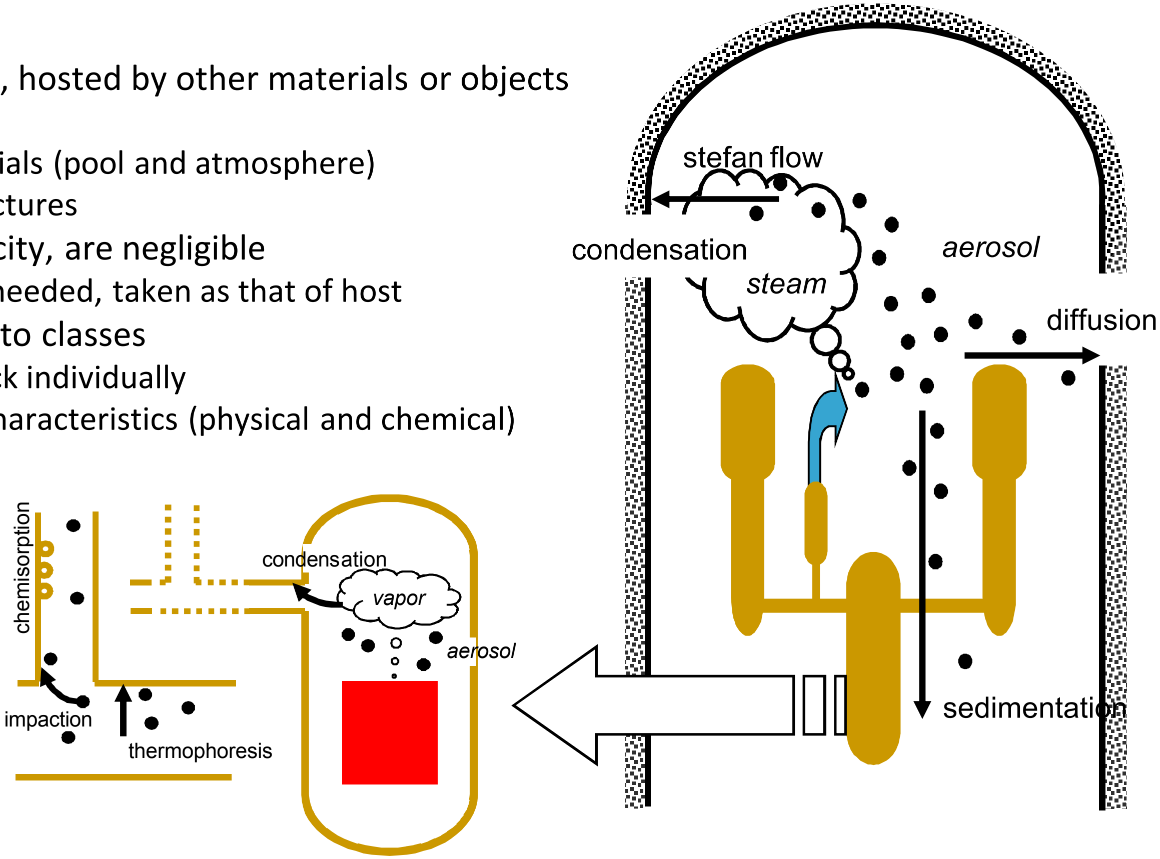
Heat Structure (HS) Package

- MELCOR heat structures used to model thermal response of solid objects
  - Used for everything except parts of core
- Limited ability to decompose or melt
  - Degassing of hot concrete, with gases to CVH
  - Melting of ice condensers, with water to CVH
  - Melting of core shroud, with debris to COR package
- One-Dimensional Conduction
  - Rectangular, cylindrical, spherical
- Surface boundary conditions
  - Interfaces with CVH
    - Condensation, evaporation
  - Radiation (to gases or other HS surfaces)
  - Adiabatic, specified temperature, specified heat flux
- Film Drainage models



RadioNuclide (RN) Package

- What is RN Package
  - Originally intended to treat behavior (release, transport, interactions) of RadioNuclides
  - Radionuclides are a source of decay heat
    - Important coupling to fuel, fluids, or HS surfaces
- Basic assumptions
  - RN materials are “traces”, hosted by other materials or objects
    - Fuel and/or debris
    - Hydrodynamic materials (pool and atmosphere)
    - Surfaces of heat structures
  - Mass, volume, heat capacity, are negligible
    - Temperature, when needed, taken as that of host
  - Radionuclides grouped into classes
    - Too many RNs to track individually
    - Grouped by similar characteristics (physical and chemical)



Ex-Vessel Debris Phenomena (1)

- If reactor vessel fails, debris can be ejected
  - Ends up on floor
  - Can interact with gases and/or water pools on the way
- CAV (CAVity) Package models behavior of "core on the floor"
  - Essentially CORCON Mod 3
    - Concrete ablation
      - Release of interstitial and hydrated water
      - Decomposition of hydroxides and carbonates
      - Addition of oxides to debris
    - Oxidation of metal in debris by released H_2O and CO_2
  - Mass sources, heat transfer to CVH fluids
    - Heat transfer from debris surface
    - Reduced gases, primarily H_2 and CO

Ex-Vessel Debris Phenomena (2)

- FDI (Fuel Dispersion Interactions) Package models interactions between vessel and floor
  - Use is optional, depends on user input
  - Low pressure melt ejection (LPME) option
    - Debris falls under gravity
    - Break up of debris in water pool
    - Heat transfer to water pool in CVH
  - High pressure melt ejection (HPME) option
    - More violent expulsion of debris
    - Heat transfer to CVH fluids
    - Oxidation of debris
    - Deposition of some debris on structure surfaces

Support Packages

- Equations of State, EOS Package
  - Implements a mixed-material equation of state for hydrodynamic materials (water and gases)
    - Water properties from H2O package
      - Keenan & Keyes formulation
      - Augmented by JANAF data (T>1589)
    - NonCondensible Gas properties from NCG Package
  - H2O and NCG properties are also available separately
- Materials Properties, MP Package
  - Provides thermal EOS for non-hydrodynamic materials
  - Provides thermophysical properties for all materials
    - Thermal conductivity, viscosity, diffusivity, etc
    - Mixture rules used where appropriate
- Decay Heat, DCH Package
  - Can provide whole-core decay heat and/or distribution of that heat among fission products (discuss later)

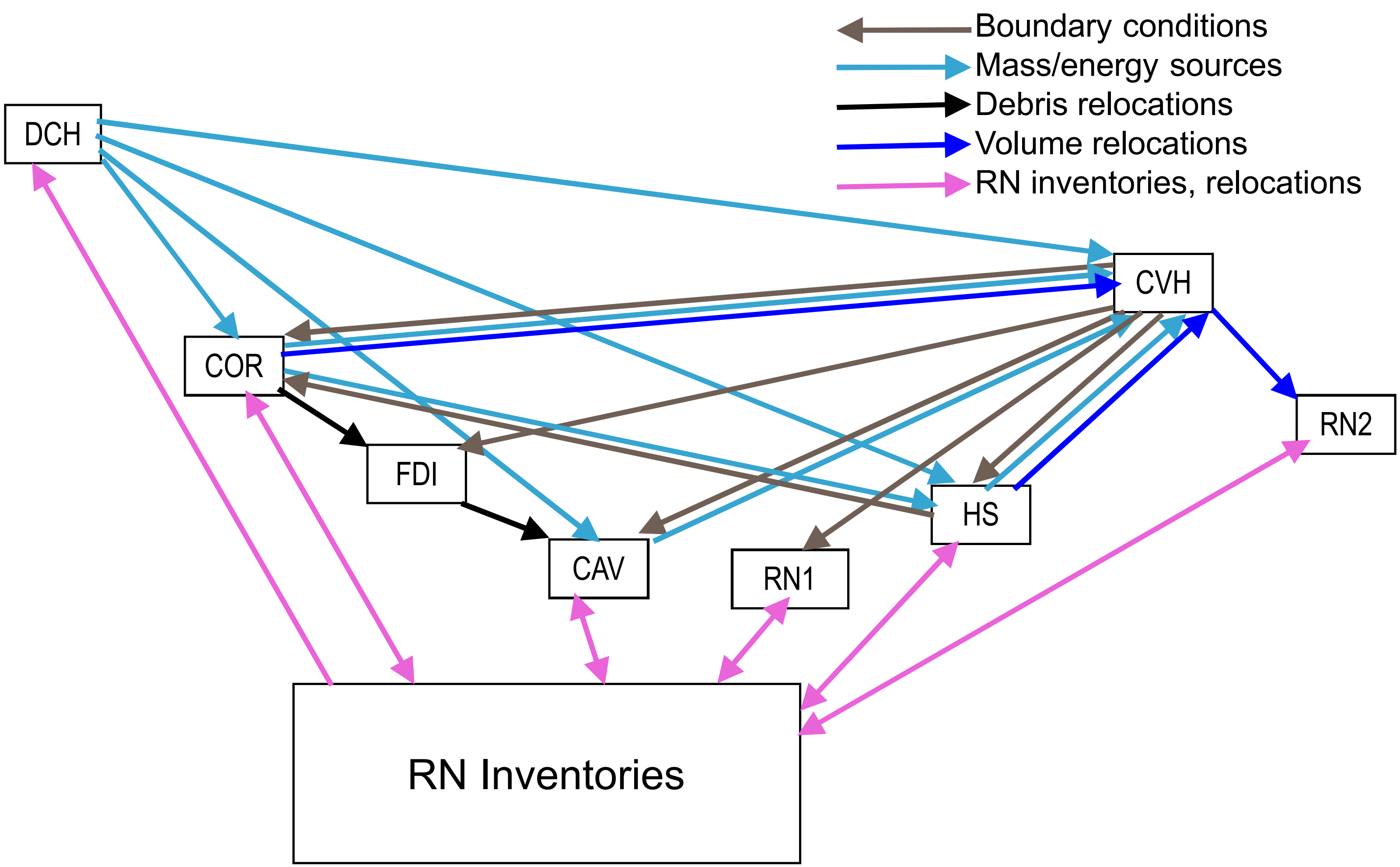
Phenomena Closely Tied to Hydro (1)

- BUR handles combustion (BURn) of H_2, CO
  - Permitted in any volume
  - Deflagration only (no detonations)
  - Includes modeling of igniters
- Various containment models, some grouped as ESFs (Engineered Safety Features)
  - SPR models containment SPRays
  - PAR models Passive Autocatalytic Recombiners
  - FCL models Fan CooLers
  - CND models an Isolation CoNDenser System (ICS) and/or Passive Containment Cooling System (PCCS)

Order of Advancement

- Advance packages that evaluate sources or relocations before those that use them
  - DCH: First to update time-dependent decay heat data
  - COR: Before CVH and HS that will receive heat/mass
  - SPR: Before CVH that will receive heat/mass
  - BUR: Before CVH that will receive mass changes
  - FDI: After COR to receive debris, before CAV and CVH
  - CAV: After COR and FDI to receive debris, before CVH
  - ESF: Before CVH
  - RN1: After COR and CAV to receive releases
  - HS: After COR to receive sources, before CVH
  - CVH: After COR, CAV, and HS to receive sources
  - RN2: After CVH to use fluid relocations

Information Communicated Between MELCOR Packages



Control Functions (CF) Package

- Control Functions, CF Package
  - Heart of MELCOR power and flexibility
  - Comes close to letting user write code as part of input
- Allows user input to define functions of MELCOR-calculated time-dependent variables
  - Values can be REAL or LOGICAL, are part of time-dependent database with all other time-dependent data
    - Calculated from definition using *current* conditions
    - Relatively easy, *very* flexible way to model complex systems
  - Older versions used own “language”, difficult to read
  - MELCOR 2.X adds ability to write function as a FORMULA, that looks much like fortran
  - Many (not all) variables are available as arguments

Control Function Use

- Can be used to generate custom output
  - Values can be printed, plotted
  - Change in value of logical can produce event message
- Function values can be used in calculations
  - Input to many packages allows reference to the value of a control function rather using than a fixed constant
    - Sources, sinks, other boundary conditions
      - Allow dependence on current state
        - » Drain liquid currently present in volume with correct enthalpy
    - Valves, pipe failures, containment failures
      - Complex control logic
      - Larson-Miller cumulative damage strain model
    - Can provide simple modeling of systems (injection, cooling, etc.) when no internal model provided
      - Define mass/energy sources and sinks with appropriate logic
      - PAR could have been done entirely with CFs

MELCOR Code Development History

- MELCOR 1.8.2 (1993)
  - One of the earliest versions for widespread release.
  - Version not recommended for use
- MELCOR 1.8.3 (1994)
  - BH Package
  - CORCON-MOD3
  - Version not recommended for use
- MELCOR 1.8.4 (1997)
  - Retention of molten metals behind oxide shells
  - Vessel creep rupture model
  - Flow blockage model
  - Radiant heat transfer between HSs
  - Hygroscopic aerosols,
  - chemsorption on surfaces,
  - SPARC 90
- MELCOR 1.8.5 (2000)
  - CF arguments could be added to plotfile
  - Consistency checks on COR/CVH volumes
  - Iterative flow solver added
  - Diffusion flame model
  - SS & NS components added for structural modeling
  - Upward & downward convective & radiative heat transfer from plates
  - Particulate debris in bypass introduced
  - Improvements to candling, debris slumping, and conductive, radiative, and candling heat transfer
  - PAR model was added
  - CsI added as a default class
  - Improvements to hygroscopic model
  - Iodine pool modeling
  - Carbon steel was added to MP package

MELCOR Code Development History

- MELCOR 1.8.6 (2005)
  - An option was added to generate input for the MACCS consequences model.
  - Input was added to simplify conformance with the latest best practices (now defaults in 2.x)
  - New control functions (LM-CREEP & PIP-STR) for modeling pipe rupture
  - Modeling of the lower plenum was revised to account for curvature of the lower head
  - Formation and convection of stratified molten pools
  - Core periphery model for PWRs to model core baffle/formers and the bypass region
  - Reflood quench model
  - Oxidation of B4C poison
  - Release of AgInCd control poison
  - Column support structures was added
  - Interacting materials added to allow modifying enthalpy tables
  - Spent Fuel Pool modeling
  - Flashing model
  - Modified CORSOR Booth release model added
  - Jet impaction model
  - Hydrogen chemistry models

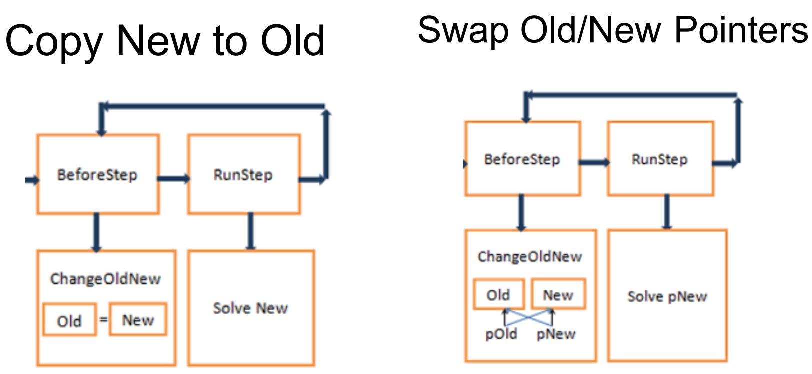
- MELCOR 2.x (Beta release in 2006)
  - Code internal structure greatly modified
  - Dynamic memory allocation
  - New input format
  - Formula type control functions
  - New HTGR modeling (PBR, PMR)
  - Counter-current flow model
  - Point kinetics model
  - Smart restart
  - Simplified accumulator model
  - Ability to track radionuclide activities
  - Turbulent deposition model & bend impaction
  - Control function for deposition mass for each deposition mechanism.
  - MELCOR/SNAP interaction in real-time
  - Full report to user of sensitivity values
  - Cell-based porosity
  - Spent fuel pool models
  - Intermediate heat exchanger /machinery models
  - Hydrogen chemistry models

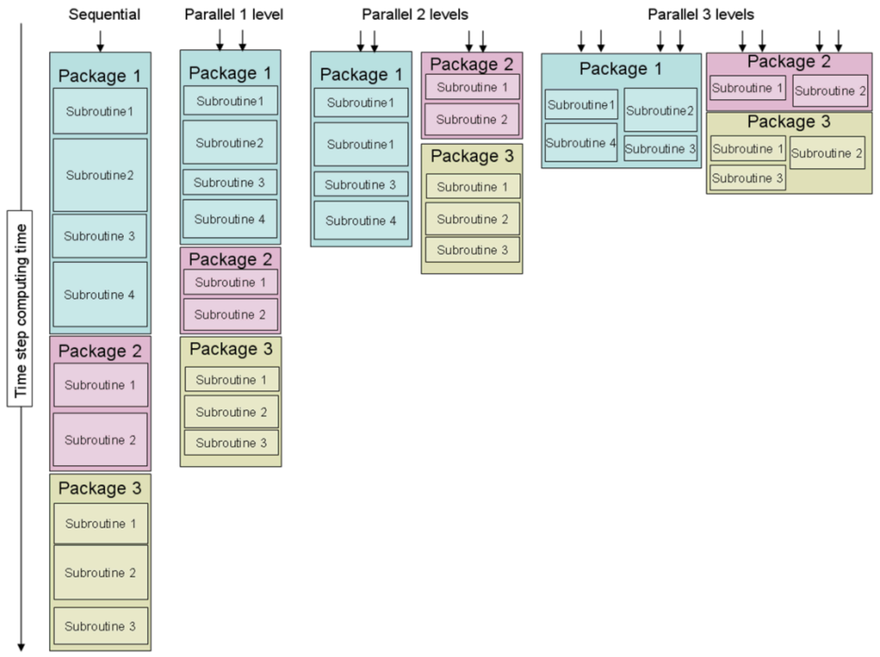
Upcoming/Ongoing Code Development

- Code Assessment and Publication of Volume III report
- CORQUENCH modeling to be added to CAV package
- CONTAIN modeling capabilities to be added to MELCOR
  - Modifications for correlations for CONTAIN/MELCOR parity
- Liquid metal reactors
  - Sodium properties to be added to MELCOR
    - Substitute working fluid
  - Other CONTAIN/LMR modeling to be added for modeling sodium fires

MELCOR Code Performance

- Ongoing work performed at Russian Academy of Science
- MELCOR code performance improvement strategies
  - Variables swapping
  - Numerical Solvers
  - Time step optimization
  - Parallelization
    - Package by package parallelization
    - MELCOR CVH/FL package parallelization results
    - RN1 and RN2 packages parallelization results
    - Further MELCOR code parallelization strategies





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Discussion on MELCOR Overview