

Fluid Transient Analysis of Propellant Feedlines during a Priming Event

André LeClair, Alexandra Boehm, and
Alok Majumdar (NASA/MSFC)

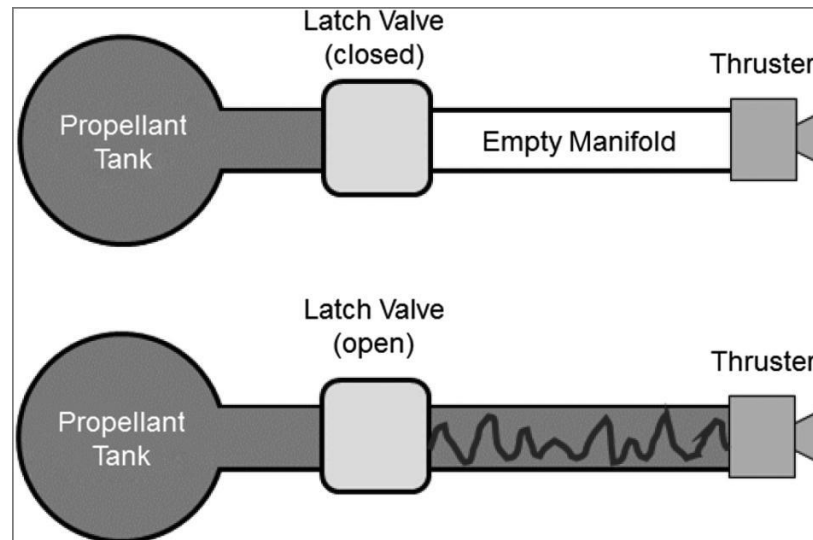


Presented By
André LeClair

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- 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.

- The velocity change when the fluid hits the dead end can cause a brief pressure surge.

- The pressure rise can be as high as:

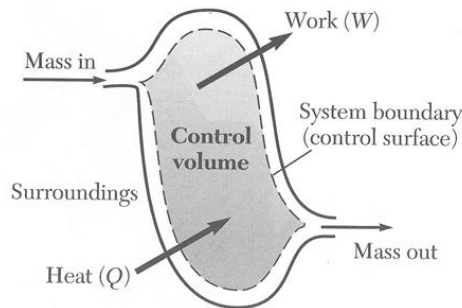
$$\Delta P = \rho c \Delta V$$

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

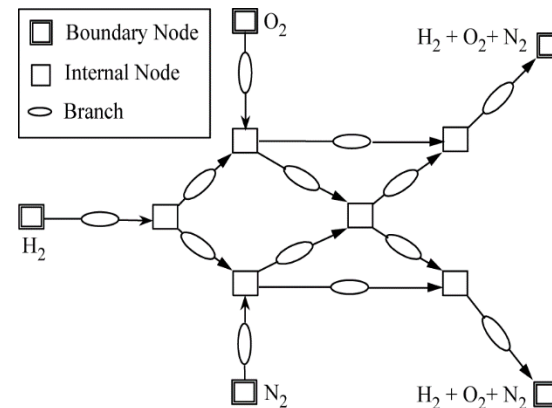
$$\Delta P = \left(1000 \frac{\text{kg}}{\text{m}^3} \right) \left(1500 \frac{\text{m}}{\text{s}} \right) \left(10 \frac{\text{m}}{\text{s}} \right) = 15 \text{ MPa}$$

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

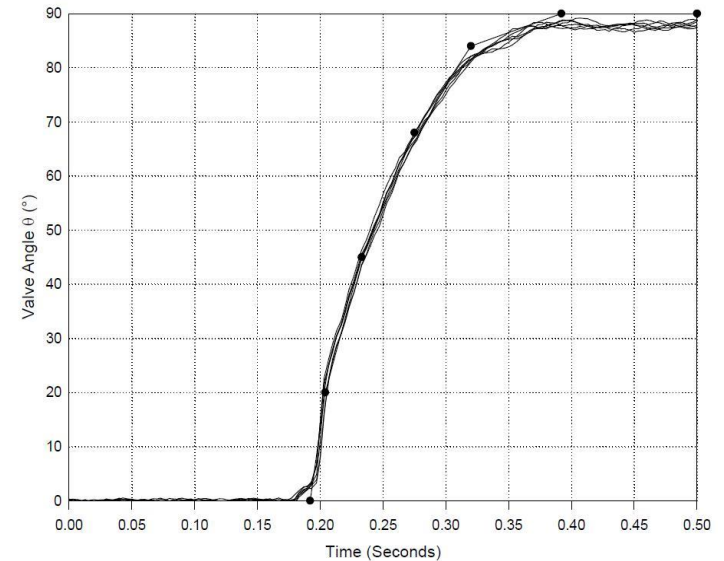
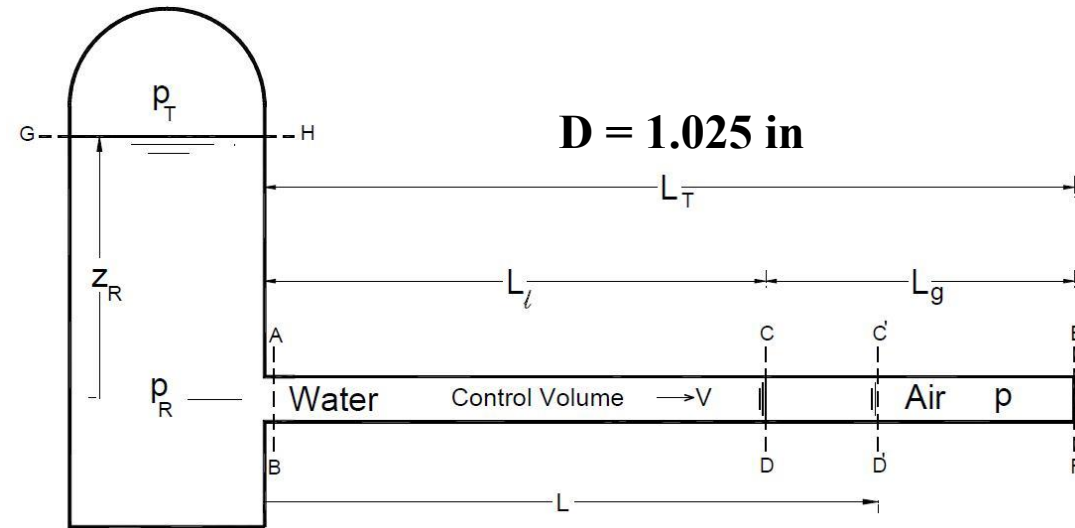
- The Generalized Fluid System Simulation Program (GFSSP) is a general-purpose computer program to calculate pressures, temperatures, and flow rates in a fluid network.
- Fluid networks are discretized into nodes and branches.
 - Mass and energy equations are solved in the nodes.
 - Momentum equation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



Control Volume Analysis



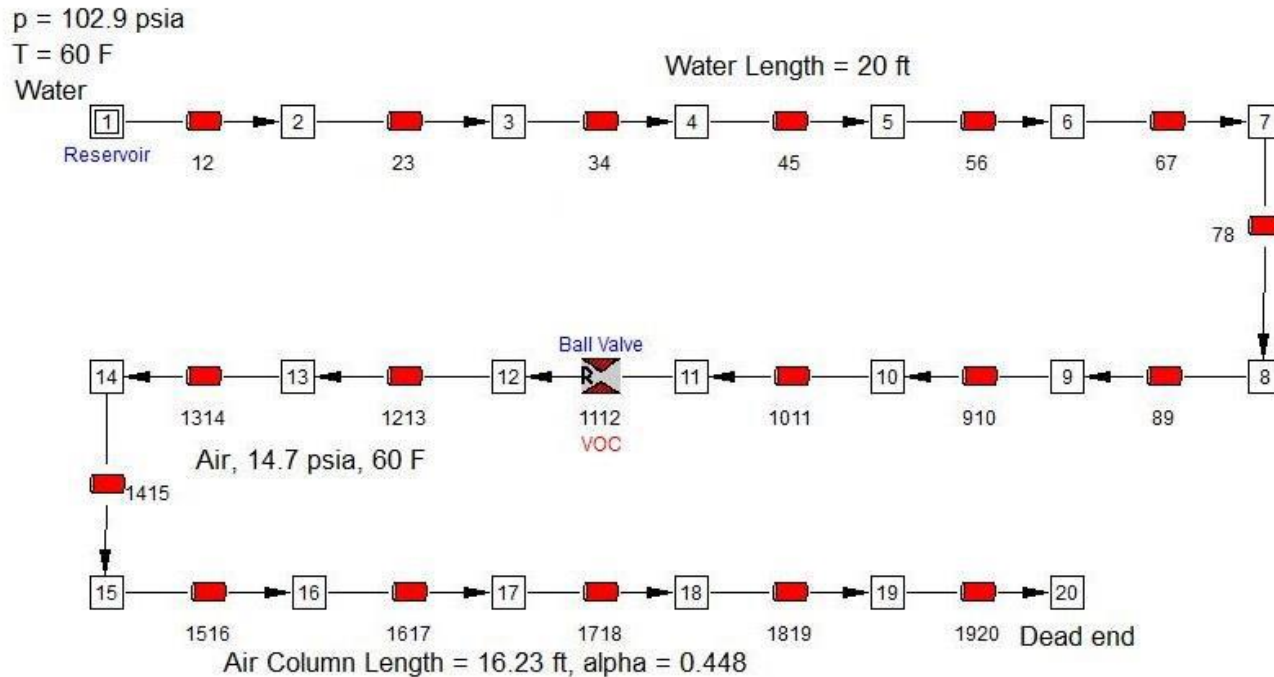
Finite Volume Analysis



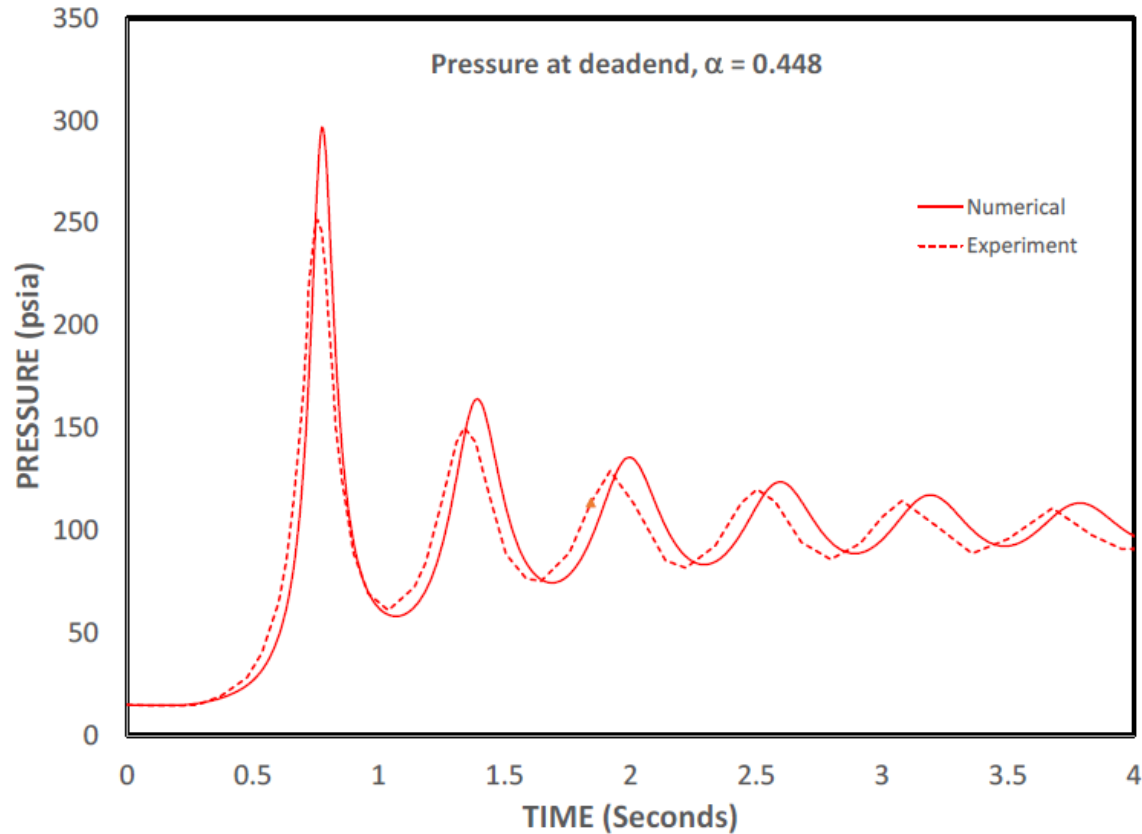
Ph.D. dissertation by N. H. Lee, 2005

Test series varied:

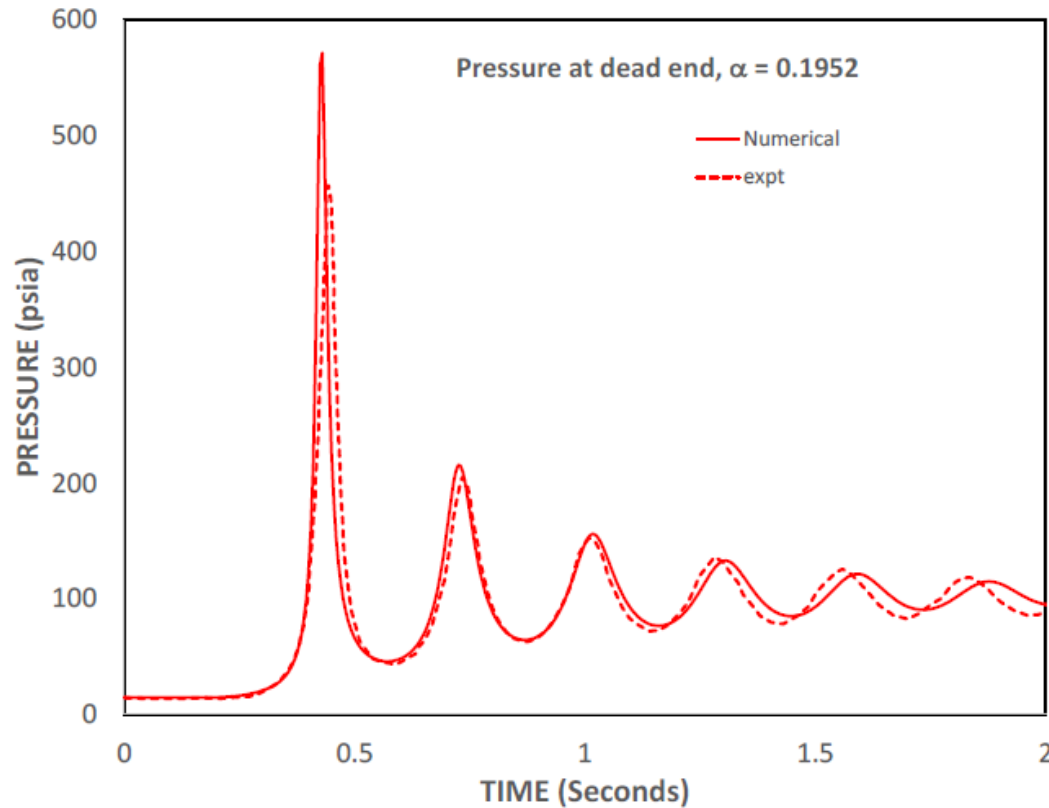
- Reservoir pressure: 2 to 7 atm
- Gas volume proportion: $\alpha = L_g/L_T$



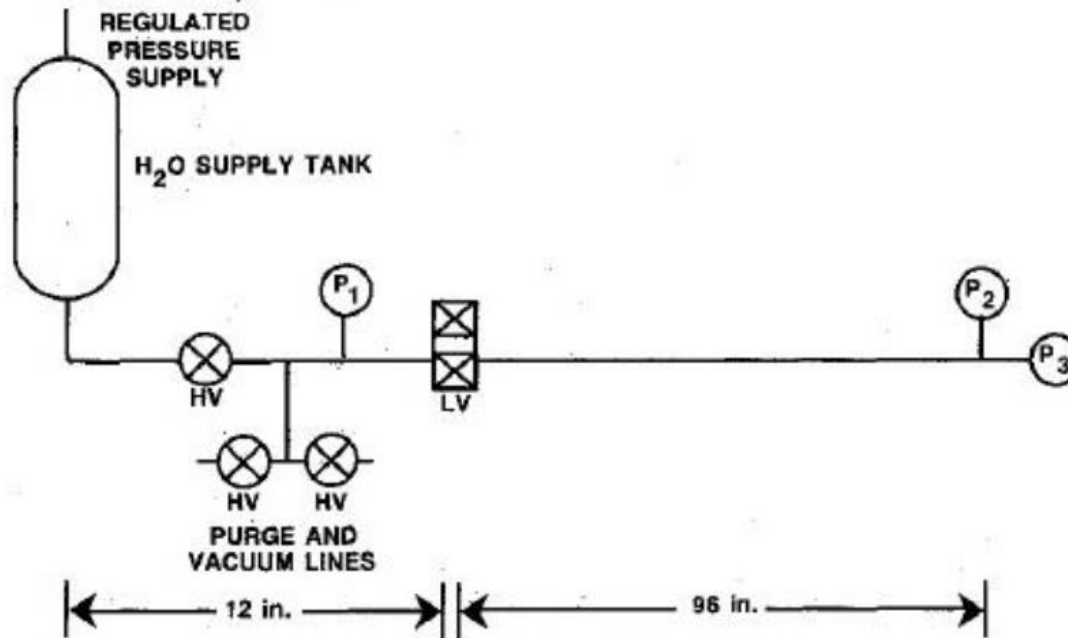
- Nodes 1-11 initially contain liquid water at 102.9 psia.
- Nodes 12-20 initially contain air (as an ideal gas) at 14.7 psia.
- A Fortran user subroutine fixes all temperatures in model at 60° F. Air temperature increase by compression is neglected.



- Predicted peak pressure is 20% higher than experimental.



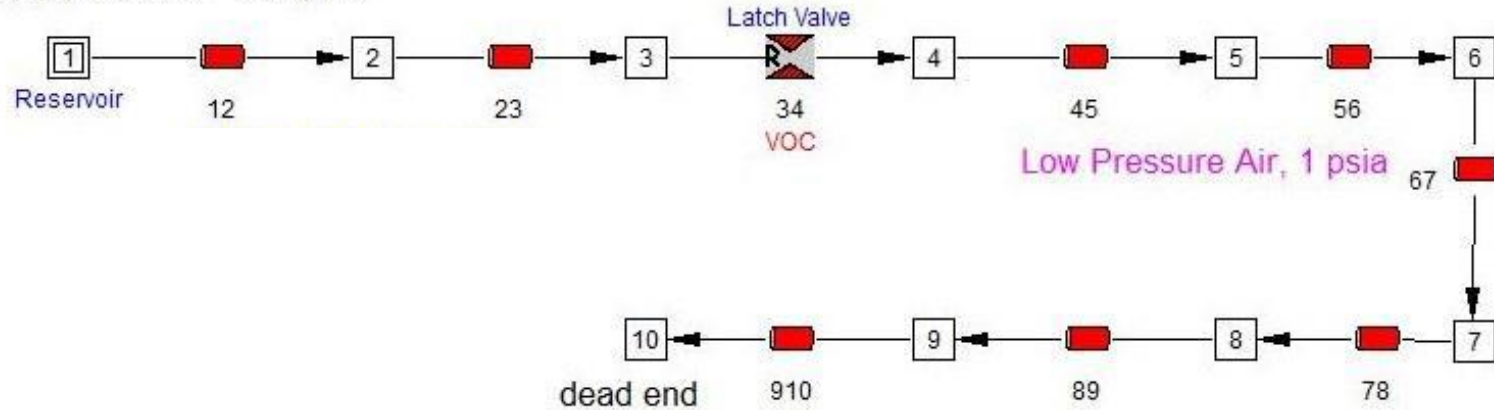
- Maximum pressure increases when trapped air length is decreased:
 - $\alpha = 0.448$, $P_{\max} = 250$ psia
 - $\alpha = 0.195$, $P_{\max} = 450$ psia



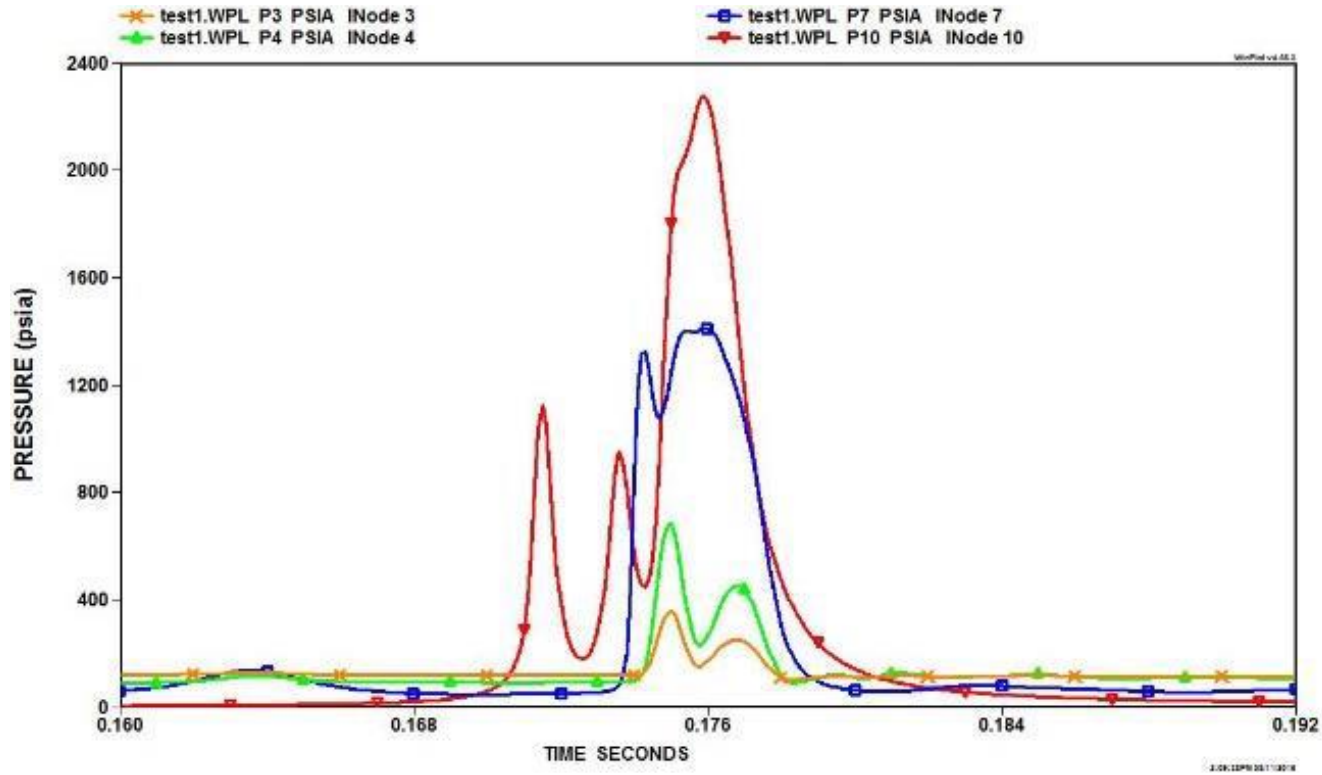
Prickett et al., 1992

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

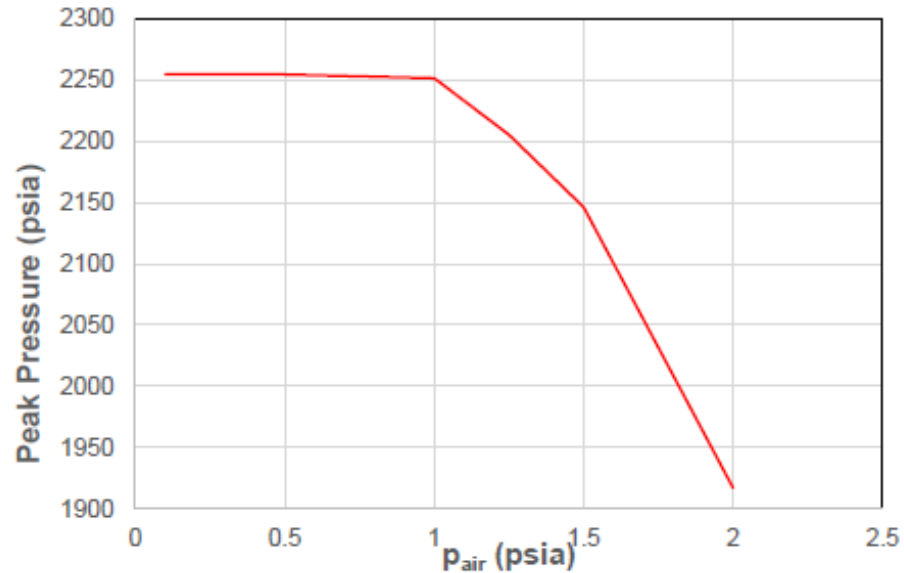
Supply pressure = 120 psia



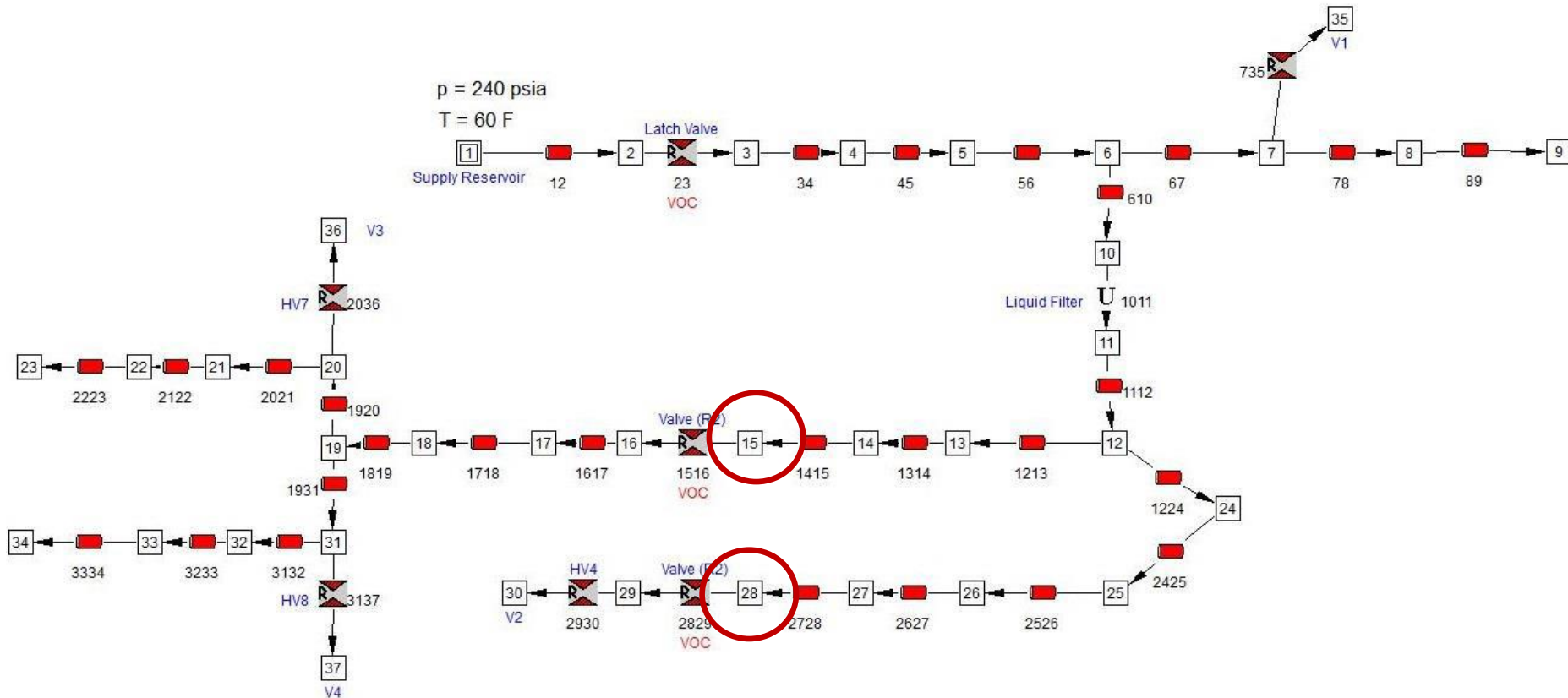
- GFSSP does not understand “empty”, so the evacuated line is initially filled with ideal gas air at low pressure.



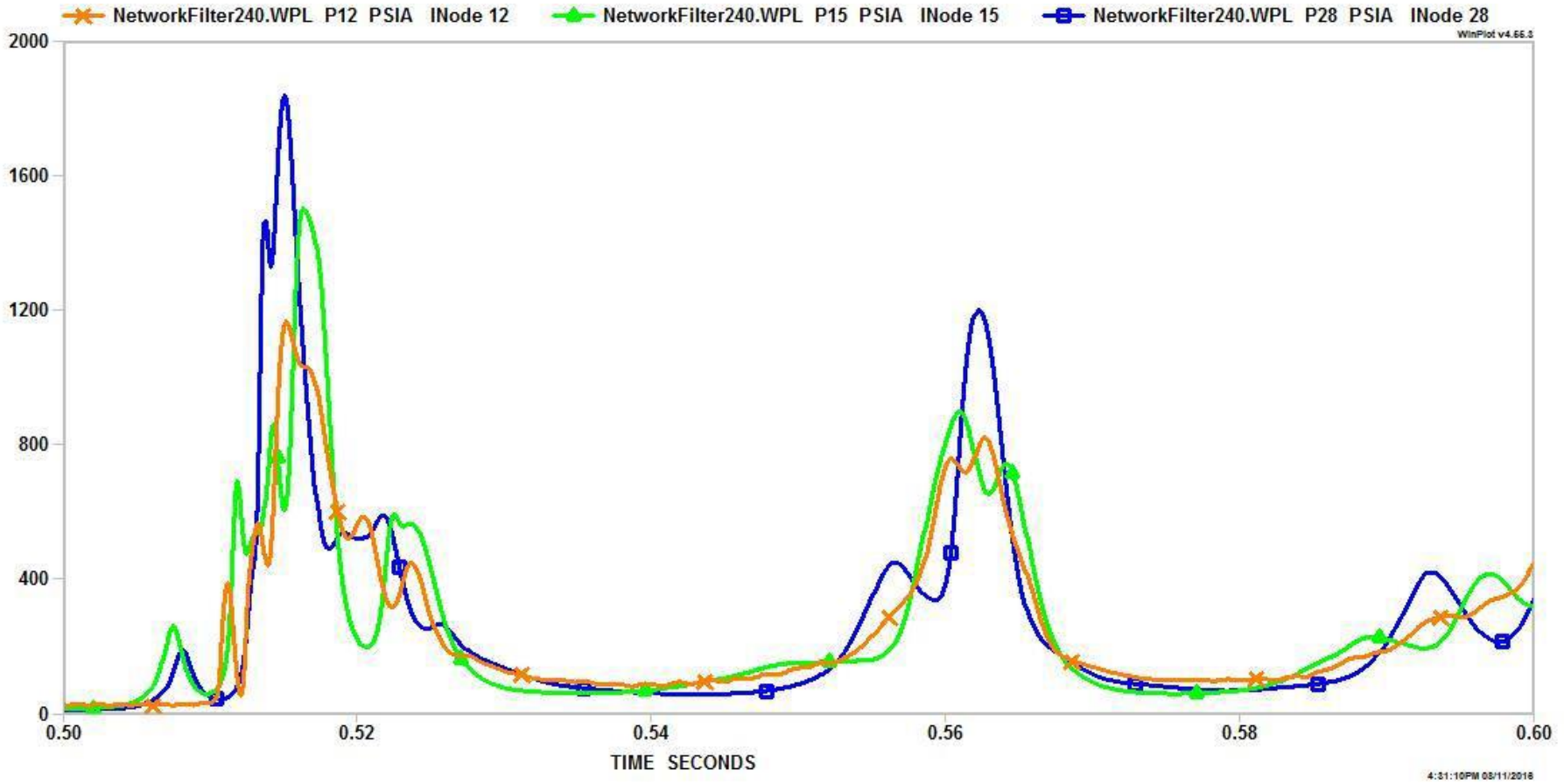
- Reported maximum pressure is 2350 psia in the dead end at 0.17 sec.
- GFSSP predicts 2279 psia at 0.176 sec.



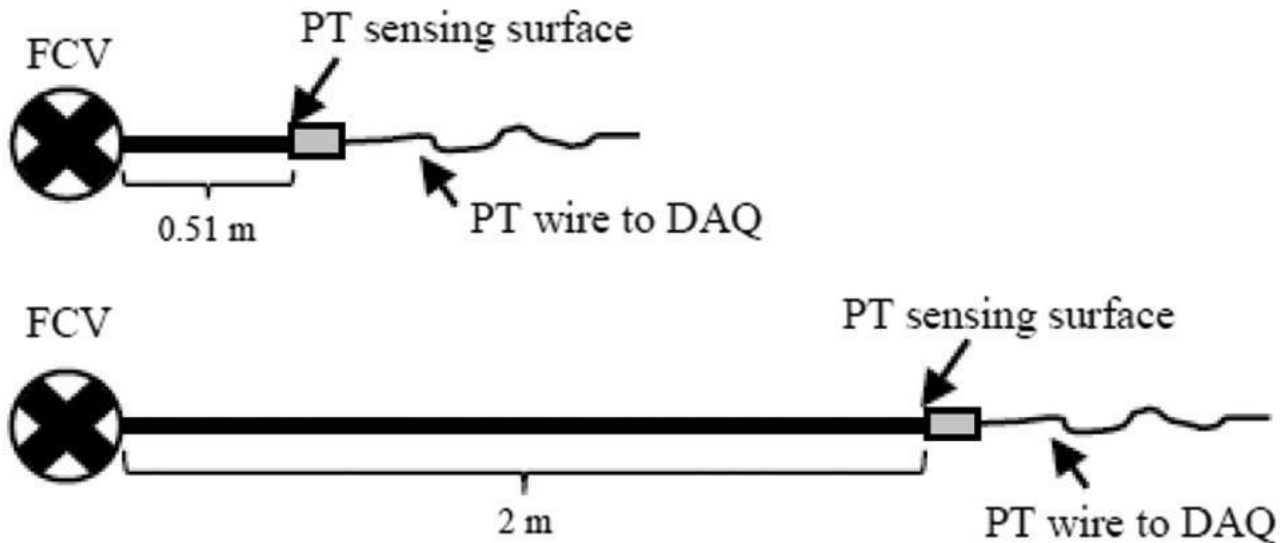
- Decreasing initial air pressure of evacuated lines increased the maximum pressure, although there was little change when $P_{\text{air}} < 1$ psia.



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



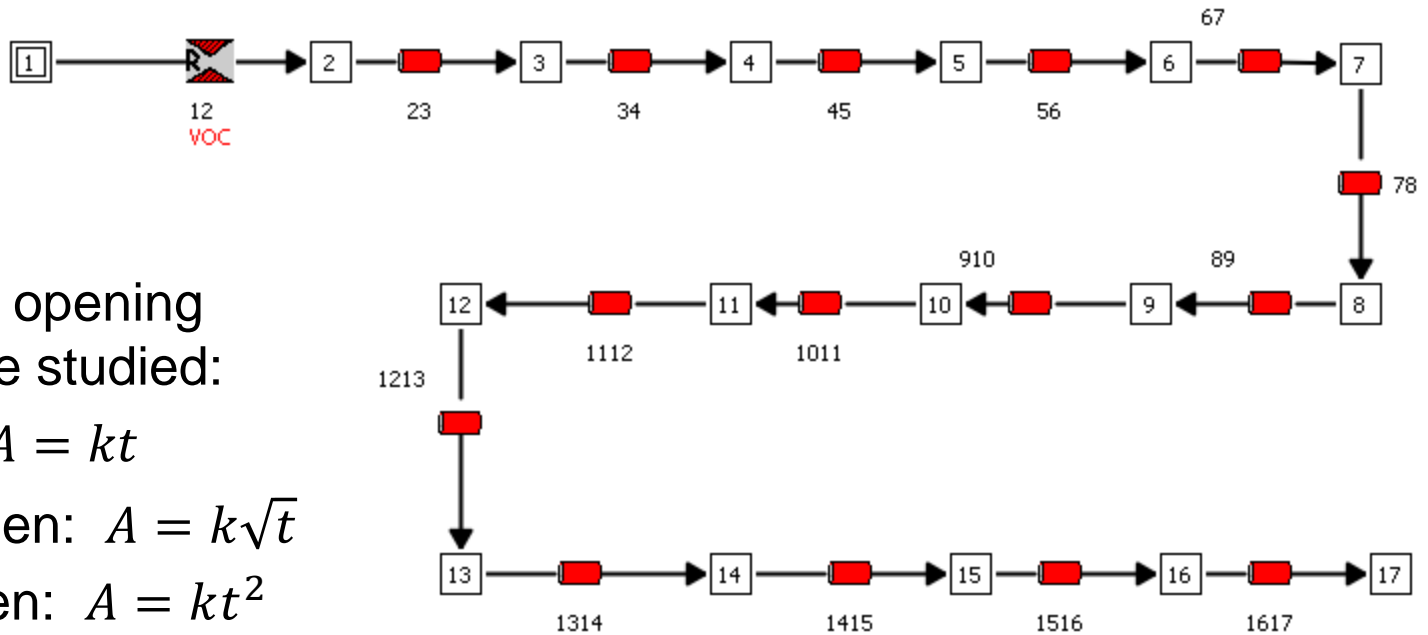
- Maximum pressure in lower branch is 1837 psia at node 28. Measured pressure at this location is 1800 psia.
- Maximum pressure in upper branch is 3500 psia at node 9. No test data were reported for this location.



Moore et al., JSR, 2019

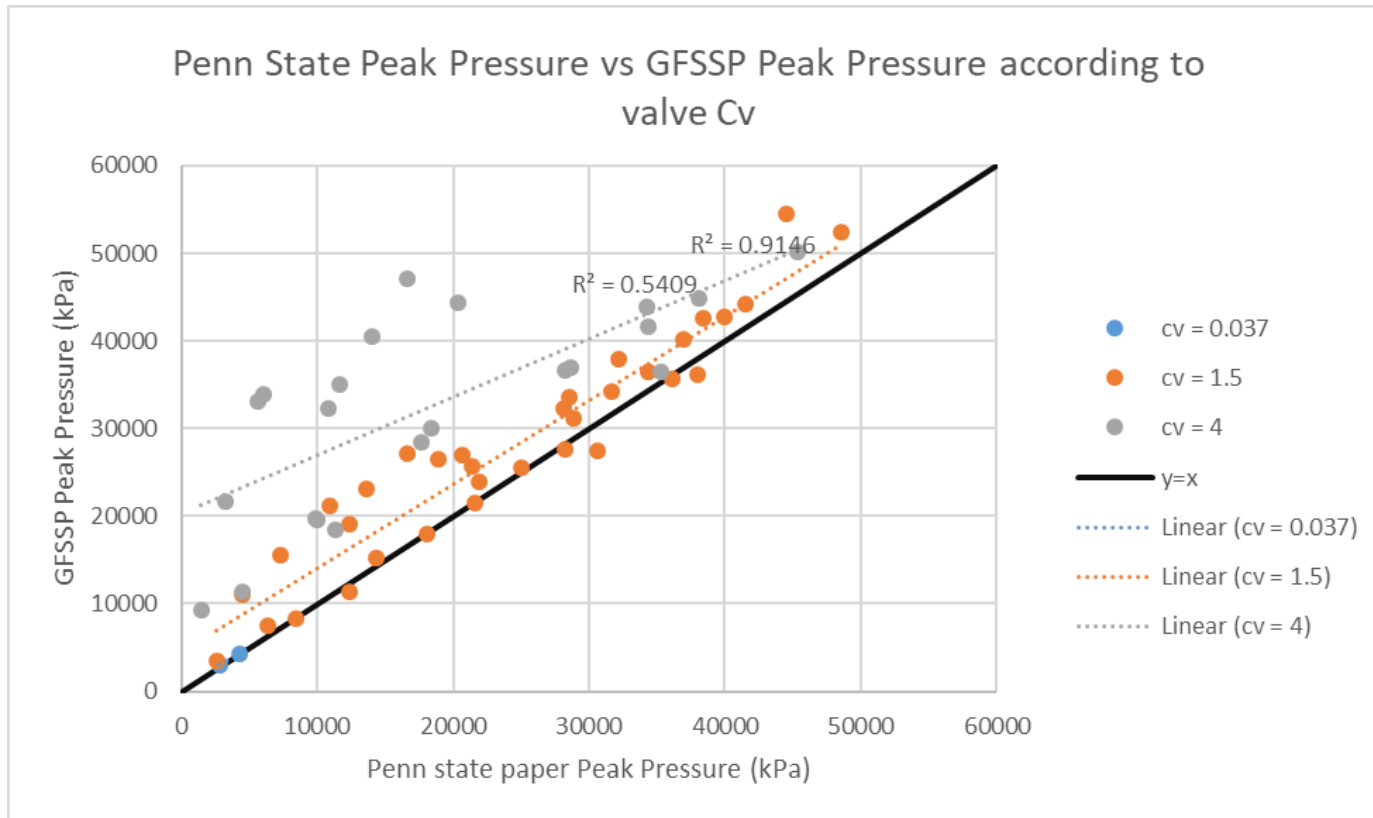
- Reservoir pressure: 1.5, 2.2, or 2.9 MPa
- Line lengths: 0.51 or 2.0 m
- Line diameters: 6.5, 9.5, or 12.7 mm
- Flow Control Valve C_v : 0.037, 1.5, or 4.0
- Initial air pressure in line: 4, 15, 101 kPa

Main Model

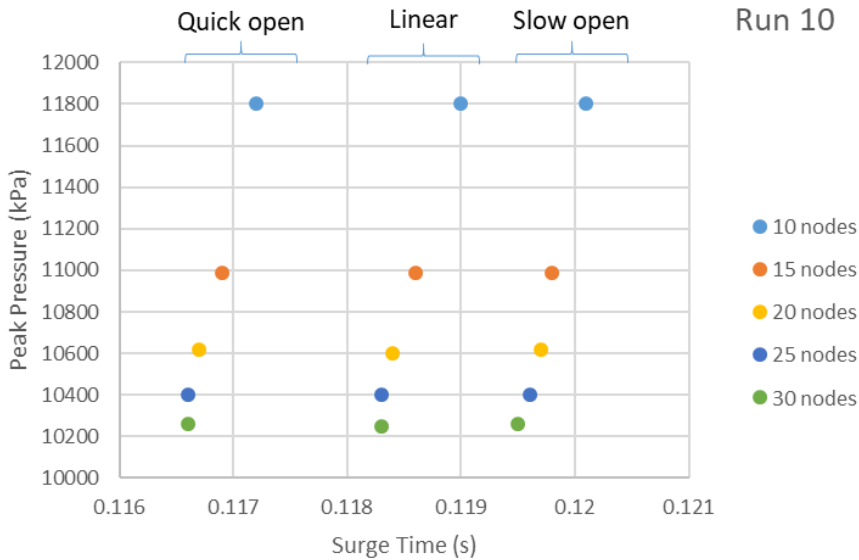


Three valve opening profiles were studied:

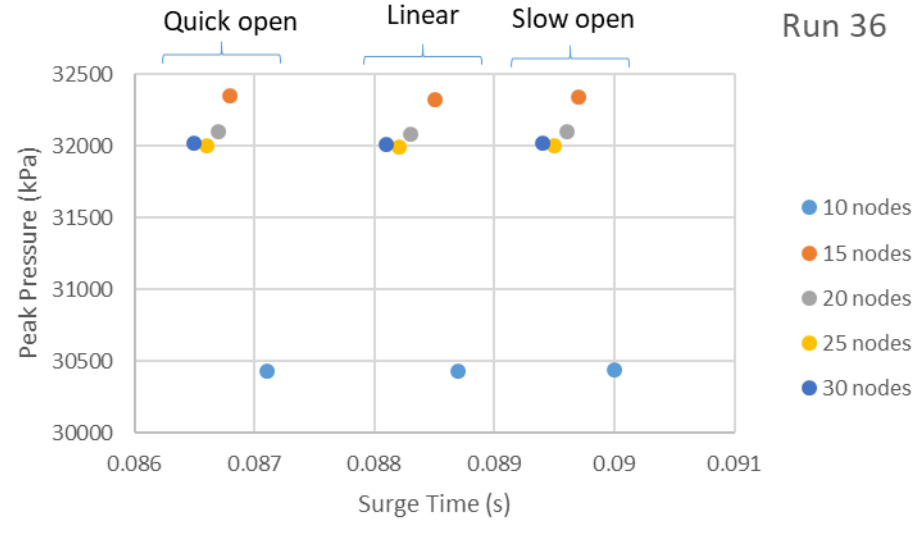
- Linear: $A = kt$
- Quick open: $A = k\sqrt{t}$
- Slow open: $A = kt^2$



- 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.

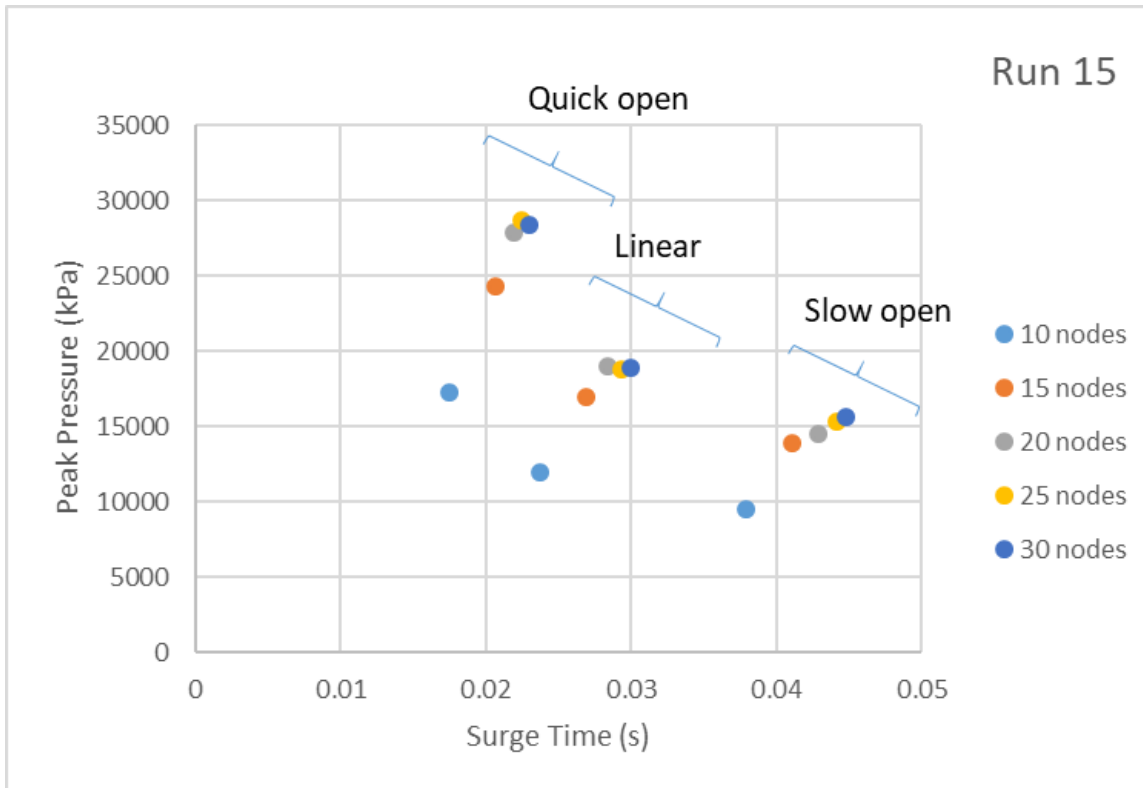


$C_v = 1.5$, $D = 12.7$ mm, $L = 2$ m
 $P_{\text{tank}} = 2.9$ MPa, $P_{\text{init}} = 101$ kPa
 $P_{\text{meas}} = 4510$ kPa at 0.172 sec



$C_v = 1.5$, $D = 9.53$ mm, $L = 2$ m
 $P_{\text{tank}} = 2.2$ MPa, $P_{\text{init}} = 15$ kPa
 $P_{\text{meas}} = 28,140$ kPa at 0.106 sec

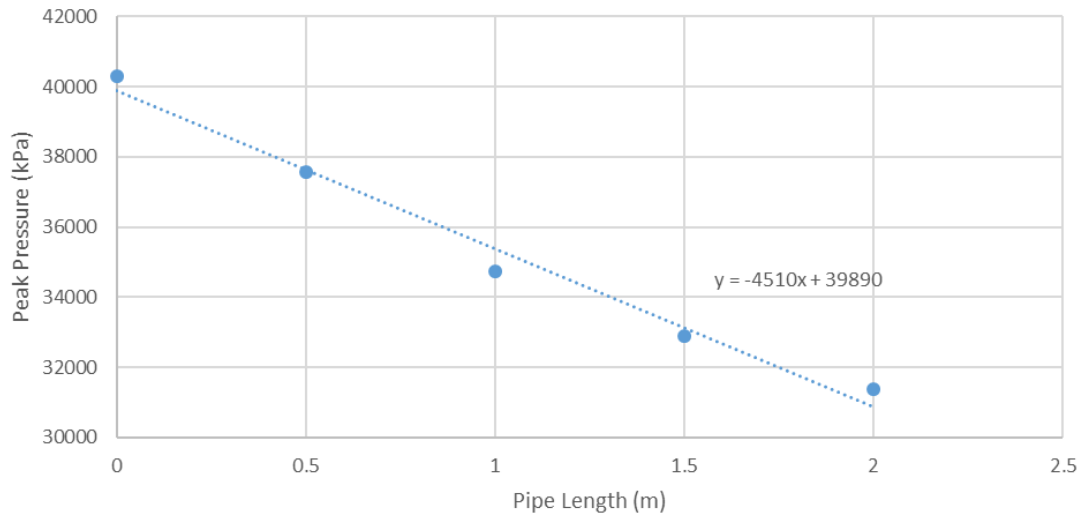
- Discretization study found that predicted peak pressure values slowly converged as more nodes were added to model.
- Valve history profile (linear or parabolic) usually had little effect on the peak pressure, and only a small effect on predicted time of peak pressure.



$C_v = 4$, $D = 9.53$ mm, $L = 0.51$ m
 $P_{\text{tank}} = 2.2$ MPa, $P_{\text{init}} = 101$ kPa
 $P_{\text{meas}} = 11,290$ 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 C_v valve with slow opening time (0.075 s)

Effect of a Pipe before the Valve (Run 45)

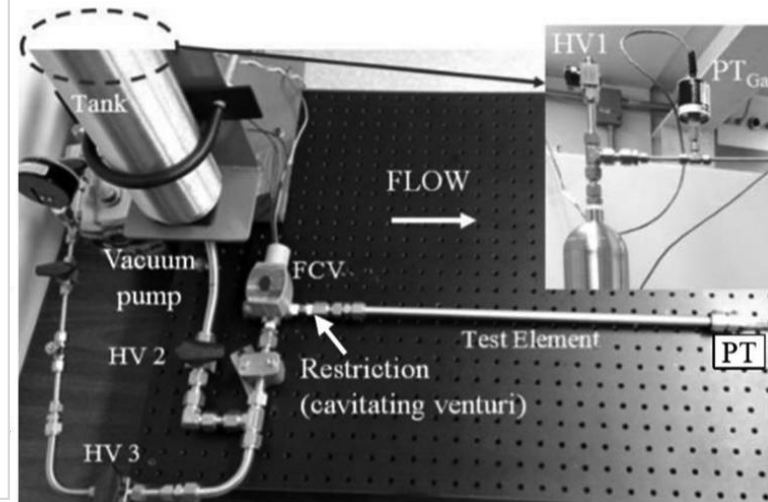


$C_v = 4$, $D = 9.53$ mm, $L = 2$ m

$P_{\text{tank}} = 2.2$ MPa, $P_{\text{init}} = 15$ kPa

$P_{\text{meas}} = 14,080$ kPa

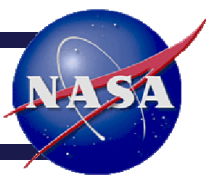
- Penn State paper did not provide line length and minor losses between tank and flow control valve.
- Adding an arbitrary line length between the boundary and the valve decreased peak pressure, but not enough to match data.



Moore et al., JSR, 2019



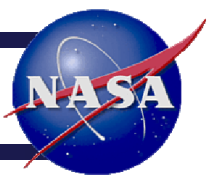
Discussion



- 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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