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RELAP-7: Demonstrating the integration of two-phase flow components for an ideal BWR loop

Hongbin Zhang, Haihua Zhao, Ling Zou, David Andrs, John Peterson, Ray Berry and Richard Martineau

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EXECUTIVE SUMMARY

The RELAP-7 code is the next generation nuclear reactor system safety analysis code being developed at the Idaho National Laboratory. RELAP-7 will become the main reactor systems toolkit for the Risk-Informed Safety Margin Characterization Pathway of the Light Water Reactor Sustainability (LWRS) Program and the next generation tool in the RELAP reactor safety/systems analysis application series (i.e., the replacement for RELAP5). The code is being developed based on Idaho National Laboratory's modern scientific software development framework – MOOSE (the Multi-Physics Object-Oriented Simulation Environment).

During Fiscal-Year 2013, a number of physical components have been developed to support the demonstration calculations presented in this report. The case selected for demonstration of an idealized BWR loop in RELAP-7 includes the major components for the primary system of a BWR. The BWR loop has been successfully simulated to steady state with the RELAP-7 code. The next major stage of development is to demonstrate two-phase flow modeling capability through a simplified boiling water reactor station blackout analysis, which will be reported in the subsequent demonstration simulation report.

ACKNOWLEDGMENTS

Acknowledgement is made to the MOOSE team and our collaborators Rui Hu and Thomas Fanny from Argonne National Laboratory. Their close collaboration and support is essential to the success of this project. We would also like to acknowledge Stephen Hess and Greg Swindlehurst of EPRI for their valuable contributions to the development of the RELAP-7 application. Their expertise in nuclear engineering, systems analysis, and understanding of the industry needs is much appreciated.

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1. INTRODUCTION

During FY2013 of the RELAP-7 code development, the efforts have been focused on building two-phase flow capability [1]. A number of components which were previously developed to demonstrate a steady state PWR problem simulation [2], such as Pipe, Core Channels, etc., have been further extended to include two-phase flow modeling capability. In addition, a number of new components required for BWR simulation, such as Separator/Dryer, Downcomer Branch, etc., have also been developed. The following table shows the components that have been developed in RELAP-7 with two-phase flow capability:

Table 1. A list of components with two-phase flow modeling capability in RELAP-7.

Component Name	Descriptions
TimeDependentVolume	Time Dependent Volume to set pressure, temperature, and void fraction boundary conditions
TimeDependentJunction	Time Dependent Junction to set velocity and temperature boundary conditions
Branch	Multiple in and out 0-Dimensional (0-D) volume/junction, which provides form loss coefficients (K), for either isothermal flow and non-isothermal flow
Pipe	1-Dimensional (1-D) fluid flow within 1-D solid structure with wall friction and heat transfer
PipeWithHeatStructure	Simulating real 1-D pipe with solid walls (fluid flow coupled with 1-D heat conduction through the pipe wall); can take Adiabatic, Dirichlet, or Convective boundary conditions at the outer surface of the pipe wall
CoreChannel	Simulating flow channel and fuel rod thermal hydraulics, including 1-D fluid flow and fuel rod heat conduction for either plate type or cylinder type of fuel
HeatExchanger	Co-current or counter-current Heat exchanger model, including fluid flow in two sides and heat conduction through the solid wall
SeparatorDryer	Separating steam and water with mechanical methods, 1 in and 2 outs, 0-D volume
DownComer Branch	Large volume to mix different streams of water and steam and track water level

Other components required to simulate an ideal BWR loop includes:

1). Pump: which provides a driving head and reverse flow form loss coefficients (K), for either isothermal flow or non-isothermal flow.

2). Time Dependent Mass Flow Rate: which sets the mass flow rate boundary condition.

3). Reactor: which is a new virtual component, where users can specify reactor/heat source parameters. A few options are available with the Reactor component. Users can set the initial reactor/heating power, or a decay heat curve as a function of time, or use the reactor power computed by the point kinetics component.

4). Steam Dome: which is 0-Dimensional volume to provide pressure buffer for the whole primary system.

2. FLOW DEMONSTRATION RESULTS

Figure 1 shows the flow diagram of an ideal BWR loop that has been simulated with RELAP-7. The Lower Plenum component represents the volume within the reactor vessel below the reactor core. The reactor core modeling consists of three Core Channels which represent the high power region, medium power region and low power region, respectively, and a Bypass Pipe to represent the bypass flow through the reactor core. The two-phase mixture exiting the Core Channels as well as the liquid water exiting the Bypass Pipe are mixed together in the Upper Plenum above the reactor core. The two-phase mixture in the Upper Plenum flows through the Standpipes into the Separator/Dryer component. The Separator/Dryer component mechanically separates the steam from the liquid water. The steam comes out of the Separator/Dryer, flows into the Steam Dome component, and then flows into the Main Steam Line. The components downstream of the Main Steam Line are not simulated. Instead, a Time-Dependent Volume component is attached to the Main Steam Line to set the boundary condition for the steam flow. The liquid water discharged from the Separator/Dryer component flows into the Downcomer Branch component, where it is mixed with the feedwater from the feed water line. The discharge water from the Separator/Dryer and the feedwater flow downward through the Downcomer and is pumped back into the Lower Plenum of the reactor core. The components upstream of the feedwater line are not simulated. Instead, a Time-Dependent Mass Flow Rate component is attached to the feed water line to set the mass flow rate boundary condition for the feed water. A Pump component is used to represent the functions of jet pumps as well as the recirculation loops in a real BWR. The Pump component provides the necessary driving head for the ideal BWR loop simulated in this work.

A RELAP-7 input file has been prepared to represent the ideal BWR loop as shown in Figure 1 and run to steady state with the latest version of the RELAP-7 code. Figs. 2 through 5 show the simulation results generated by RELAP-7. The graphs shown on Figs. 2 through 4 were generated by the Paraview visualization software. (It should be noted that Paraview is not able to show the quantities calculated for the 0-dimensional components because there are no meshes associated with the 0-dimensional components.) Fig. 2 shows the fluid density distribution of the 1-Dimensional components simulated in the ideal BWR loop. It can be seen that the fluid density is much higher at the bottom of the core. As the heat is added to the fluids as they flow upward through the core the liquid water starts to boil, becoming two-phase mixtures and the density starts to decrease. The fluid densities are the lowest in the steam line. Fig. 3 shows the pressure distribution of the 1-Dimensional components simulated in the ideal BWR loop. Fig. 4 shows the void fraction profile of the Core Channels and Bypass Pipe in the reactor core region and Fig. 5 shows the void fraction profile of the hottest core channel. It can be seen from Figs 4 and 5 that as the subcooled water enters the reactor core and begins absorbing heat from the fuel as it flows upward through the core, it first goes through a phase transition from the liquid phase to vapor phase near the bottom of the core, and the void fraction increases as the fluid flows up through the core and absorbs more heat from the fuel.

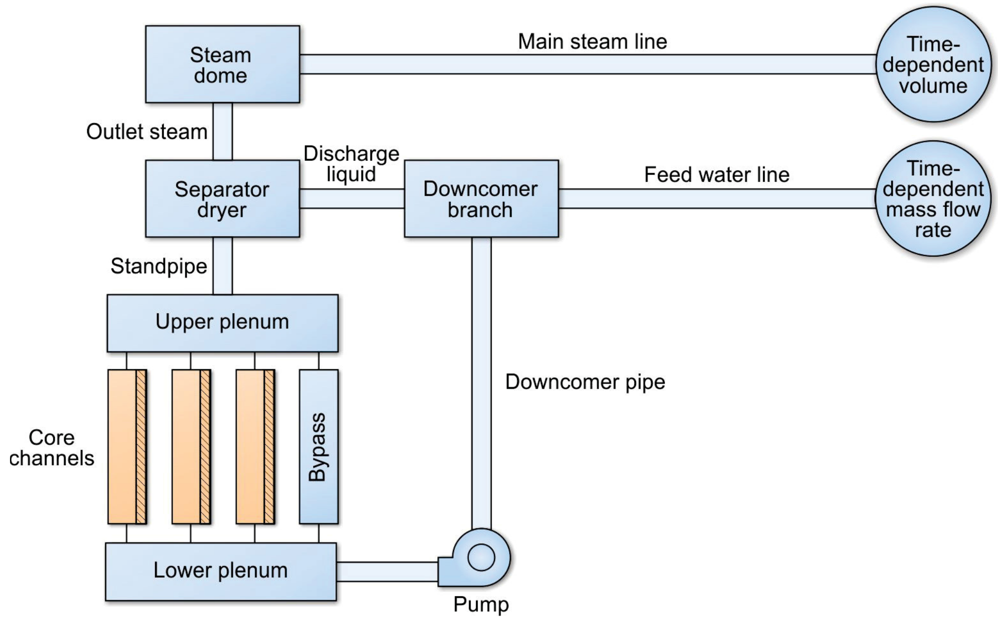

Figure 1. Schematics of an ideal BWR primary loop.

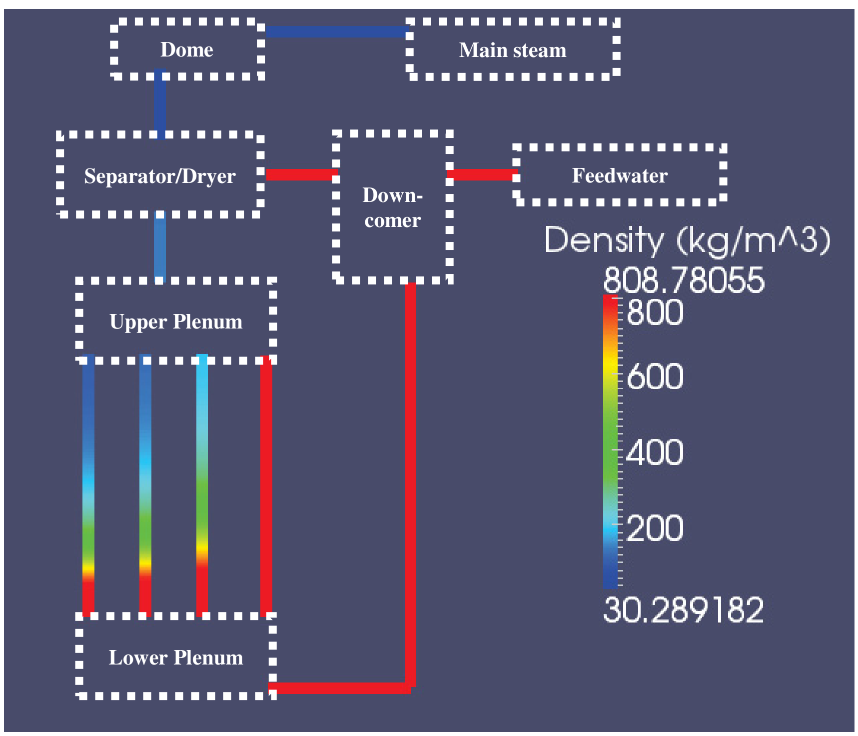

Figure 2. RELAP-7 calculated fluids density distribution for the ideal BWR primary loop.

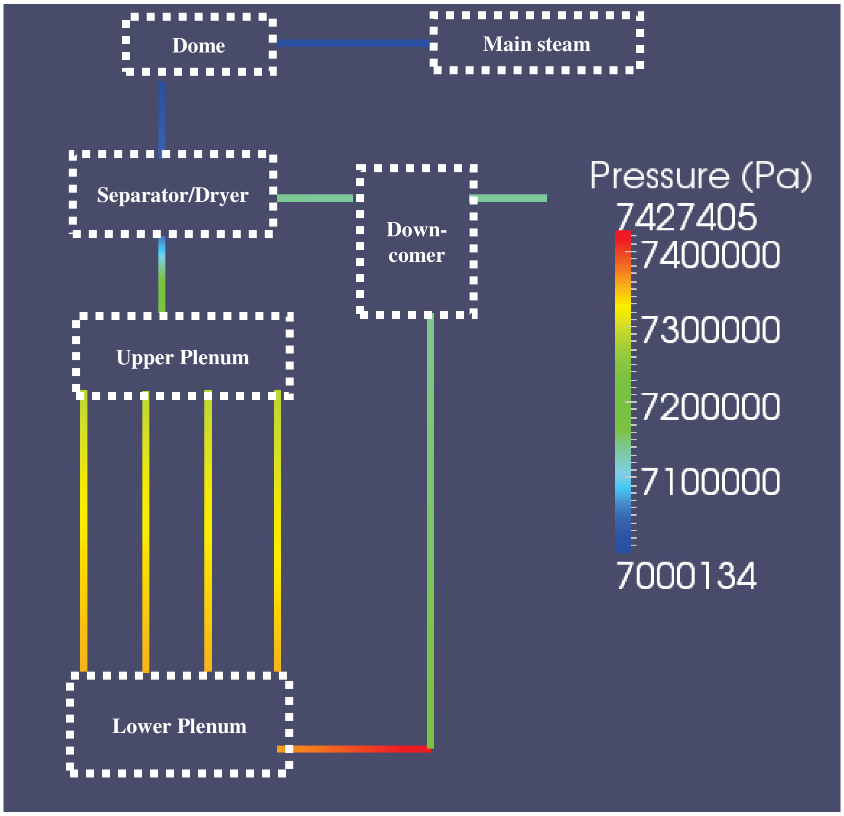

Figure 3. RELAP-7 calculated steady-state pressure distribution for the ideal BWR primary loop.

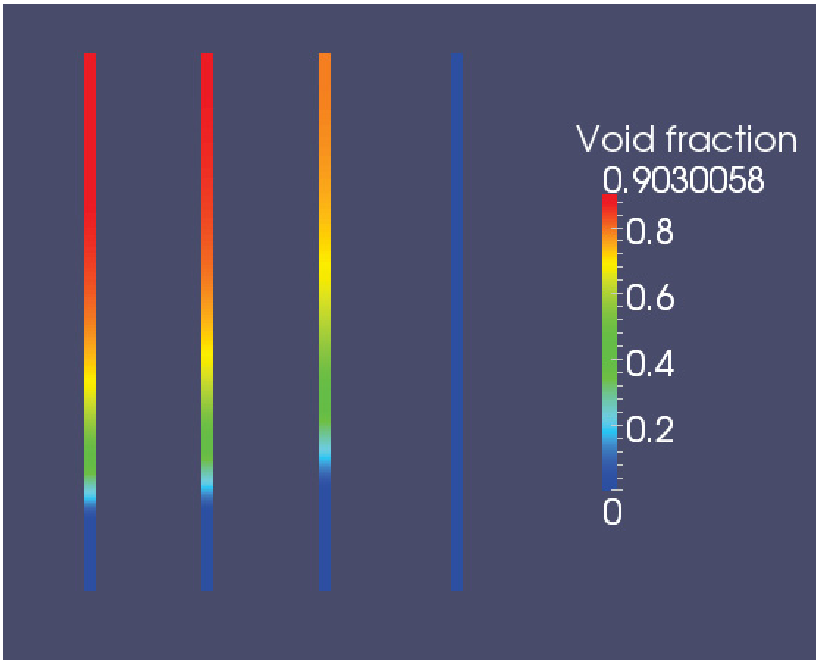

Figure 4. RELAP-7 calculated void fraction distribution for the Core Channels and the Bypass channel.

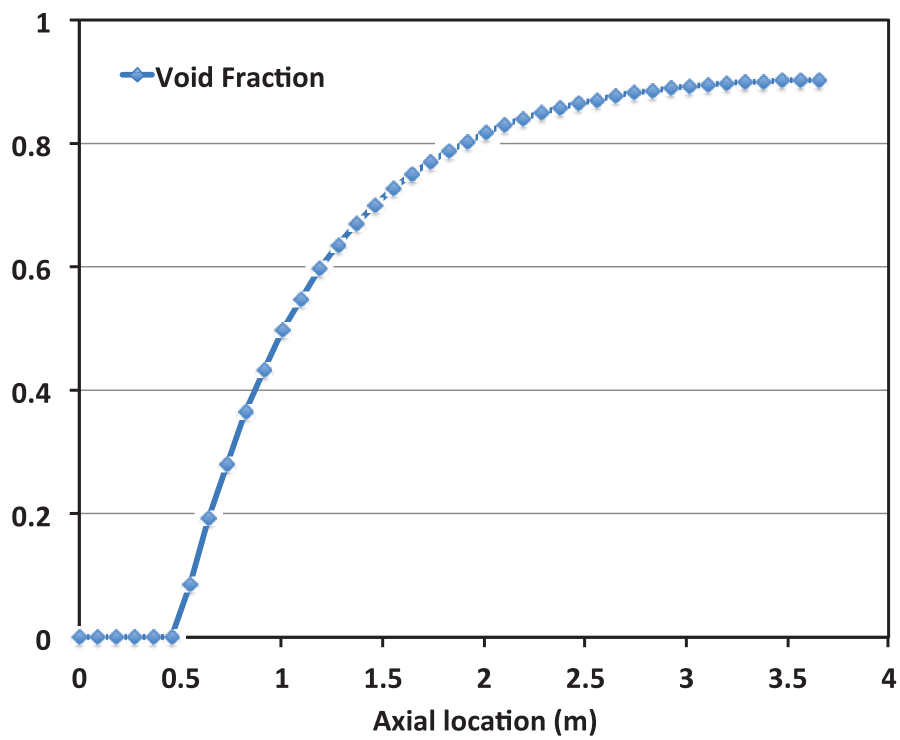

Figure 5. Void fraction distribution for the hot channel.

3. CONCLUSION AND FUTURE WORK

The two-phase flow simulation capability has been demonstrated for an ideal BWR loop. The next simulation goal is to perform a simplified BWR station blackout (SBO) analysis. Table 2 shows the major components that are being developed to perform such demonstration simulations. The BWR simplified SBO demonstration will be reported in a subsequent milestone report.

Table 2. A list of components being developed to perform the BWR SBO analysis.

Component Name	Descriptions
RCIC Turbine	Simulate Reactor Core Isolation Cooling (RCIC) turbine which drives the RCIC pump through a common shaft, 0-D junction
RCIC Pump	Simulate Reactor Core Isolation Cooling (RCIC) pump which is driven by the RCIC turbine through a common shaft, 0-D junction
Wet Well	0-D volume to simulate suppression pool and it's gas space
Dry Well	0-D volume to simulate dry well space

4. REFERENCES

1. *RELAP-7: Demonstrating Seven-Equation, Two-Phase Flow Simulation in a Single Pipe, Two-Phase Reactor Core and Steam Separator/Dryer*, Idaho National Laboratory, INL/EXT-13-28750, April 2013.

2. *RELAP-7 Level 2 Milestone Report: Demonstration of a Steady State Single Phase PWR Simulation with RELAP-7*, Idaho National Laboratory, INL/EXT-12-25924, May 2012.

5. Appendix A – RELAP-7 Input File

```
[GlobalParams]
  model_type = 32
  global_init_P = 7.e6
  global_init_V = 3.
  global_init_T = 517.
  global_init_alpha = 0.0
  scaling_factor_var   = '1e-1 1e-3 1e-9'
  gravity = '0 0 -9.8'
  stabilization_type = 'NONE'
  temperature_sf = 1.0E-4
[]

[EoS]
  [./two_phase_eos]
    type = TwoPhaseStiffenedGasEOS
  [../]
  [./vapor_phase_eos]
    type = StiffenedGasEquationOfStateVapor
  [../]
  [./liquid_phase_eos]
    type = StiffenedGasEquationOfStateLiquid
  [../]
[]

[Materials]
  [./fuel-mat]
    type = SolidMaterialProperties
    k = 3.7
    Cp = 3.e2
    rho = 10.42e3
  [../]
  [./gap-mat]
    type = SolidMaterialProperties
    k = 0.7
    Cp = 5e3
```

```
    rho = 1.0
  [../]
  [./clad-mat]
    type = SolidMaterialProperties
    k = 16
    Cp = 356.
    rho = 6.551400E+03
  [../]
[]

[Components]
  [./reactor]
    type = Reactor
    initial_power = 150e3
  [../]

  [./pipe1]
    type = Pipe
    position =    '0 3.5 1'
    orientation = '0 -1 0'
    A = 1.907720E-04
    Dh = 0.01
    length = 2.0
    n_elems = 10
    initial_void_fraction = 0.0
    f = 0.1
    Hw = 0.0
    aw = 400
    Tw = 528
    eos = liquid_phase_eos
    model_type = 3
  [../]

  [./ch1]
    type = CoreChannel
    eos = two_phase_eos
    position = '0 -1.0  2'
```

```
  orientation = '0 0 1'
  A = 1.907720E-04
  Dh = 1.698566E-02
  length = 3.6576
  n_elems = 40
  f = 0.2
  Hw = 5.0e4
  aw = 2.354927E+02
  Ts_init = 517.
  fuel_type = cylinder
  dim_hs = 1
  n_heatstruct = 3
  name_of_hs =  'FUEL GAP CLAD'
  width_of_hs = '6.057900E-03  1.524000E-04  9.398000E-04'
  elem_number_of_hs = '5 1 2'
  material_hs = 'fuel-mat gap-mat clad-mat'
  power_fraction = '0.4 0.0 0.0'
  stabilization_type = 'NONE'
  model_type = 32
[../]

[./ch2]
  type = CoreChannel
  eos = two_phase_eos
  position = '0 -0.2 2'
  orientation = '0 0 1'
  A = 1.907720E-04
  Dh = 1.698566E-02
  length = 3.6576
  n_elems = 40
  f = 0.2
  Hw = 5.0e4
  aw = 2.354927E+02
  Ts_init = 517.
  fuel_type = cylinder
  dim_hs = 1
  n_heatstruct = 3
```

```
  name_of_hs =  'FUEL GAP CLAD'
  width_of_hs = '6.057900E-03  1.524000E-04  9.398000E-04'
  elem_number_of_hs = '5 1 2'
  material_hs = 'fuel-mat gap-mat clad-mat'
  power_fraction = '0.35 0.0 0.0'
  stabilization_type = 'NONE'
  model_type = 32
[../]

[./ch3]
  type = CoreChannel
  eos = two_phase_eos
  position = '0 0.6 2'
  orientation = '0 0 1'
  A = 1.907720E-04
  Dh = 1.698566E-02
  length = 3.6576
  n_elems = 40
  f = 0.2
  Hw = 5.0e4
  aw = 2.354927E+02
  Ts_init = 517.
  fuel_type = cylinder
  dim_hs = 1
  n_heatstruct = 3
  name_of_hs =  'FUEL GAP CLAD'
  width_of_hs = '6.057900E-03  1.524000E-04  9.398000E-04'
  elem_number_of_hs = '5 1 2'
  material_hs = 'fuel-mat gap-mat clad-mat'
  power_fraction = '0.25 0.0 0.0'
  stabilization_type = 'NONE'
  model_type = 32
[../]

[./bypass]
  type = Pipe
  position = ' 0 1.5 2'
```

```
  orientation = '0 0 1'
  A = 1.90772E-04
  Dh = 1.698566E-4
  length = 3.6576
  n_elems = 40
  f = 0.2
  Hw = 0.0
  aw = 2.354927E+2
  eos = two_phase_eos
  model_type = 32
  stabilization_type = 'NONE'
[../]

[./pipe6]
  type = Pipe
  position =    '0.0 0.0 6.6576'
  orientation = '0 0 1'
  A = 1.907720E-04 #7.854e-3  # PI/4 * (0.01)**2
  Dh = 0.01
  length = 1.0
  n_elems = 10
  f = 0.1
  Hw = 0.
  aw = 400
  Tw = 600
  eos = two_phase_eos
  model_type = 32
[../]

[./pipe7]
  type = Pipe
  position =    '0.0 0.0 8.6576'
  orientation = '0 0 1'
  A = 1.907720E-04
  Dh = 0.01
  length = 1.0
  n_elems = 10
```

```
  f = 0.1
  Hw = 0.
  aw = 400
  Tw = 600
  eos = vapor_phase_eos
  model_type = 3
[../]

[./pipe8]
  type = Pipe
  position =    '0.0 1.5  8.1576'
  orientation = '0 1 0'
  A = 1.907720E-04
  Dh = 0.01
  length =1.0
  n_elems = 10
  f = 0.01
  Hw = 0.
  aw = 400
  Tw = 600
  eos = liquid_phase_eos
  model_type = 3
[../]

[./pipe9]
  type = Pipe
  position =    '0.0 1.5  10.1576'
  orientation = '0 1 0'
  A = 1.907720E-04
  Dh = 0.01
  length =2.0
  n_elems = 10
  f = 0.01
  Hw = 0. #1e5
  aw = 400
  Tw = 600
  eos = vapor_phase_eos
```

```
    model_type = 3
  [../]

 [./branch1]
    type = SeparatorDryer
    eos = two_phase_eos
    center = '0.0  0.0  8.1576'
    inputs = 'pipe6(out)'
    outputs = 'pipe7(in) pipe8(in)'
    K = '1.0 1.0 5.0'
    volume = 3.14e-4
    Area = 3.14e-4
    initial_T = 517.0
  [../]

  [./lowerplenum]
    type = VolumeBranch
    eos = two_phase_eos
    center = '0.0  0.0  1.5'
    inputs = 'pipe1(out)'
    outputs = 'ch1(in) ch2(in) ch3(in) bypass(in)'
    K = '1.0 1.0 1.0 1.0 5'
    volume = 3.14e-4
    Area = 3.14e-4
    initial_T = 517.0
  [../]

  [./upperplenum]
    type = VolumeBranch
    eos = two_phase_eos
    center = '0.0  0.0  6.1576'
    inputs = 'ch1(out) ch2(out) ch3(out) bypass(out)'
    outputs = 'pipe6(in)'
    K = '1.0 1.0 1.0 1.0 1.0'
    volume = 3.14e-4
    Area = 3.14e-4
    initial_T = 517.0
```

```
 [../]

 [./dome]
  type = VolumeBranch
  eos = vapor_phase_eos
  center = '0.0 0.0 10.1576'
  inputs = 'pipe7(out)'
  outputs = 'pipe9(in)'
  K = '1.0 1.0'
  volume = 3.14e-4
  Area = 3.14e-4 #3.14e-2
  initial_T = 517.0
[../]

[./downcomer]
  type = DownComer
  eos = liquid_phase_eos
  center = '0.0  3.0 8.1576'
  inputs = 'pipe8(out) pipe10(out)'
  outputs = 'pipe11(in)'
  K = '1.0 1.0 1.0'
  Area = 3.14e-4
  volume = 3.14e-4
  initial_T = 517.0
  initial_level = 1.0
  dome_component = 'dome'
[../]

[./pipe10]
  type = Pipe
  position =    '0 5.0  8.1576'
  orientation = '0 -1 0'
  A = 1.907720E-04 #7.854e-3  # PI/4 * (0.01)**2
  Dh = 0.01
  length = 1.0
  n_elems = 10
  f = 0.01
```

```
  Hw = 0.
  aw = 400
  Tw = 600
  eos = liquid_phase_eos
  model_type = 3
[../]

[./pipe11]
  type = Pipe
  position =    '0 3.5  6.6576'
  orientation = '0 0 -1'
  A = 1.907720E-04
  Dh = 0.01
  length = 5.6576
  n_elems = 50
  f = 0.01
  Hw = 0.
  aw = 400
  Tw = 600
  eos = liquid_phase_eos
  model_type = 3
[../]

[./Pump]
  type = IdealPump
  eos = liquid_phase_eos
  inputs = 'pipe11(out)'
  outputs = 'pipe1(in)'
  Area = 1.90772E-4
  Initial_pressure = 7.0e6
  mass_flow_rate = 0.44
[../]

[./outlet1]
  type = TimeDependentVolume
  input = 'pipe9(out)'
  p_bc = 7.0e6
```

```
    T_bc = 517
    eos = vapor_phase_eos
    weak_bc = false
  [../]

  [./inlet1]
    type = TDM
    input = 'pipe10(in)'
    massflowrate_bc = 0.1
    T_bc = 508.
    eos = liquid_phase_eos
  [../]
[]

[Preconditioning]
   # Uncomment one of the lines below to activate one of the blocks...
   #active = 'SMP_Newton'
   #active = 'SMP_PJFNK'
   active = 'FDP_PJFNK'
   #active = 'FDP_Newton'

  [./SMP_Newton]
    type = SMP
    full = true
    petsc_options = '-snes'
  [../]

  # The definitions of the above-named blocks follow.
  [./SMP_PJFNK]
    type = SMP
    full = true
    petsc_options = '-snes_mf_operator'
    petsc_options_iname = '-mat_fd_type -mat_mffd_type'
    petsc_options_value = 'ds ds'
  [../]

  [./FDP_PJFNK]
```

```
    type = FDP
    full = true
    petsc_options = '-snes_mf_operator'
    #petsc_options = '-snes_fd'
    petsc_options_iname = '-mat_fd_type  -mat_mffd_type'
    petsc_options_value = 'ds             ds'
    #petsc_options_iname = '-mat_fd_coloring_err'
    #petsc_options_value = '1.e-10'
    # petsc_options_iname = '-mat_fd_type'
    # petsc_options_value = 'ds'
  [../]

  [./FDP_Newton]
    type = FDP
    full = true
    petsc_options = '-snes'
    petsc_options_iname = '-mat_fd_coloring_err'
    petsc_options_value = '1.e-10'
    # petsc_options_iname = '-mat_fd_type'
    # petsc_options_value = 'ds'
  [../]
[] # End preconditioning block

[Executioner]
  type = Transient
  #type = DT2Transient
  #predictor_scale = 0.5
  #n_startup_steps = 10
  dt = 1e-2
  dtmin = 1.e-7
  [./TimeStepper]
    type = FunctionDT
    time_t = '0       0.1   0.6      1       5      10    20     1e5'
    time_dt = '1e-3   1.e-3 1.e-1   1.e-1   1.e-1  1e-1  2e-1   5e-1'
  [../]
  #petsc_options = '-ksp_monitor'
  #petsc_options_iname = '-ksp_gmres_restart'
```

```
  #petsc_options_value = '60'
  petsc_options_iname = '-pc_type'
  petsc_options_value = 'lu'
  #petsc_options_iname = '-pc_type -pc_hypre_type -ksp_gmres_restart'
  #petsc_options_value = 'hypre boomeramg 300'
  nl_rel_tol = 1e-8
  nl_abs_tol = 1e-5
  #nl_abs_step_tol = 1e-15
  nl_max_its = 40
  l_tol = 1e-8 # 1e-8 # Relative linear tolerance for each Krylov solve
  l_max_its = 100 #100 # Number of linear iterations for each Krylov solve
  start_time = 0.0
  end_time = 1500
  num_steps = 500000

   [./Quadrature]
     type = TRAP
     order = FIRST
   [../]
[] # close Executioner section

[Output]
  # Turn on performance logging
  perf_log = true
  #interval = 50
  output_initial = true
  output_displaced = true
[]
```