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Coupled Fluid-Structure Interaction Simulation of the Opening of the Target Rock Vacuum Relief Valve

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ABSTRACT

This paper discusses a study that was performed to optimize the design of the Target Rock vacuum relief valve for nuclear power plant applications. The valve design optimization was performed using the CFD-ACE+ software package. A key portion of the study was a fully coupled transient simulation of the valve opening that was performed using CFD-ACE+ and MDICE. The moving body simulation was set up to mimic field conditions during the opening of the valve. It was performed to ensure that the valve would perform its required function.

Keywords: Fluid Structure Interaction, Relief Valve, Multiphysics Simulation, CFD-ACE+

INTRODUCTION

Nuclear power plant emergency cooling systems serve the essential purpose of providing cooling for the reactor core in the event of failure of normal cooling systems. The most severe form of failure is a loss of coolant accident in which a pipe rupture causes a breech of the primary containment system. In this case, the function of emergency cooling systems is to provide as high a flow rate and volume of water as possible to the core to prevent fuel element damage. A common source of water for emergency cooling is on-site fresh water storage tanks. The large flow rate of water from the storage tanks during emergency cooling draws a vacuum within those tanks.

Modern nuclear power plant storage tanks are generally structurally optimized for internal pressure, water weight and postulated earthquake loadings using finite element analysis (FEA) techniques. This results in lighter weight, and lower cost tanks. The consequence of this optimized design is that the tanks have less margin that can be relied upon to provide a factor of safety for off-design conditions. For these optimized tanks, buckling under evacuated conditions is a real possibility. Rather than modifying the structural design for evacuated operation, tank manufacturers equip the tanks with one or more vacuum relief valves. The vacuum relief valves must pass a flow rate of air that is sufficient to prevent the pressure in the tank from decreasing beyond a fixed level that was used in the structural design of the tank.

This paper discusses the virtual prototyping efforts that were performed by the authors on the recently designed Target Rock vacuum relief valve. These efforts were broken into two phases. The first phase consisted of a series of axisymmetric simulations using the CFD-ACE+ software package to ensure that the conceptual valve design met the flow rate requirements of the water storage tank design. This allowed the selection of an adequate valve design before a physical prototype was manufactured, which saved considerable time and monetary resources.

The second phase of the effort involved the performance of transient, moving body simulations to study the valve opening characteristics. This valve in particular is designed for a narrow operating range. These simulations allowed detailed examination of valve dynamic motions. The tendency for the valve to flutter under expected flow conditions was studied.

VALVE GEOMETRY and FUNCTION

The Target Rock vacuum relief valve is a reverse seated, spring loaded valve that opens when the differential pressure between the air outside the tank and inside the tank exceeds a set pressure. The valve consists of a body that bolts to a flanged opening on the top of a water storage tank. The disk is located below the valve seat. The valve is held closed by a spring that acts against the top of the valve stem. The vacuum relief valve is shown in Figure 1, below.

The vacuum relief valve simulations were performed using an axisymmetric model. This required the assumption that the posts that support the valve yoke from the valve body do not significantly affect the flow. The results discussed later in this

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paper show that to be a reasonable assumption.

During normal plant operation, the vacuum relief valve remains in the closed position. When the tank is used as a source of water for emergency cooling, pumps begin to draw water from the tank. This results in a partial vacuum being drawn in the tank. As the differential pressure between outside air at ambient pressure and the inside of the tank increases, a net force acts on the valve disk. The force causes the spring to compress, which allows the valve to open. At full flow, the valve is designed to pass a mass flow rate of air that is sufficient to prevent buckling collapse of the tank.

This valve is required to begin to open at a differential pressure of 0.25 psi (1723 Pa), and reach the fully open position at a differential pressure of 0.5 psi (3445 Pa). The pressure change in the tank from ambient to a partial vacuum of 0.5 psi (3445 Pa) is expected to take 20 seconds. The valve is required to pass a flow rate of 690 scfm (0.3256 m^3/sec) at a differential pressure of 0.5 psi.

AXISYMMETRIC VALVE DESIGN STUDIES

The design of the Target Rock vacuum relief valve evolved during the design study that was performed. The initial valve design was different than the final design shown in Figure 1. The initial design is shown in Figure 2, below.

The sections that follow describe the valve models that were developed in more detail. The simulation results and the design decisions that were made based on those results are also discussed.

INITIAL VALVE DESIGN

The initial proposed design for the Target Rock vacuum relief valve was somewhat different from the final design shown in Figure 1. The valve disk was significantly thinner, and the clearance from the disk to the valve wall in the open position was less. The initial design is shown in Figure 2.

Some key dimensions of the valve are:

Inlet diameter:	3.75"
Outlet diameter:	4.03"
Disk full opening:	0.875"
Body length:	8.00"

The valve design was developed in SDRC IDEAS. The valve geometry information was saved in IGES format files and read into the CFD-GEOM geometry creation and grid generation software package. The lines and curves that define the axisymmetric shape of the valves were extracted from the 3D IGES geometry information. These lines and curves were used to develop the hybrid mesh that is shown in Figure 3.

The grid was used to perform a steady state simulation of air flow through the valve at the full open position. The working fluid was air, and the flow was considered turbulent and compressible. Constant pressure boundary conditions were applied both upstream and downstream of the valve. The differential pressure across the valve was 0.5 psi (3445 Pa).
Figure 4 shows the steady state flow pattern through the valve computed using CFD-ACE+. The simulation was run using the flow and turbulence modules. The air was treated as compressible. The simulation results show a significant recirculation region behind the valve disk. There is a smaller recirculation near the inlet of the valve.

The computed mass flow rate through the valve was 0.3717 kg/sec. For air at standard temperature and pressure, this corresponds to a volumetric flow rate of 643 scfm (0.3034 m^3/sec). This is 7% less than the required flow rate of 690 scfm.

REDESIGNED VALVE

The valve was redesigned based on the insights gained from the CFD simulation results. The key insights that were gained were:

? The valve area should be opened up to allow more flow to pass at a lower differential pressure.

? The large recirculation region behind the valve disk should be eliminated by re-shaping the disk. This also allows the valve disk to become thicker, which simplified the structural design of the disk.

? The shape of the valve body upstream of the disk should be modified to try to minimize the tendency for a recirculation to form. The strategy that was adopted was to keep the top surface of the disk and the inner wall of the valve roughly parallel.

The redesigned valve is shown in Figure 1, and Figure 5, below. The valve is shown with the disk in the closed position, but simulations were run with the disk 1.5" open. The valve body was lengthened to accommodate a larger disk travel.

Some key dimensions of the valve are:

Inlet diameter:	5.00"
Outlet diameter:	4.03"
Disk full opening:	1.5"
Body length:	10.50"

Figure 6 shows the hybrid grid that was generated for the axisymmetric flow simulation of the redesigned valve.

Figure 7 shows the steady state flow pattern through the redesigned valve with the disk 1.5" open. The reshaping of the disk and body results in much smoother flow through the throat and outlet regions of the valve. There is a small flow recirculation in the wake of the valve disk, but the recirculation near the throat of the valve has been eliminated.

More significant is that the redesigned Target Rock vacuum relief valve passes a greater flow rate of air at the required 0.5 psi (3445 Pa) differential pressure than the initial valve design. The computed flow rate through the valve is 850 scfm (0.401 m^3/sec). This flow rate exceeds the required flow rate of 690 scfm by 23%.

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RELIEF VALVE TESTING

All pressure relief devices, which conform to ASME Boiler and Pressure Vessel Code (sections I, III, VIII), require capacity certification by The National Board of Boiler and Pressure Vessel Inspectors. Capacity certifications are performed with air, steam or water. The Target Rock vacuum relief valve was installed on a large tank for the test (the volume allows time to gather the necessary data during test).

Capacity certification consists of flowing the valve up to the accumulation pressure (in this case 0.5 psi), and recording the flow through the valve. With air, the flow measurement is made with a sonic nozzle upstream of the test valve. Since The National Board does not have the capability to flow a valve with a vacuum, the inlet was pressurized to the required differential pressure. A large test can was fitted over the valve to allow pressurized inlet air to flow into the valve. The outlet was open to the atmosphere.

The air flow rate through the valve measured by the National Board was 880 scfm. The computed flow rate through the valve was 850 scfm, an error of ~3%. The rated flow rate for the Target Rock vacuum relief valve is 790 scfm, since the National Board requires 10% margin between the measured and rated capacity of relief valves.

DYNAMIC VALVE OPENING SIMULATON

One of the limitations of the testing performed by the National Board of Boiler and Pressure Vessel Inspectors is that the test is focused on measuring the flow rate at the required differential pressure. The test is performed such that the pressure at the inlet to the valve is rapidly increased, and held constant for the duration of the test. The valve, therefore, opens rapidly to the maximum open position.

In the actual plant application, the expected duration of the pressure ramp across the valve disk is much slower, on the order of 20 seconds. A dynamic simulation was performed to examine the movement of the valve disk as it opens. In particular, valve flutter while open was a concern, since flutter can lead to excessive wear and failure.

The dynamic simulation were performed using the MDICE code along with CFD-ACE+. MDICE is a program that enables the performance of simulations in which there is significant movement of a part of the simulation domain. MDICE includes tools for Chimera overset meshing and six degree of freedom (6DOF) motion.

In this case CFD-ACE+ was used to perform the flow simulation (calculation of pressures and velocities), and MDICE was used to provide a communication linkage between the flow solver, the 6DOF motion module, and the Chimera overset mesh module. The problem domain was broken into two computational grids that interact. One grid included the valve disk and a small region of fluid around it as shown in Figure 8. The other grid included the air outside the tank, inside the tank and within the valve body, as shown in Figure 9.

The coupled simulation was run with a differential pressure across the valve that increased from 0 psi to 0.5 psi (3445 Pa) over the span of 20 seconds. The CFD-ACE+ flow calculations determine the fluid forces acting on the valve disk at each time step. The 6DOF model considers the simultaneous action of the fluid force, the spring force and gravity on the valve disk to determine the disk motion. The spring force model includes an initial (preload) force of 23.57 N (5.3 lbs), a spring constant of 87.56 N/m (0.5 lbs/in), and linear motion constraints. The motion constraints prevent the disk from moving upward from its initial position, and moving downward more than 0.38 m (1.5 in).

Figure 10 shows the flow through the valve at several times during the valve opening process. The simulation shows that the valve does have a tendency to open fully, and then partially close before remaining fully open. The valve position is shown as a function of time in Figure 11.

CONCULSIONS

This study has demonstrated the power of even relatively simple CFD simulation as a design tool. The axisymmetric simulations that were performed clearly saved time and money in the design process. The simulation of the initial valve design showed that the design would not pass an adequate flow rate at the design differential pressure. Perhaps more importantly, the ability to visualize the flow patterns allowed the design team to make informed decisions about what design changes would have the biggest impact on the flow rate through the valve. The final design of the Target Rock vacuum relief valve clearly reflects the insights gained from the initial valve simulations. The accuracy of axisymmetric simulation is shown by the small difference between the flow rate computed using CFD-ACE+ and measured by the National Board of Boiler and Pressure Vessel Inspectors.

The moving body simulations performed using MDICE and CFD-ACE+ were used to assess the dynamics of the valve opening process. The valve initially burps, a process of rapid opening, followed by partial closing. This is followed by the disk opening fully and remaining open. This behavior is typical for a relief valve subject to a slow pressure ramp. The simulation also demonstrated that once open, the valve is not prone to flutter.

ACKNOWLEDGEMENTS

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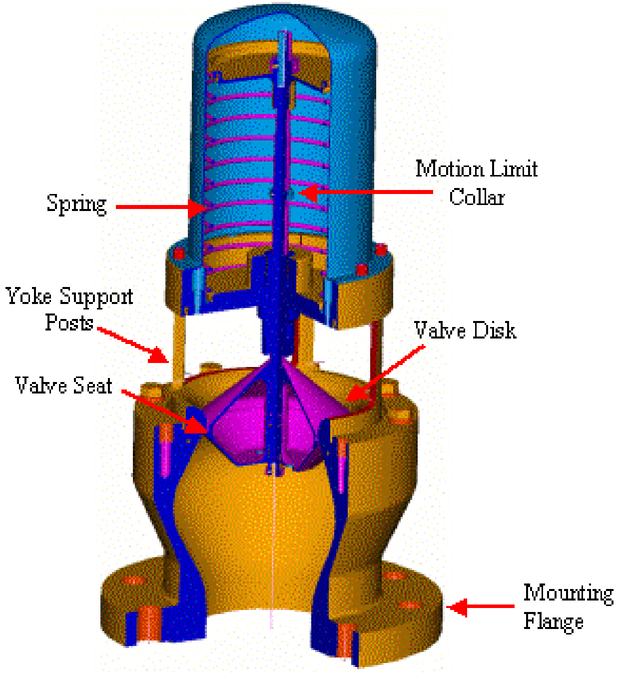

Figure 1. Target Rock Vacuum Relief Valve Geometry

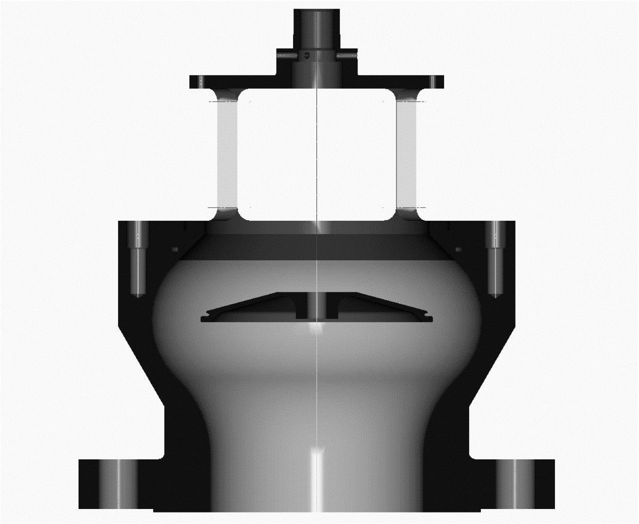

Figure 2. Initial Vacuum Relief Valve Design

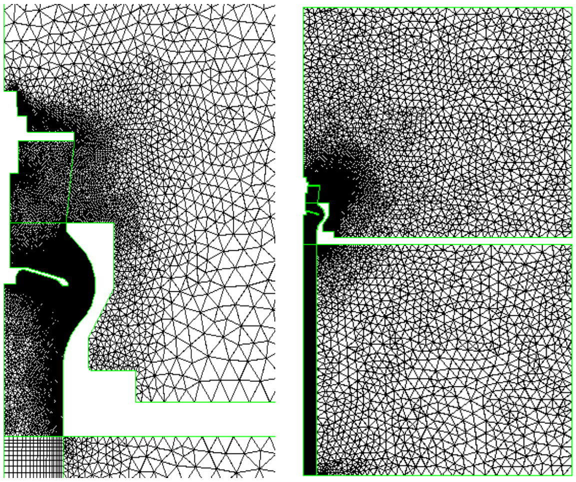

Figure 3. Original Valve Design Hybrid Grid

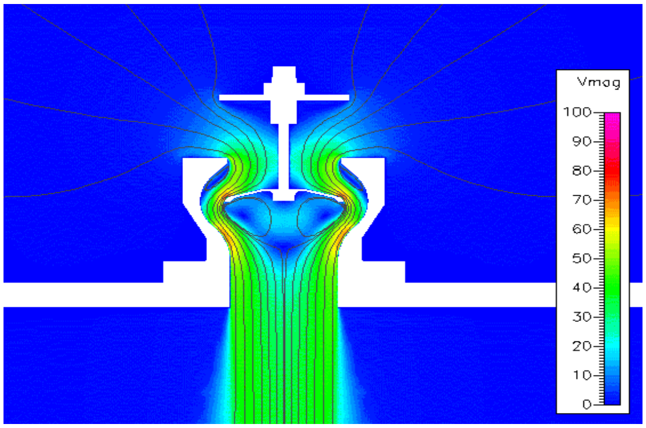

Figure 4. Flow Streamlines for Original Valve Design

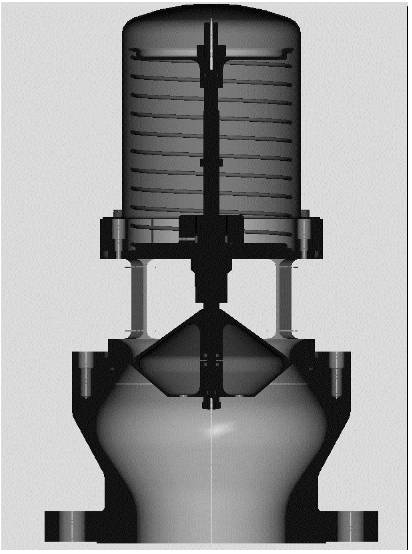

Figure 5. Redesigned Vacuum Relief Valve

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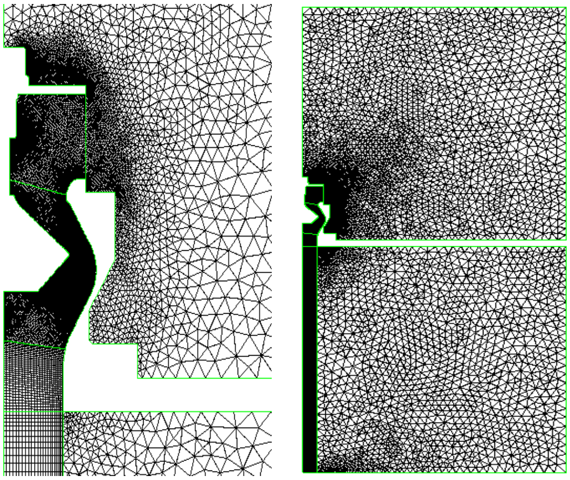


Figure 6. Redesigned Valve Hybrid Grid - 1.5" Full Open

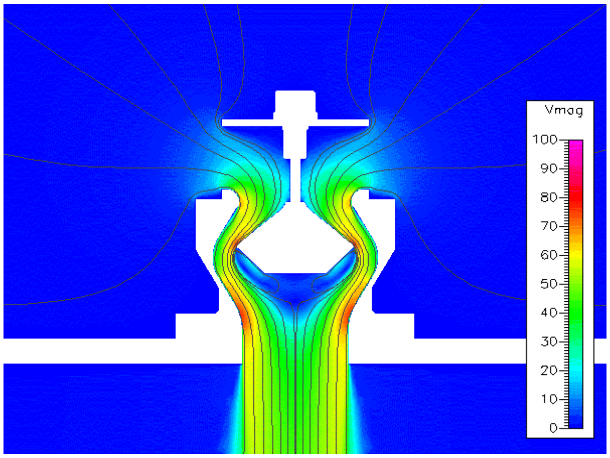


Figure 7. Flow Streamlines for the Redesigned Valve

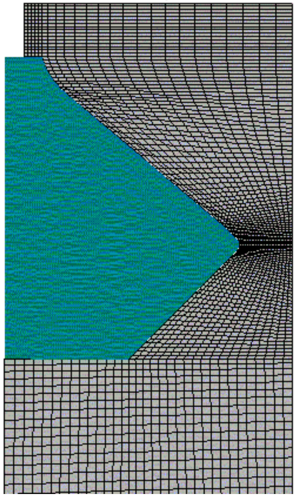


Figure 8. Valve Disk Grid

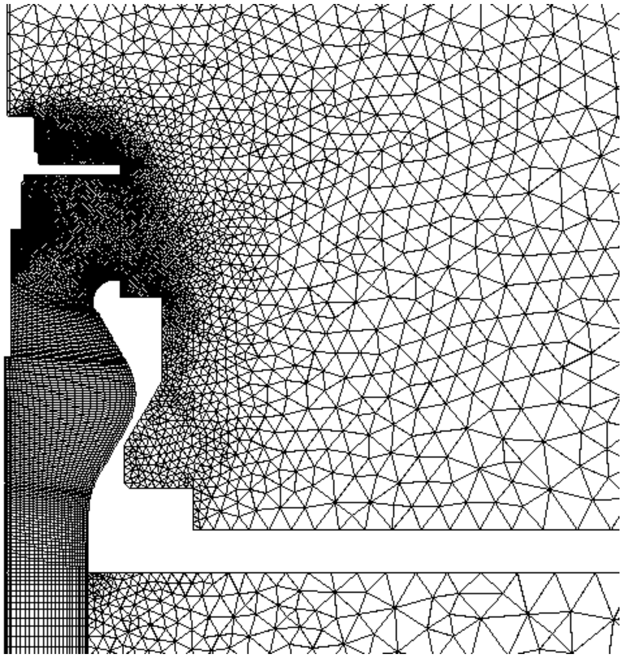
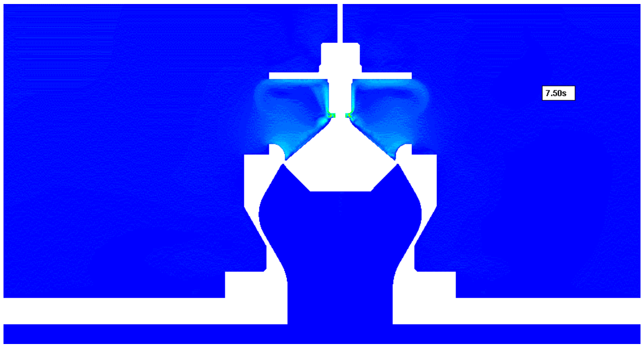


Figure 9. Valve Body Grid (Partial View)



a) Valve Position at t = 7.5 seconds

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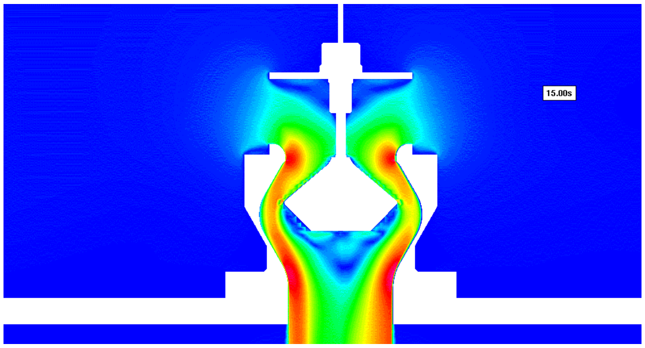
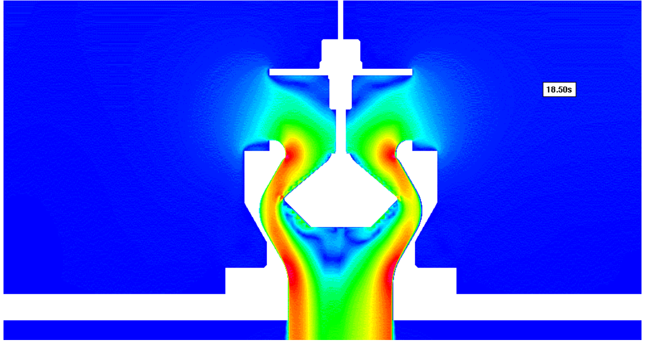
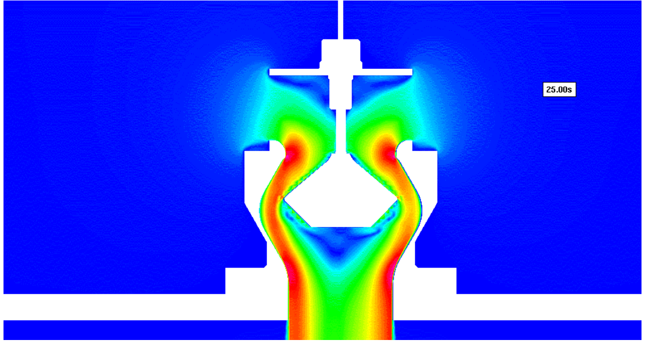


b) Valve Position at t = 15.0 seconds



c) Valve Position at t = 18.5 seconds



d) Valve Position at t = 25.0 seconds

Figure 10. Flow Through the Valve at Different Intervals During the Valve Opening Process

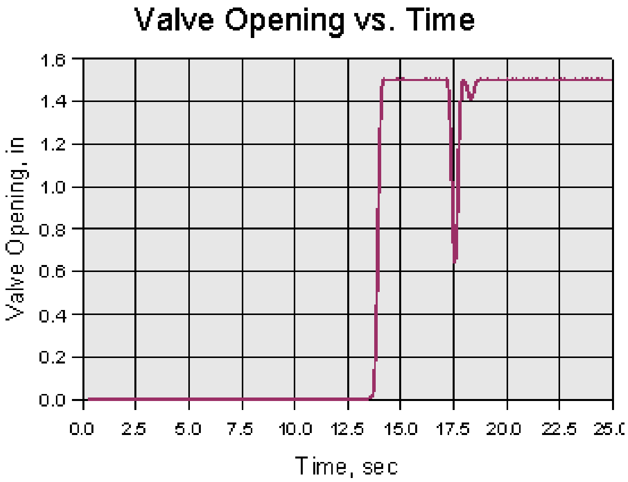


Figure 11. Valve Opening V. Time

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