Fluid Transient Analysis of Propellant Feedlines during a Priming Event

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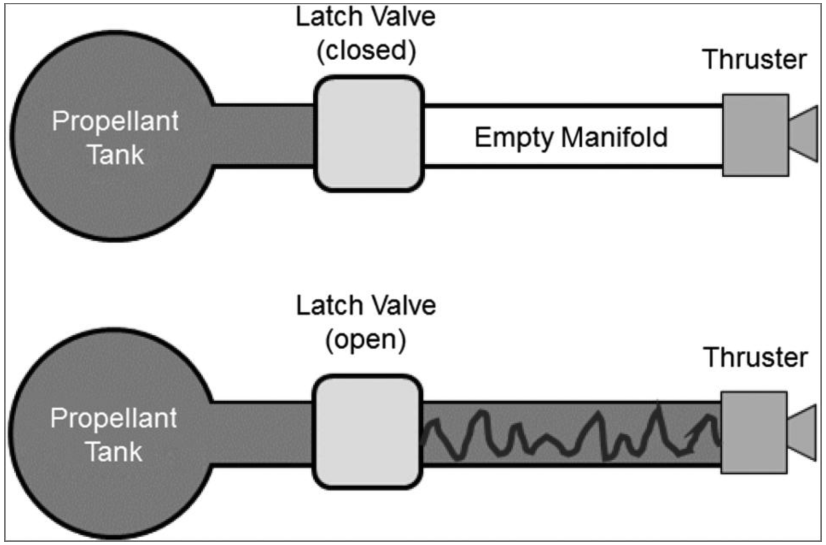
Background

- Priming is the process of filling an evacuated pipe line.
  - For safety reasons, storable propellants such as hydrazine are separated from thrusters by one or more valves.
  - Once in orbit, the valve is opened, and the evacuated line is filled with propellant.



Picture Credit: Moore et al., JSR, 2018.

Background

- The velocity change when the fluid hits the dead end can cause a brief pressure surge.
  - The pressure rise can be as high as:

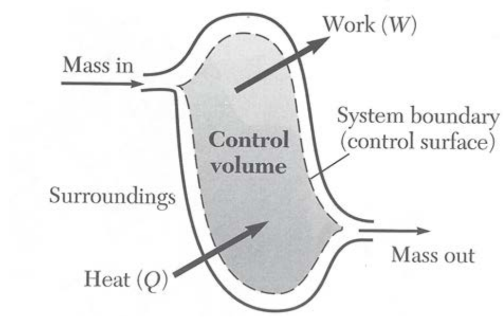
$$\Delta P = \rho c \Delta V$$

  - For example, if liquid water is suddenly stopped from 10 m/s, the pressure rise could be:

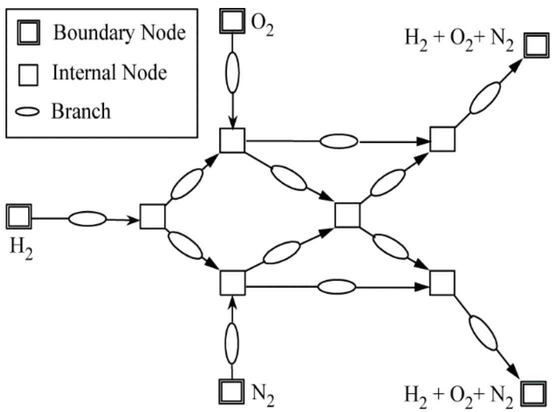
$$\Delta P = \left(1000\ \frac{kg}{m^3}\right)\left(1500\frac{m}{s}\right)\left(10\frac{m}{s}\right) = 15\ MPa$$

- Accurate prediction of maximum pressure aids in the design of a propulsion system that is not too conservatively heavy.

- The Generalized Fluid System Simulation Program (GFSSP) is a general-purpose computer program to calculate pressures, temperatures, and flow rates in a fluid network.
- Fluid networks are discretized into nodes and branches.
  - Mass and energy equations are solved in the nodes.
  - Momentum equation is solved in the branches.

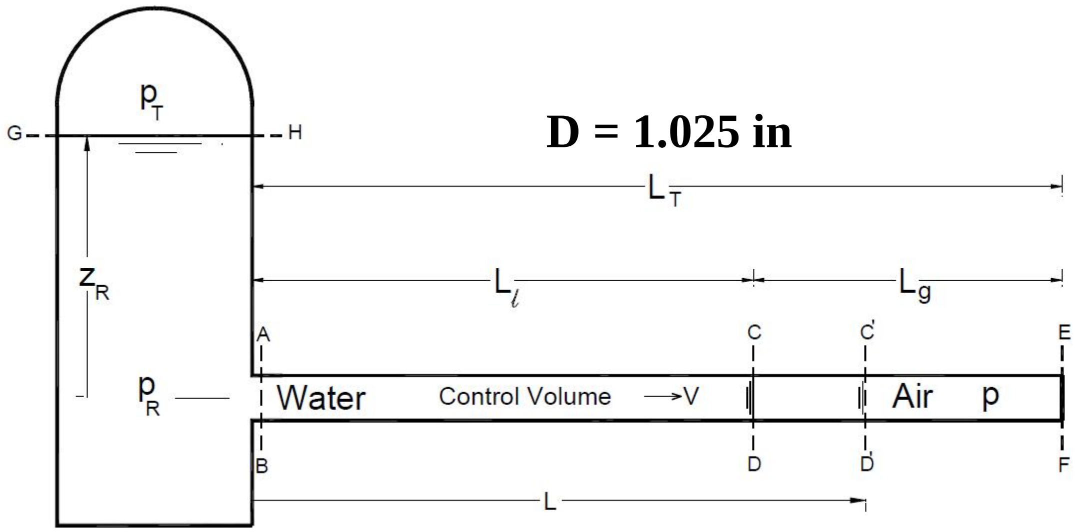


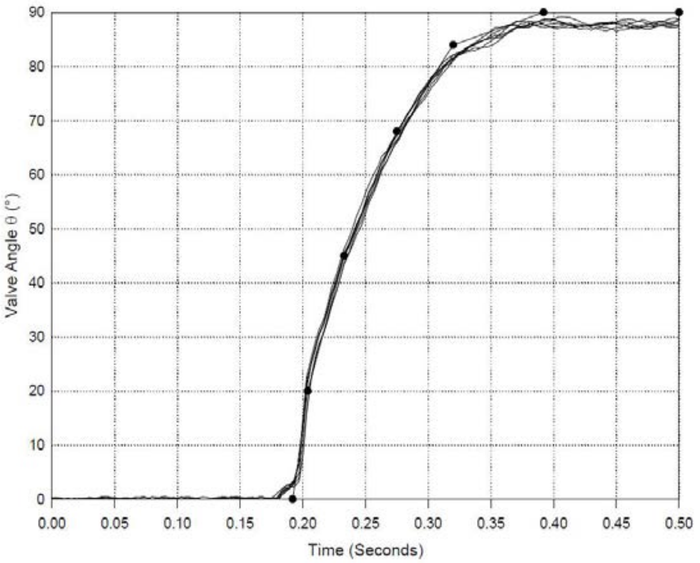
Control Volume Analysis



Finite Volume Analysis

Georgia Tech Experiment



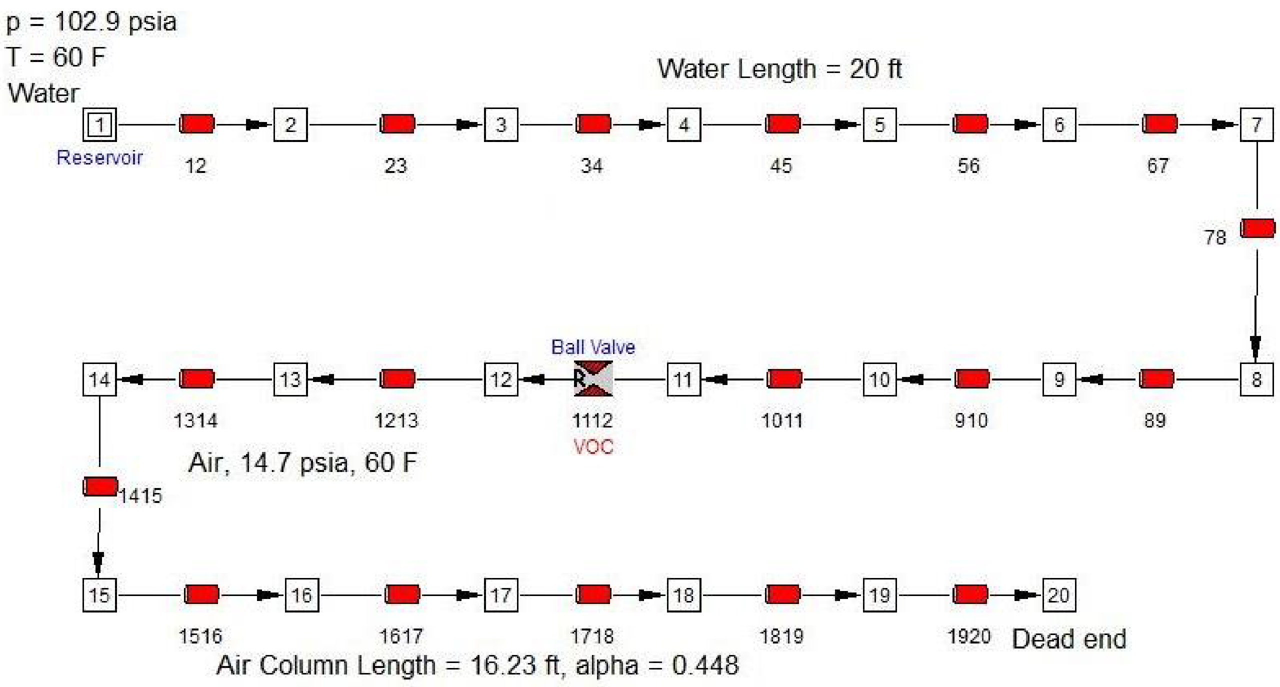


Ph.D. dissertation by N. H. Lee, 2005

Test series varied:

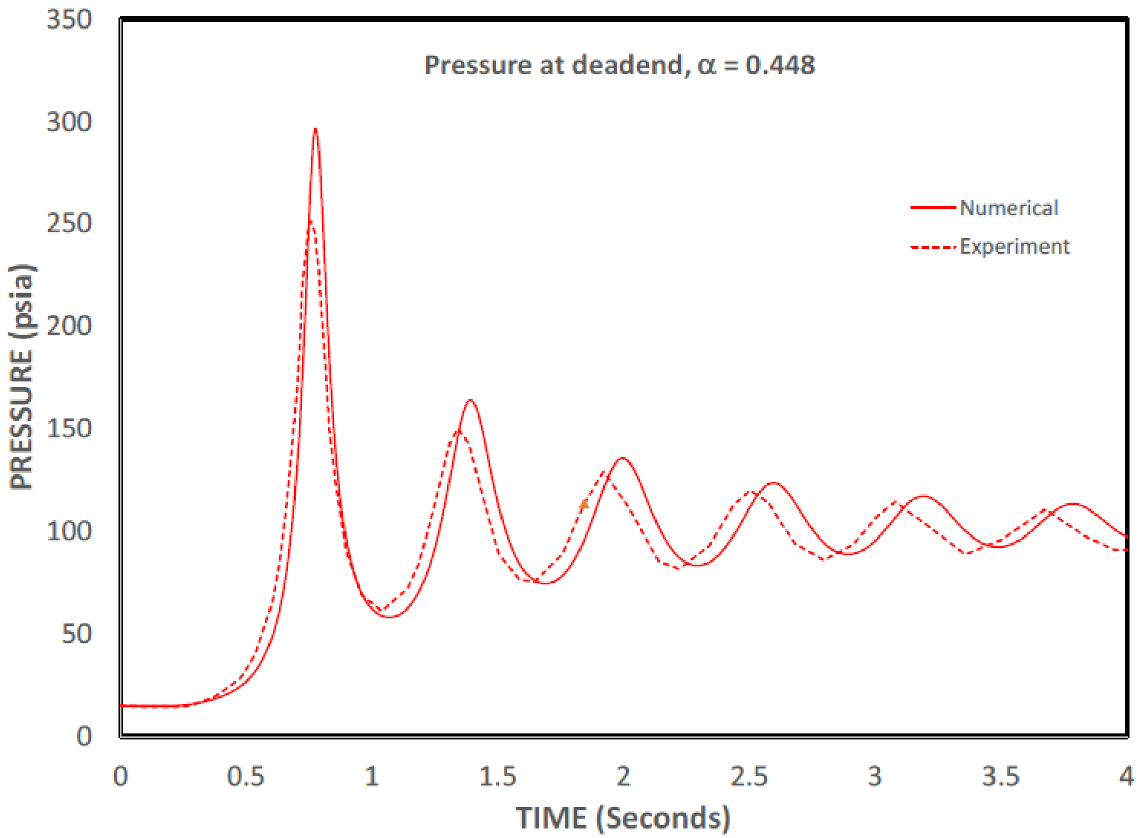
- Reservoir pressure: 2 to 7 atm
- Gas volume proportion: $\alpha = L_g/L_T$

Georgia Tech Experiment



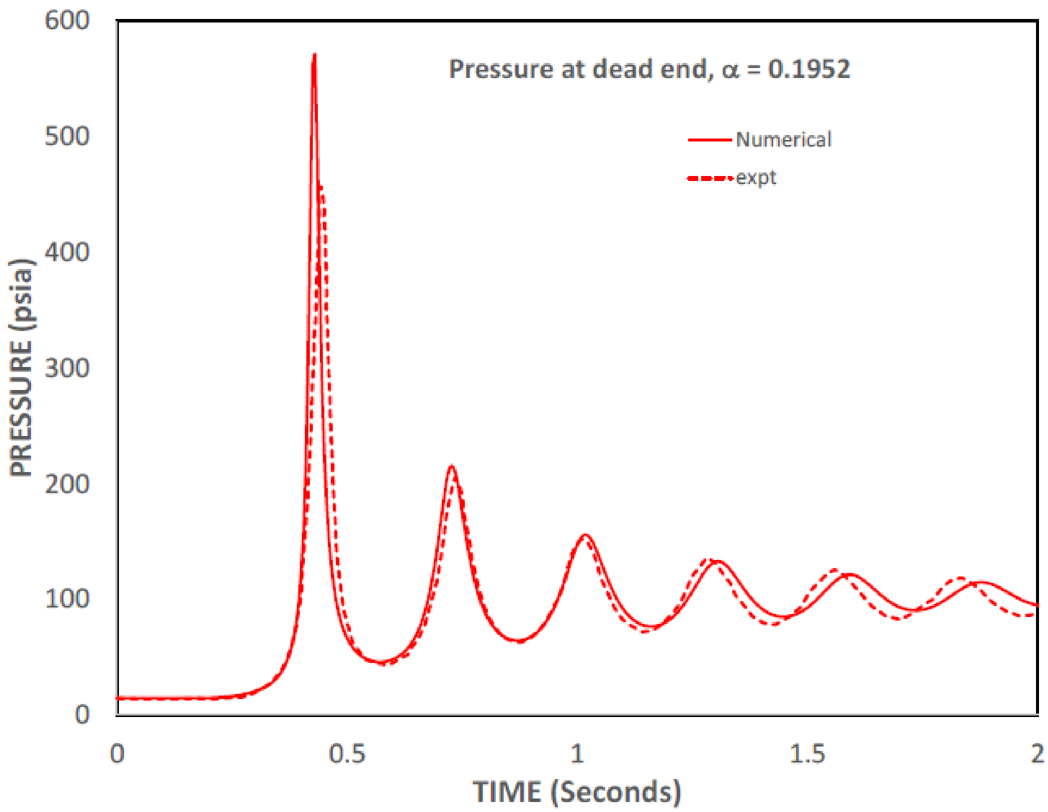
- Nodes 1-11 initially contain liquid water at 102.9 psia.
- Nodes 12-20 initially contain air (as an ideal gas) at 14.7 psia.
- A Fortran user subroutine fixes all temperatures in model at 60° F. Air temperature increase by compression is neglected.

Georgia Tech Experiment

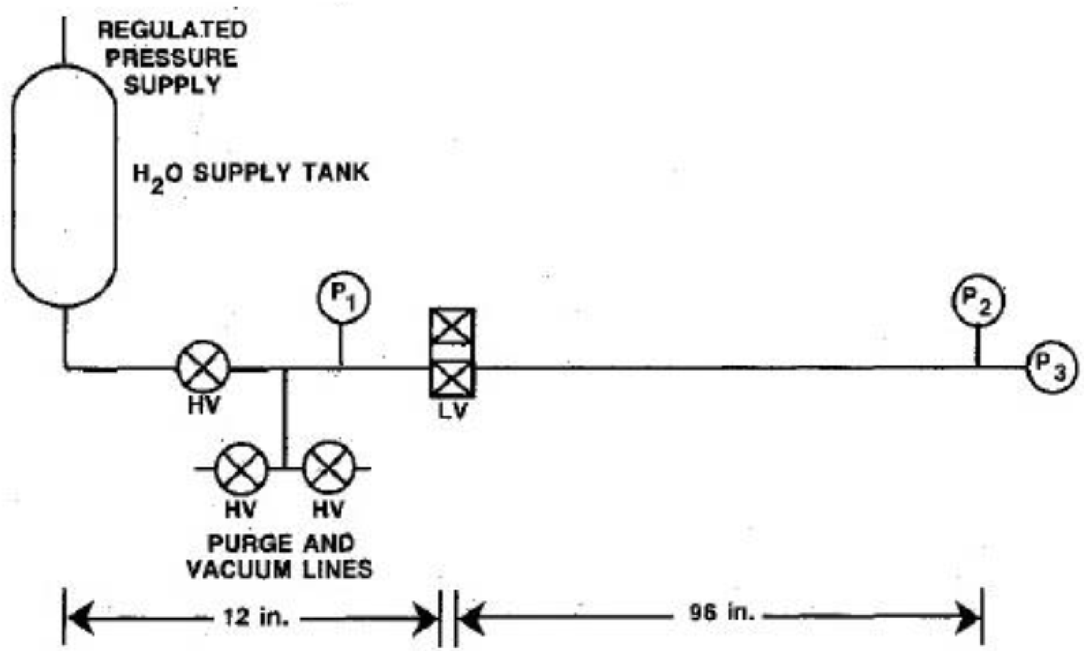


- Predicted peak pressure is 20% higher than experimental.

Georgia Tech Experiment



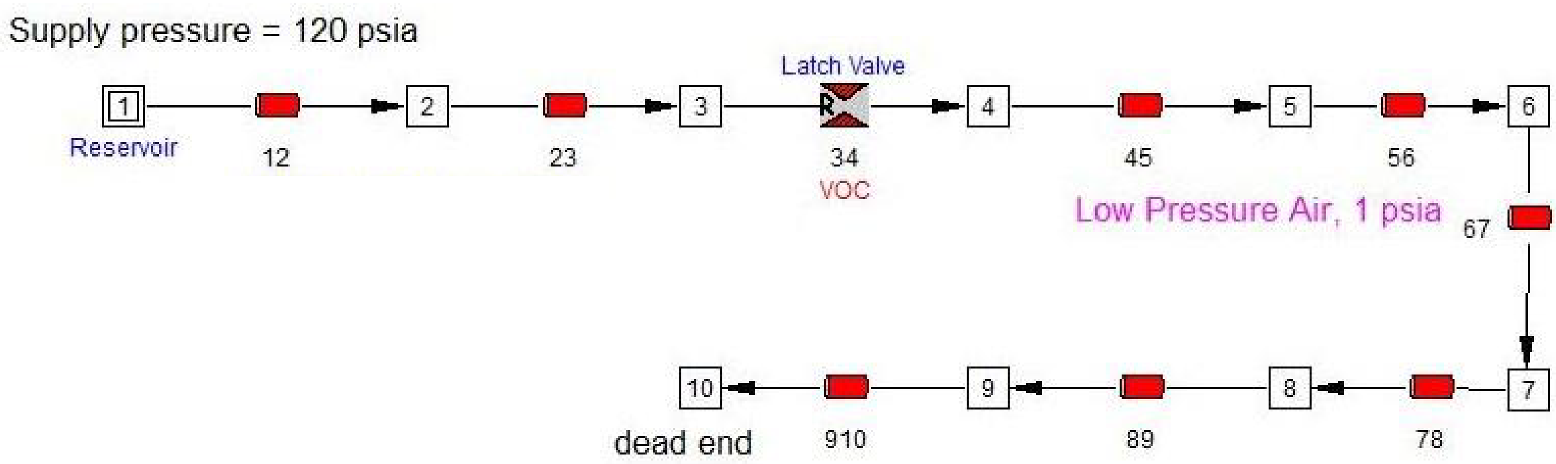
- Maximum pressure increases when trapped air length is decreased:
  - $\alpha = 0.448$, $P_{max} = 250$ psia
  - $\alpha = 0.195$, $P_{max} = 450$ psia



Prickett et al., 1992

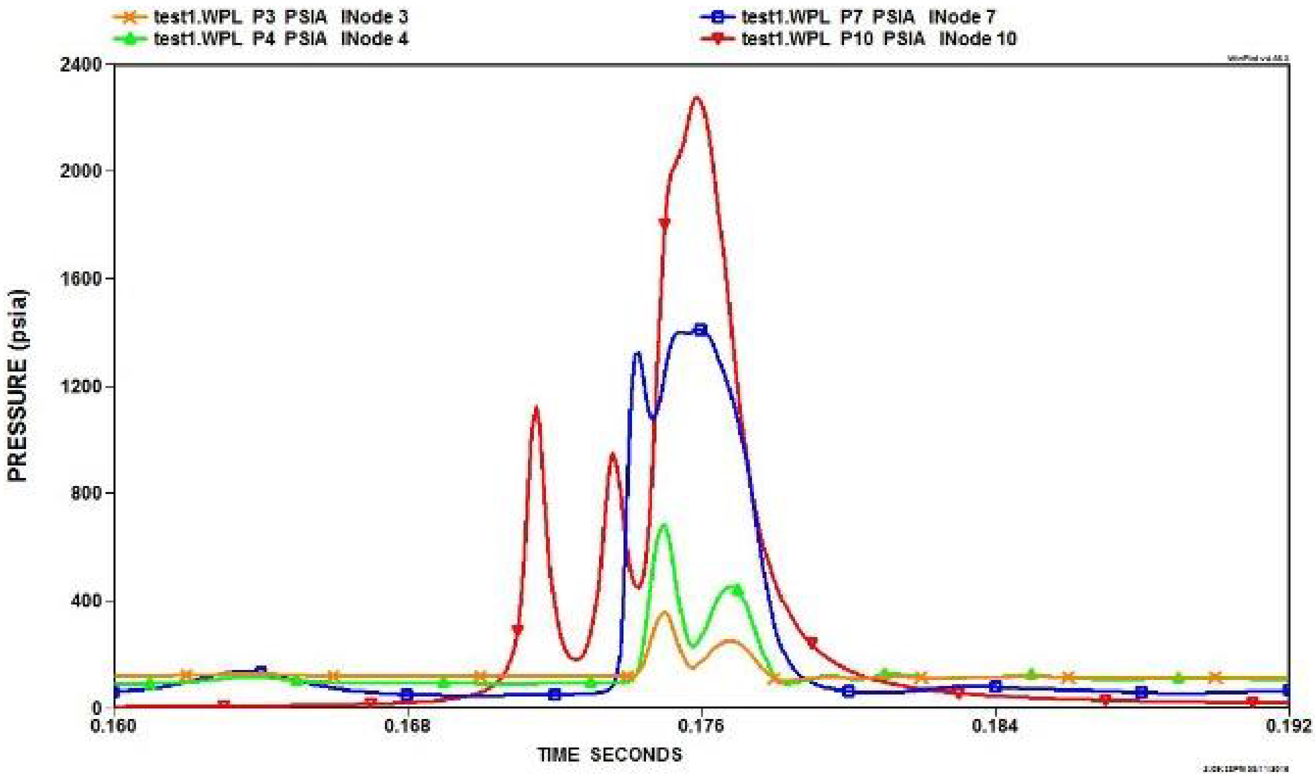
- Test series varied reservoir pressure: 30 to 120 psia
- Pipe diameter: 0.25 in.
- Pipe downstream of latch valve (LV) is initially evacuated.

Hughes Aircraft Experiment



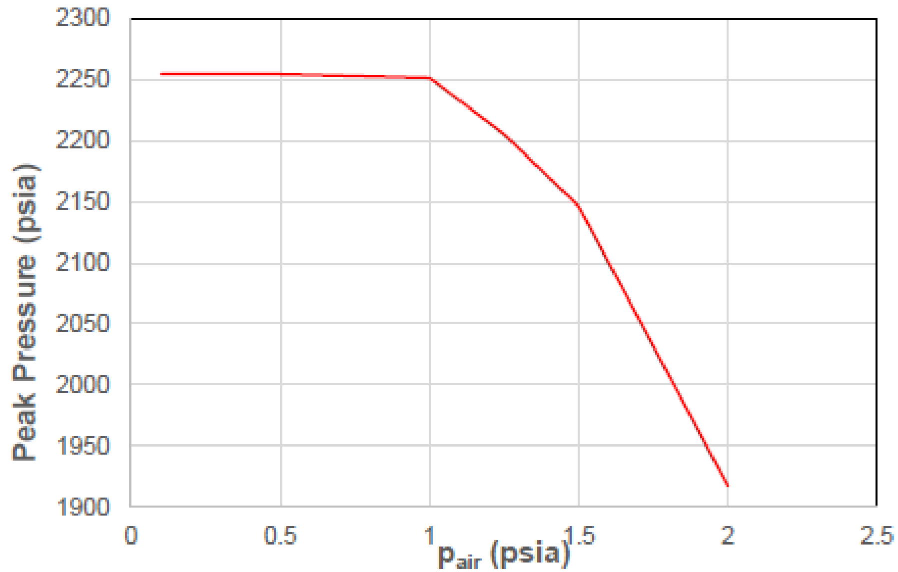
- GFSSP does not understand “empty”, so the evacuated line is initially filled with ideal gas air at low pressure.

Hughes Aircraft Experiment



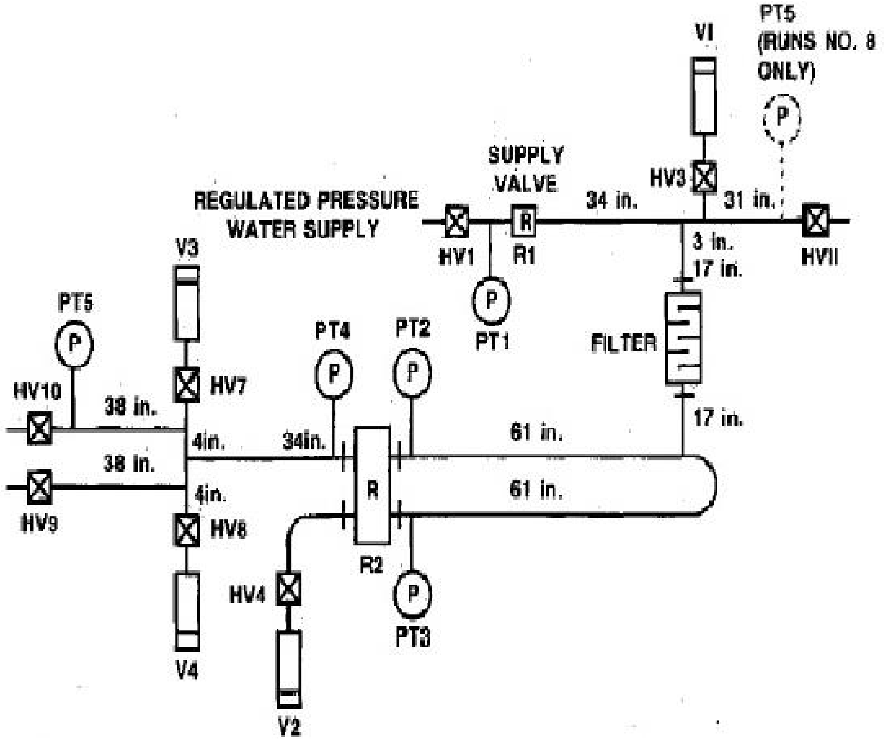
- Reported maximum pressure is 2350 psia in the dead end at 0.17 sec.
- GFSSP predicts 2279 psia at 0.176 sec.

Hughes Aircraft Experiment



- Decreasing initial air pressure of evacuated lines increased the maximum pressure, although there was little change when $P_{air} < 1$ psia.

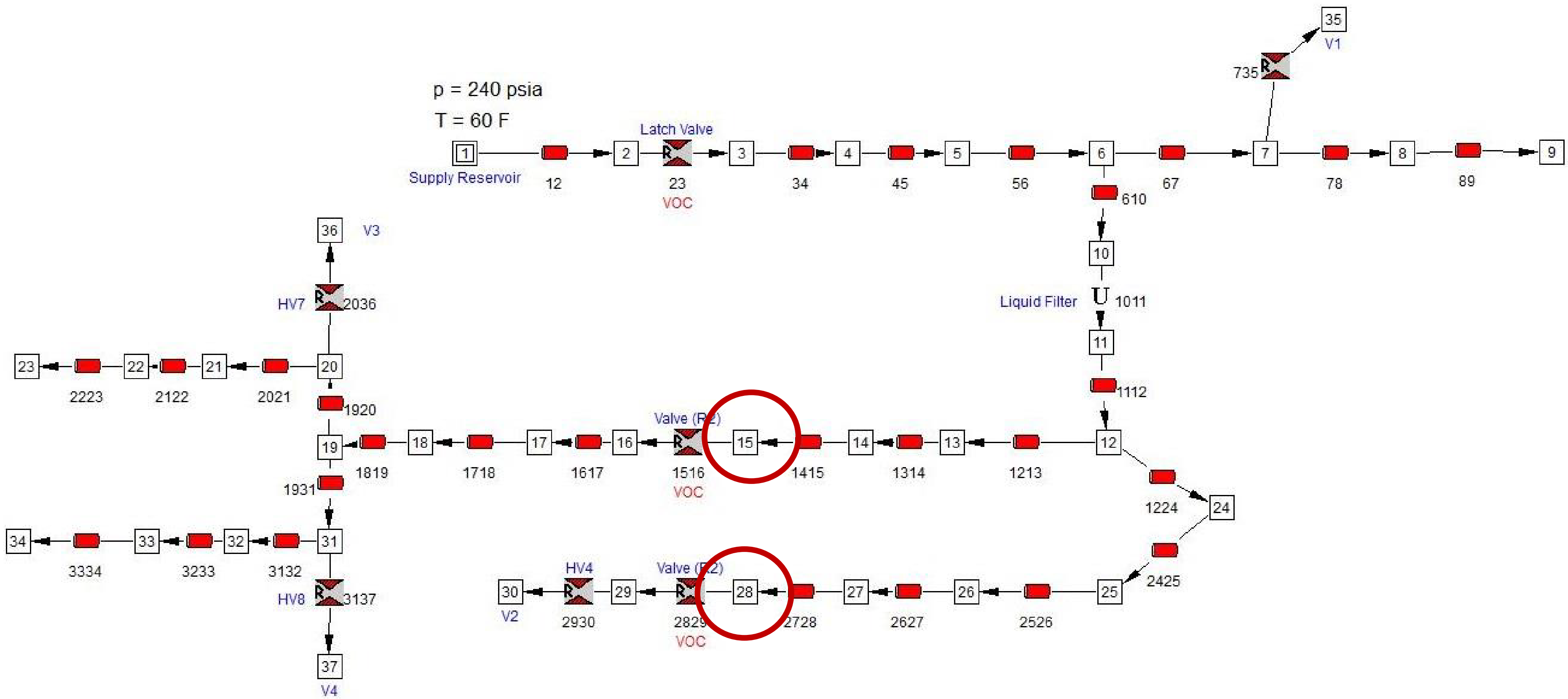
Hughes Network Experiment



Prickett et al., 1992

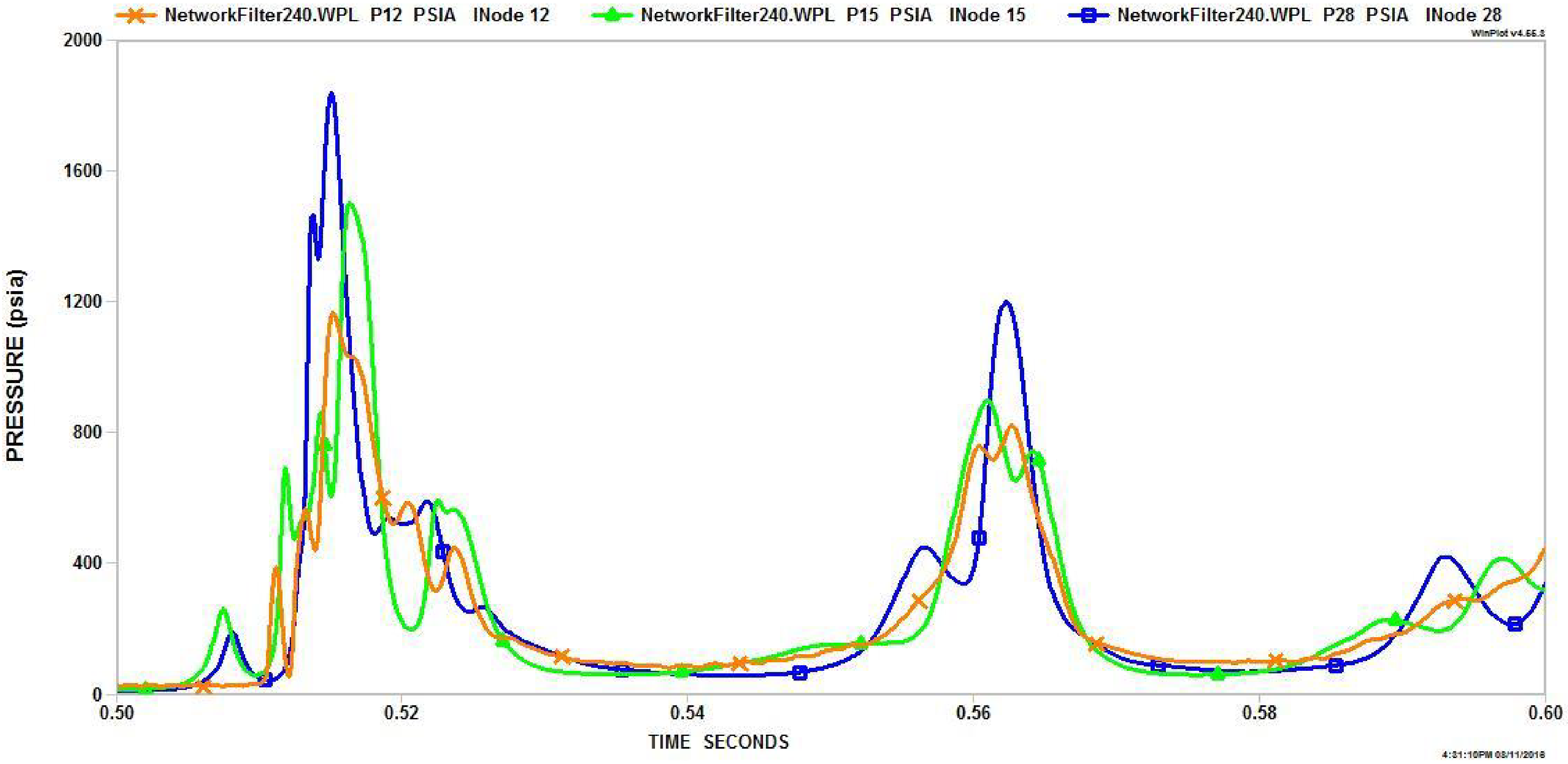
- Reservoir pressure: 240 psia
- Pipe diameter: 0.25 in.
- R1 is the suddenly opening valve.
- R2 is a pair of valves that close quickly during priming event.

Hughes Network Experiment



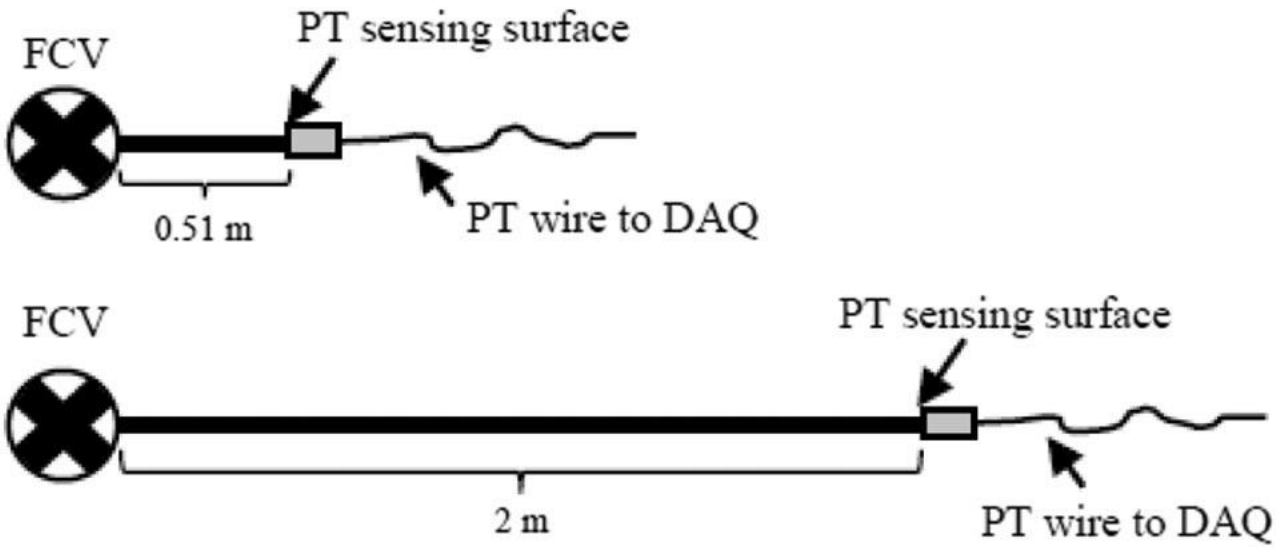
- Evacuated nodes are modeled as ideal gas air initially at 1 psia.
- Pressure data available at nodes 15 and 28.

Hughes Network Experiment



- Maximum pressure in lower branch is 1837 psia at node 28. Measured pressure at this location is 1800 psia.
- Maximum pressure in upper branch is 3500 psia at node 9. No test data were reported for this location.

Penn State Experiment

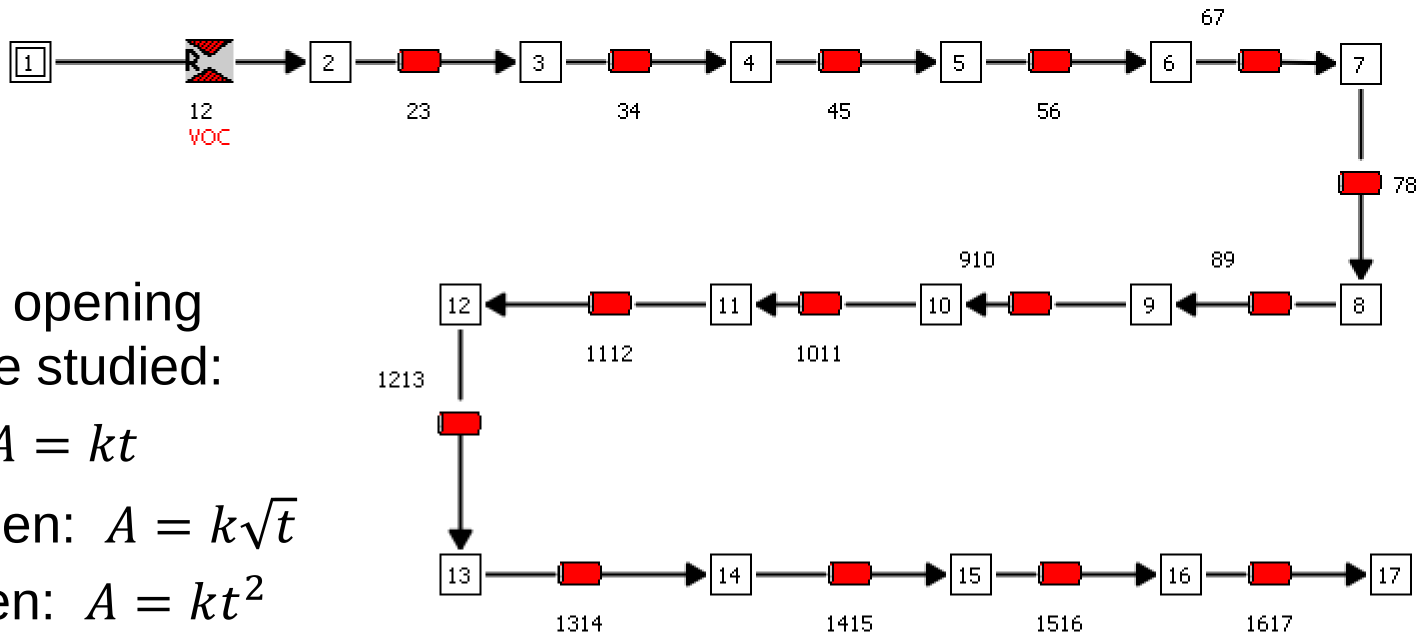


Moore et al., JSR, 2019

- Reservoir pressure: 1.5, 2.2, or 2.9 MPa
- Line lengths: 0.51 or 2.0 m
- Line diameters: 6.5, 9.5, or 12.7 mm
- Flow Control Valve C_v: 0.037, 1.5, or 4.0
- Initial air pressure in line: 4, 15, 101 kPa

Penn State Experiment

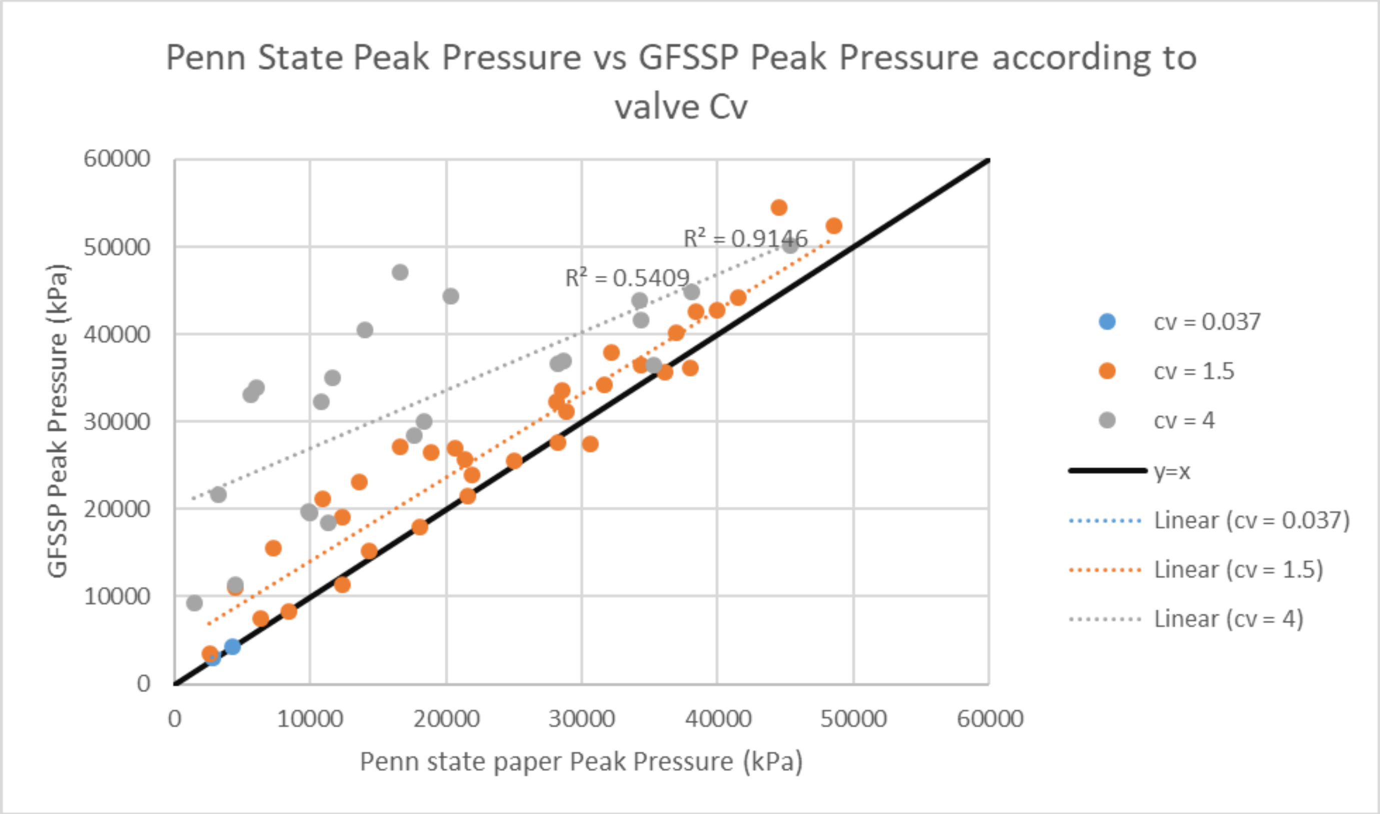
Main Model



Three valve opening profiles were studied:

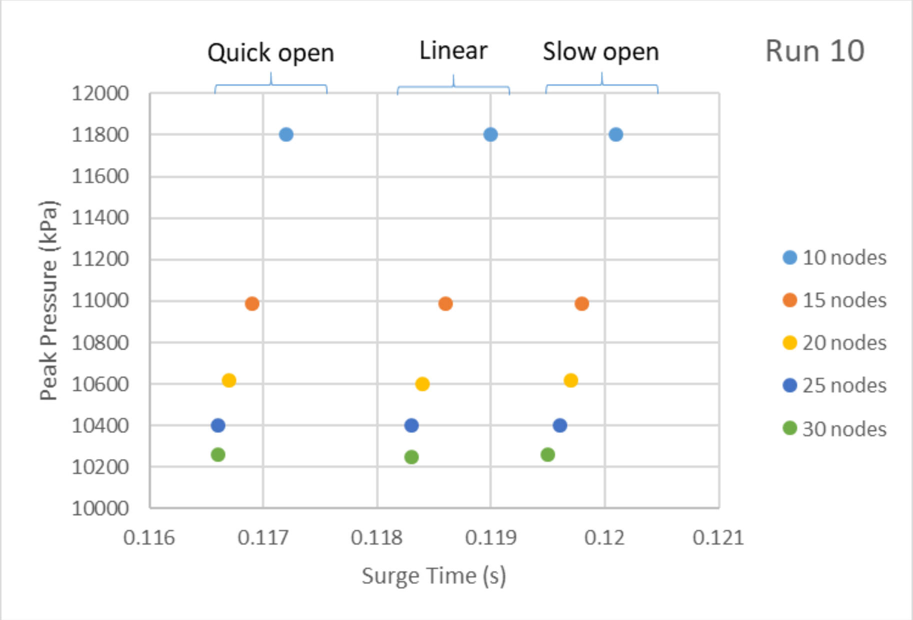
- Linear: $A = kt$
- Quick open: $A = k\sqrt{t}$
- Slow open: $A = kt^2$

Penn State Experiment



- Predictions are reasonable for cases with FCV C_v = 0.037 and 1.5.
- For cases with C_v = 4.0, GFSSP consistently over-predicts peak pressure.
- No clear relationship seen between GFSSP prediction accuracy and tank pressure or initial line pressure.

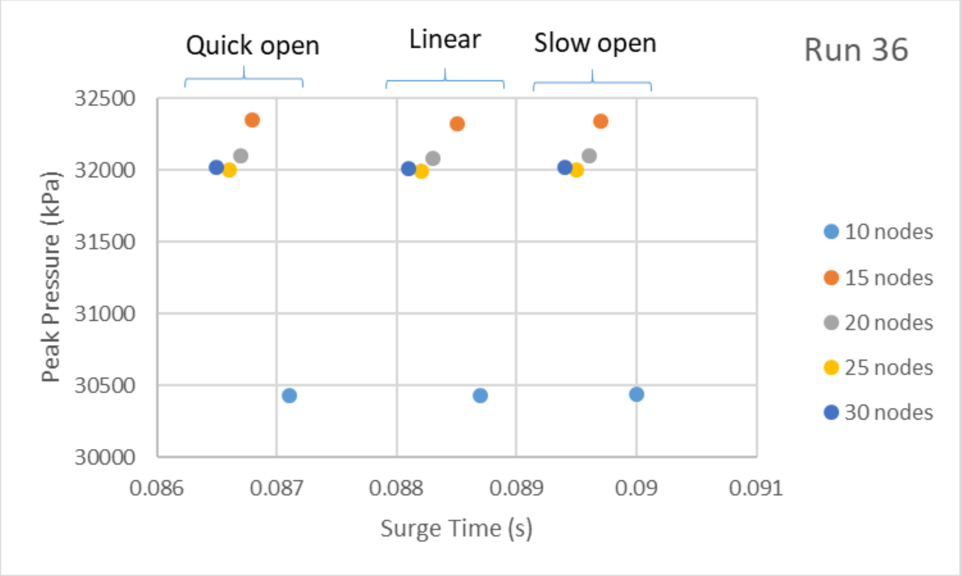
Penn State Experiment



Cv = 1.5, D = 12.7 mm, L = 2 m

P_{tank} = 2.9 MPa, P_{init} = 101 kPa

P_{meas} = 4510 kPa at 0.172 sec



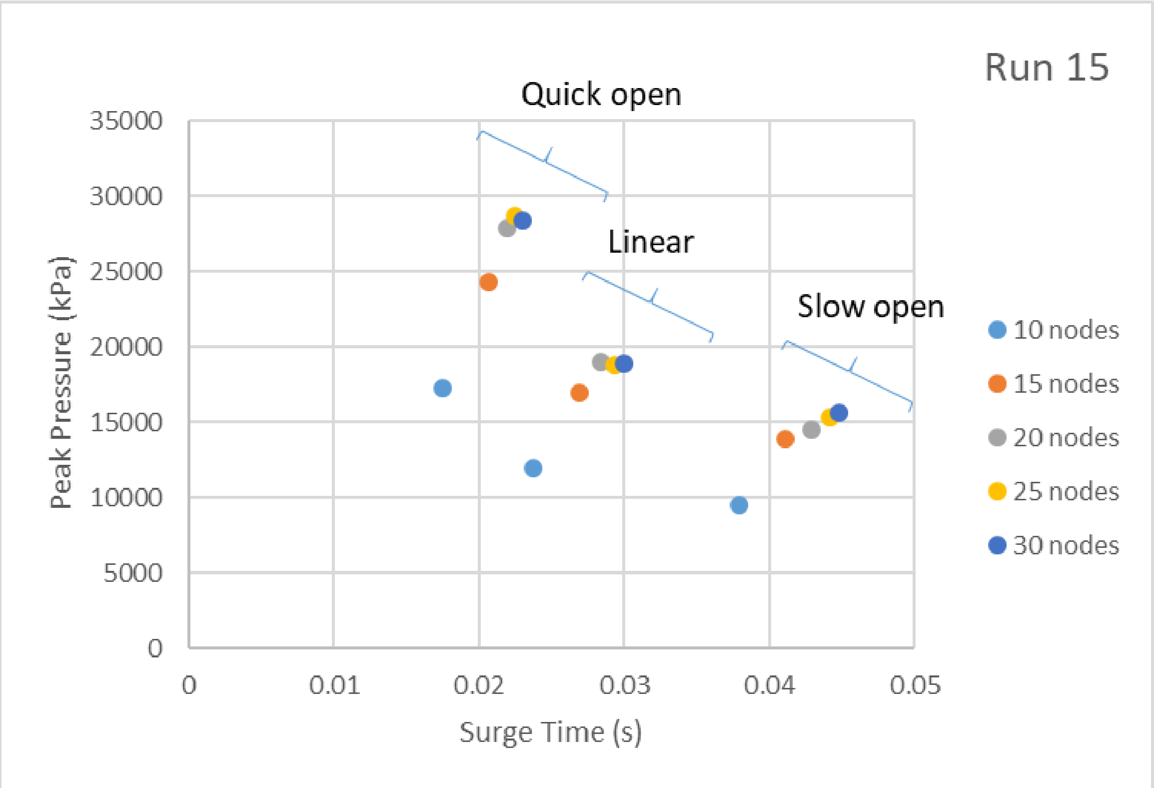
Cv = 1.5, D = 9.53 mm, L = 2 m

P_{tank} = 2.2 MPa, Pinit = 15 kPa

P_{meas} = 28,140 kPa at 0.106 sec

- Discretization study found that predicted peak pressure values slowly converged as more nodes were added to model.
- Valve history profile (linear or parabolic) usually had little effect on the peak pressure, and only a small effect on predicted time of peak pressure.

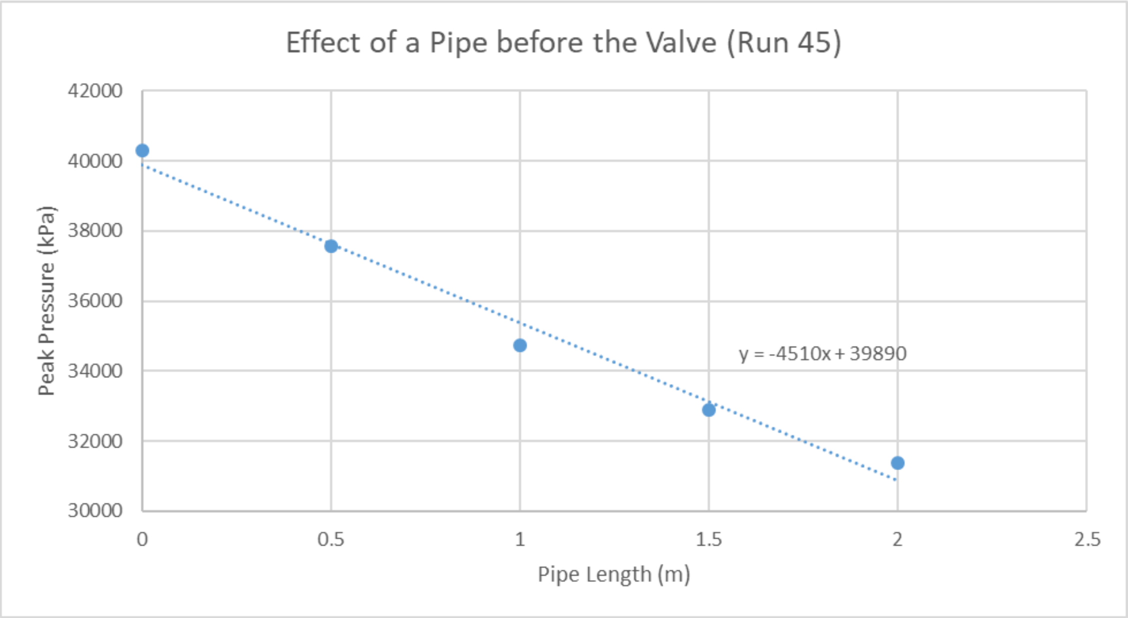
Penn State Experiment

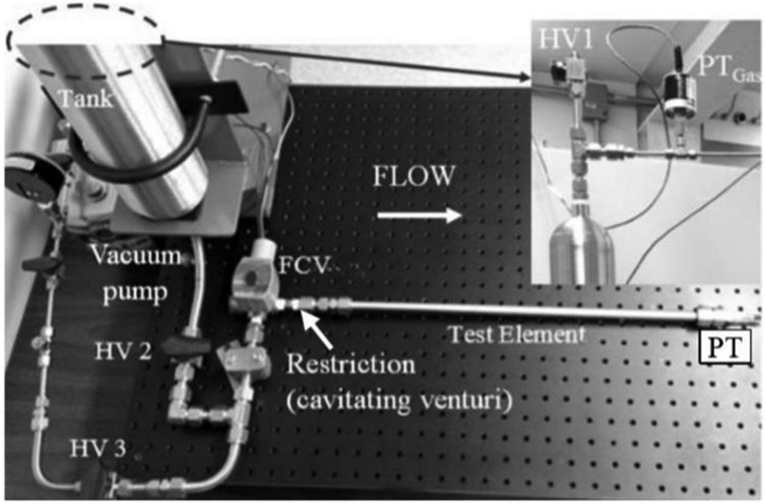


Cv = 4, D = 9.53 mm, L = 0.51 m
P_{tank} = 2.2 MPa, P_{init} = 101 kPa
P_{meas} = 11,290 kPa at 0.055 sec

- However, choice of valve opening profile did have an effect on those runs where the valve was not completely open before the pressure surge time.
  - Shorter line with narrow-or-medium diameter.
  - Moderate-or-high tank pressure
  - High Cv valve with slow opening time (0.075 s)

Penn State Experiment





Cv = 4, D = 9.53 mm, L = 2 m

P_{tank} = 2.2 MPa, P_{init} = 15 kPa

P_{meas} = 14,080 kPa

Moore et al., JSR, 2019

- Penn State paper did not provide line length and minor losses between tank and flow control valve.
- Adding an arbitrary line length between the boundary and the valve decreased peak pressure, but not enough to match data.

Discussion

- GFSSP's predictions of peak pressure during a priming event are usually either accurate or too high.
- Models of the Penn State Experiments stress the importance of the valve opening time and profile shape to the peak pressure prediction when a slow-opening valve is matched with a small volume to be filled.
- Future work:
  - More complex fluid networks
  - Effect of a cavitating venturi in the line
  - Implicit vs. explicit solution of the conservations equations

References

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