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Performance Analysis of Gas Purging Operation in Volume Control Tank

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Abstract

The Volume Control Tank (VCT) is designed to provide for control of hydrogen concentration in the coolant and the means for the removal of radioactive gases by purging the accumulated gases in the tank. NRC notified the licensees that the charging pump with the minimum bypass line could be damaged by the gas binding in the suction piping. It is caused by the evolution of hydrogen gas at the point where the local pressure is less than the saturated pressure. The purging operation results in the pressure reduction of the VCT. The computer code is developed to evaluate the capacities and set points of the pressure regulating valves which are installed on the gas control system of the VCT. In order to exclude the hydrogen evolution during the purging operation with the supply capacity of 20 SCFM, the set points of the regulating valves for nitrogen gas and hydrogen gas shall not be higher than 45 psig and 30 psig, respectively. The capacities shall be more than 25 SCFM for nitrogen gas and 55 SCFM for hydrogen gas to get the adjustable set point of 20 through 50 psig. To minimize the purging time and the wasted gas mass during the purging operation, the set point shall be reduced as low as possible within this set point range.

1. Introduction

The VCT of the Korean Standard Nuclear Plant (KSNP) is designed to collect letdown water from the primary coolant system, to provide for control of hydrogen concentration in the reactor coolant and to provide an adequate NPSH for the charging pump. Also, the VCT provides the means for removal of unwanted gases such as fission gases, O_2, H_2, or N_2 from the VCT or the reactor coolant by purging the accumulated gases in the VCT which has hydrogen and nitrogen gas supply lines and a vent line to the gaseous waste management system. Figure 1 shows the configuration of gas control system in VCT. The pressure regulating valves (PRVs) are installed on the gas supply and vent line and maintain the VCT pressure during all the operating modes including the purging operation. The purging operation results in the pressure transient in the tank. During the purging operation, the tank pressure depends on the capacity and set point of the supply and vent pressure regulating valves.

The hydrogen is normally used for the cover gas in the VCT; thus, the letdown flow is saturated with hydrogen in the VCT. If the local pressure between the VCT and charging pump suction nozzle or in the re-circulation line of the charging pump is less than the VCT pressure, the dissolved hydrogen will evolve into the gas and it will not dissolve in solution immediately even if the downstream pressure is higher than VCT pressure. The hydrogen gas will be gathered and become binding at the highest point [1]. Nuclear Regulatory Commission (NRC) alerted licensees to potential problems resulting from hydrogen transport from the VCT and accumulation in emergency core cooling system piping [1]. Licensee Event Report (LER) reported that at least one charging/high pressure safety injection pump might not have been available to provide emergency core cooling due to an intrusion of gas into the suction of the pumps [2]. The source pressure of the charging pump suction is important to prevent the hydrogen gas from evolving out of coolant.

In this study, the PRVs, the associated piping and the pressurized VCT are modeled, and a computer code is developed to analyze the pressure transient of the mixture gas in the tank, the supplied gas mass, and the purging time of the tank during the purging operation. The optimum set point and capacity of the PRVs are determined to prevent gas from evolving at the suction of the charging pump while providing the required hydrogen concentration in the reactor coolant during the normal operation.

2. Modeling for the Gas Control System of the Pressurized Volume Control Tank

2.1 Basic assumptions

The properties of the mixture gas are obtained on the assumption that the gases behave as an ideal gas and are completely mixed in the tank and the vent line. No interaction between the gas and liquid is considered during the purging operation. The maximum operable tank level, 60% is assumed to minimize the waste of gases and purging time.
The gas flow rate through the valve and the piping are calculated based on the assumption that the gas flow at the given time step is at a steady state.

2.2 System modeling

The system modeling of the VCT is shown in Figure 2. It consists of the VCT, two pressure regulating valves, and related piping. The downstream pressure regulating valves are installed on the supply and vent lines. The downstream pressure regulating valve supplies or vents the gas whenever the downstream pressure is lower than the set point. But the supplied or vented mass depends on the downstream pressure as well as the upstream pressure.

A. Tank modeling

The tank is divided into two regions, one for mixture gas and the other for the sub-cooled liquid. The gas region contains hydrogen and nitrogen mixture and is connected to a gas supply line and a vent line. The liquid region is connected to the letdown line and the charging pump suction line.

Considering the gas volume with the supplied gas flow and vented gas flow, the mass conservation for each component of gas mixture becomes

$$\frac{dm_k}{dt} = W_{sg,k} - W_{vg,k}$$

Considering the liquid volume with the letdown flow and charging flow, the mass conservation equation becomes

$$\frac{dm_l}{dt} = W_{L/D} - W_{C/G}\,, \qquad \rho\,\frac{dV_l}{dt} = W_{L/D} - W_{C/G}$$

The total pressure of the mixture gas in the tank is given by

$$P_{n+1} = \frac{\left(\sum m_{k,n+1}\right) R_{n+1} T}{\left(V_g - \left(V_{l,n} + \frac{(W_{L/D} - W_{C/G})\Delta t}{\rho}\right)\right)}$$

where

$$R_{n+1} = \Re\left(\sum_k \frac{y_{k,n+1}}{M_k}\right), \qquad y_{k,n+1} = \frac{m_{k,n+1}}{\sum m_{k,n+1}}$$

B. Pressure regulating valve modeling

The flow rate of a compressible fluid varies as a function of the ratio of the pressure differential to the absolute inlet pressure ($\Delta P/P_{up}$), designated by the symbol x. Because of compressibility, gases and vapors expand as the pressure drops at the vena contracta, decreasing their specific weight. To account for the change in specific weight, an expansion factor, Y, is introduced into the valve sizing formula. The following equation is used to calculate the mass flow rate through the regulating valve [3].

$$W = 19.3 F_p C_v P_{up} Y \sqrt{\frac{xM}{TZ}}$$

a) In order to model the change of opening fraction due to the regulated pressure, the valve sizing coefficient is given by

$$Cv = Cv_{\max} \sqrt{\frac{P_D{}^2 - P_S{}^2}{P_{SS}{}^2 - P_S{}^2}}$$

b) The expansion factor Y accounts for the change in density of a fluid as it passes from the valve inlet to the vena contracta and for the change in area of the vena contracta as the pressure drop is varied (contraction coefficient) [3].

$$Y = 1 - \frac{x}{3F_k x_T} \qquad \text{(Limits } 1.0 > Y > 0.67\text{)}$$

Chocked flow occurs when x reaches the values of $F_k\ x_T$. The value of x at the inception of the choked flow varies from the valve to valve. This factor is a function of the valve geometry. For maximum accuracy, the terminal pressure drop ratio, x_T must be established by using the test procedures [3]. From the data in Reference 4, it is recognized that the terminal pressure ratio is proportional to the form loss coefficient (K-factor) of the valve. The x_T value for the globe valve with the K-factor (form loss factor) of 1.1 through 6.8 is 0.70 - 0.75 and the value for the multi-stage under-seat valve with the high K-factor value is about 1. The Cv value of regulating valve is very low and K-factor is very high in comparison with the globe valve. Therefore, it is assumed that the terminal pressure ratio of regulating valve is 1, which corresponds to that for the multi-stage under-seat valve.

c) Valve sizing coefficients are determined from tests run with the valve mounted in a straight run of pipe which is the same diameter as the valve body. If the process piping configurations are different from the standard test manifold, the apparent valve capacity is changed. The effect of reducers and increasers can be approximated by the use of the piping geometry factor, F_P. F_P can be theoretically calculated by the following equation [3,4];

$$F_P = \left(\frac{\sum KCv}{890 d^4} + 1 \right)^{-1/2}$$

In case that the maximum capacity and the valve sizing coefficient are given or known at the design condition, the F_P value can be directly calculated by the following equation[3,4];

$$F_P = \frac{W}{19.3 Cv P_{up} Y \sqrt{\frac{xM}{TZ}}}$$

C. Piping modeling

The flow of gases in short pipe closely approximates adiabatic condition. Investigation of the complete theoretical analysis of adiabatic flow has led to the following equation including the correction factor for the expansion effect of the compressible fluid [5].

$$W = 0.525 Y d^2 \sqrt{\frac{\Delta P}{K \bar{V}_1}}$$

The expansion factor, Y, is determined from the chart [5] by using the pressure drop ratio, $\Delta P/P_{up}$.

2.3 Steady state flow through piping-PRV-piping flow path (MASSGAS)

In order to solve for the flow rate in the piping line which is composed of three nodes (piping 1, PRV, and piping 2), the following equation applies;

$$W_{pipe1}(P1, P2) \equiv W_{PRV}(P2, P3) \equiv W_{pipe2}(P3, P4)$$

The calculation of the balanced flow rate in the piping system is carried out using the incremental search method.

3. Verification of MASSGAS

Commercial program, Flo-series (Version 5.0), is used to verify the calculation of the steady state flow through the pipe. Figure 3 shows the mass flow rates and expansion factor of air in case of the downstream pressure of 14.7 psia . The evaluated pipe has the piping length of 300 feet with 1 inch NPS and Sch 40S. The Flo-series mass flow rates is greater than those predicted from MASSGAS (computer code developed for this study). If the Flo-series mass flow rates are multiplied by the expansion factor, the modified flow rate coincides with MASSGAS flow rates as shown in the figure. It shows that the Flo-series does not take account of the expansion factor and MASSGAS performs the more reasonable calculation.

4. Analysis and Results

The normal operating pressure of VCT is 20 psig through 50 psig to ensure the adequate hydrogen concentration in the reactor coolant. The purging operation is divided into two cases. One purges the hydrogen gas by the nitrogen gas and the other purges the hydrogen gas by the fresh hydrogen gas. Prior to the plant startup, the nitrogen gas in VCT is purged by hydrogen. This purging operation is not considered in this study because it is not predicted to result in severe pressure transients.

4.1 Purging hydrogen gas by nitrogen gas

Figure 4 shows the tank pressures during purging the hydrogen gas in VCT by the nitrogen gas with supply capacity of 20 SCFM. The tank pressure is radically decreased to the minimum and then increased to the equilibrium point where the supplied gas flow rate is equal to the vented gas flow rate. The initial pressure reduction is caused by the greater vented flow rate than the supplied flow rate. The vent flow rate is affected by the tank pressure and the average molecular weight of the mixture gas. Generally, the gas with the greater molecular weight results in the lower volumetric flow rate at the same condition. While the hydrogen gas is being purged by nitrogen gas, the average molecular weight is increased and the vent flow rate is decreased. It results in the minimum tank pressure for the nitrogen purging. The suction pressure of the charging pump is higher by about 20 psi than the VCT pressure due to elevation difference between the water level in VCT and the charging pump and frictional loss of suction piping at the maximum charging flow condition of 132 gpm. The saturated pressure means the gas pressure saturated in VCT and is assumed to be the initial VCT pressure. Figure 5 shows the suction pressures and the saturated pressures during the purging operation. The set point above 45 psig results in the lower suction pressure than the saturated pressure corresponding to the set point. To exclude the gas evolution during purging the hydrogen gas in VCT with the supply capacity of 20 SCFM, the set points of the nitrogen supply PRV shall not be higher than 45 psig. Therefore, the recommended set point range of the nitrogen supply PRV is 20 – 45 psig. Figure 6 shows the purging time and the minimum mass required to purge the VCT gas by 80 % (volume percent) with the supply capacity of 20 SCFM. The lower set point results in the less wasted mass and the less purging time.

4.2 Purging hydrogen gas by fresh hydrogen gas

Figure 7 shows the tank pressures during purging the hydrogen gas in VCT by the fresh hydrogen gas with supply capacity of 20 SCFM. The tank pressure is continuously decreased to the equilibrium point since the molecular weight is not changed during the purging operation. The continuous pressure reduction is caused by the difference between the vent flow rate and the supplied flow rate. The decreasing tank pressure reduces the vent flow rate and increases the supplied flow rate. Therefore, the descent rate of pressure is getting lower to the equilibrium point. Figure 8 shows the suction pressures and the saturated pressures during the purging operation. The set points above 30 psig results in the lower suction pressure than the saturated pressure. To exclude the gas evolution during purging the hydrogen gas in VCT with the supply capacity of 20 SCFM, the set points of the nitrogen supply PRV shall not be higher than 30 psig. From figure 8, the recommended set point range of the hydrogen supply PRV is 20 – 30 psig when the hydrogen gas is supplied with the capacity of 20 SCFM.

4.3 Relation between set point and capacity of PRV

In order to investigate the relation between the set point and the capacity of the PRV, the tank pressure and suction pressure were evaluated for the various capacities. Figure 9 shows the acceptable set point ranges to exclude the gas evolution during the purging operations by the nitrogen gas and the hydrogen gas at the given supply capacity. Because of the vented rate difference between the hydrogen gas and nitrogen gas, the allowable maximum set point of the supply PRV is different with each other. In order to keep the set point range of 20 – 50 psig, the capacities of the supply PRVs shall not be less than 25 SCFM for nitrogen gas PRV and 55 SCFM for hydrogen gas PRV. The set point and capacity shall be located within the window as shown in figure 9.

5. Conclusion

In this study, the possibility of the hydrogen gas evolution, the supplied gas mass and the purging time are evaluated while the VCT in CVCS is purged by the hydrogen gas and nitrogen gas. The set point of the pressure regulator valve on the supply line affects the purging time, supplied gas mass, and the suction pressure of the charging pump. The lower set point results in the shorter purging time, the less supply mass and the less pressure transient at the suction line of charging pump for the purging operation. Regarding the gas evolution, the supply capacity of the PRV results in the wider range of the acceptable set point.

When the supply capacity is 20 SCFM, the recommended set points for the nitrogen supply PRV and for the hydrogen supply PRV are 20 – 45 psig and 20 – 30 psig, respectively.

If the higher set point is required, the capacity of the PRV shall be increased. In order to keep the set point range of 20 – 50 psig which is the set point range of KSNP, the capacities of the supply PRVs shall be increased to 25 SCFM for nitrogen gas PRV and to 55 SCFM for hydrogen gas PRV.

Nomenclature

Cv : valve sizing coefficient,
d : inside diameter of pipe,
F_k : ratio of specific heats factor,
M : Molecular weight of gas,
m_k : mass of gas k in VCT,
m_l : mass of coolant in VCT,
P_D : downstream pressure,
P_{SS} : trickling opening set point,
P_S : wide open pressure,
$\Re$: universal gas constant,
R : gas constant of the mixture gas,
T : operating temperature,
V_g : gas volume in VCT,
V_l : water volume in VCT,
W : mass flow rate,
$W_{C/G}$: charging mass flow rate,
$W_{L/D}$: letdown mass flow rate,
$W_{sg,k}$: supply mass flow rate of gas k,
$W_{vg,k}$: vent mass flow rate of gas k,
x : pressure ratio ($\Delta P / P_{up}$),
x_T : terminal pressure ratio,
y_k : mass fraction of gas k,

Z : compressibility of gas

References

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3. Instrument Society of America, ANSI/ISA S75.02, Control Valve Capacity Test Procedure, Instrument Society of America, Research Triangle Park, NC, 1981.
4. Instrument Society of America, ANSI/ISA S75.01, Flow Equation for Sizing Control Valve, 1985.
5. Flow of Fluids through Valves, Fittings, and Pipe, Crane, 1980 Edition.

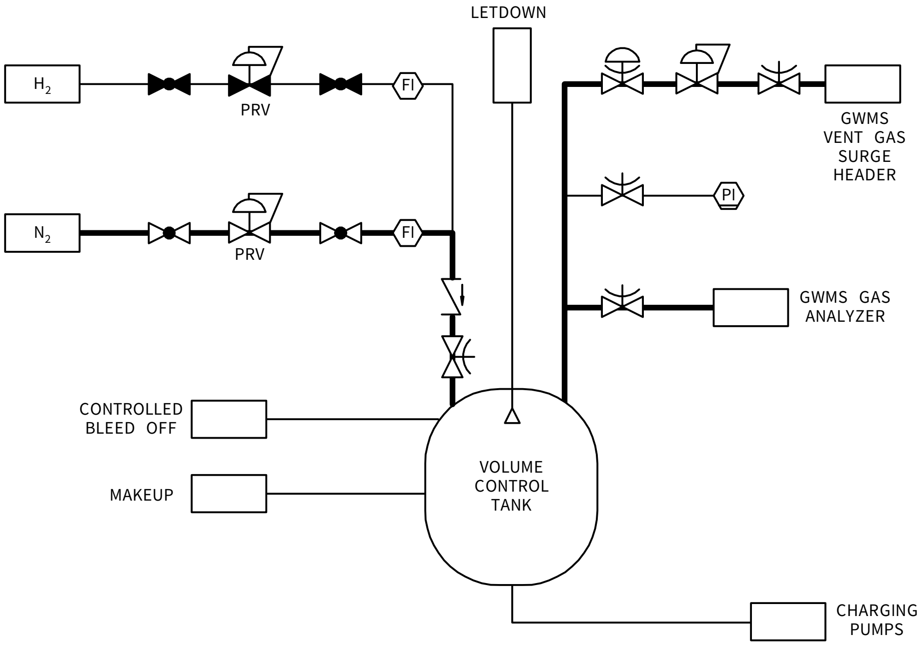

Figure 1 Schematic Diagram of Gas Control System in VCT

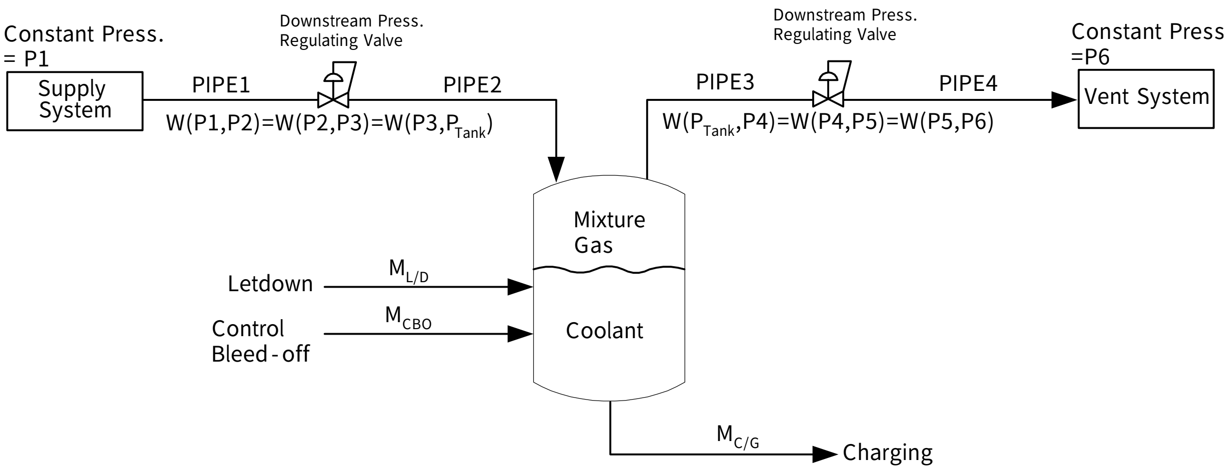

Figure 2. System Modeling for Purging Performance Analysis of VCT in CVCS

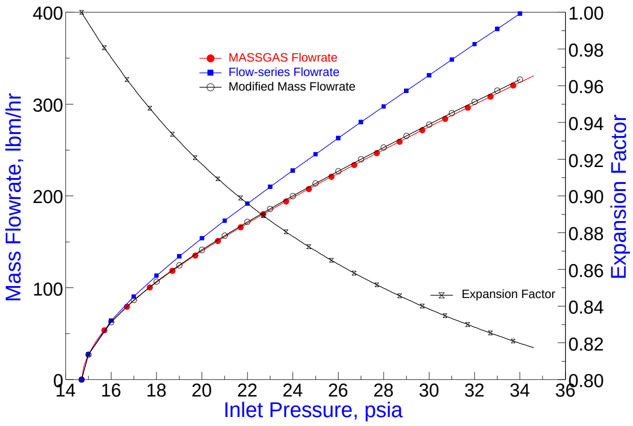

Figure 3. Mass Flow Rates Calculated by MASSGAS and Flo-series for the Mixture Gas (air).

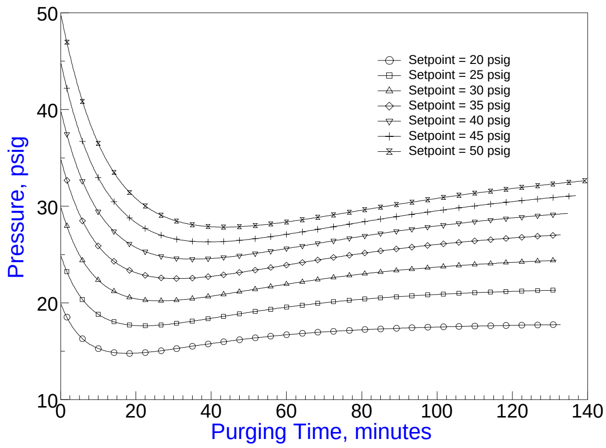

Figure 4. Tank Pressure During Purging Operation With 20 SCFM Nitrogen Supply

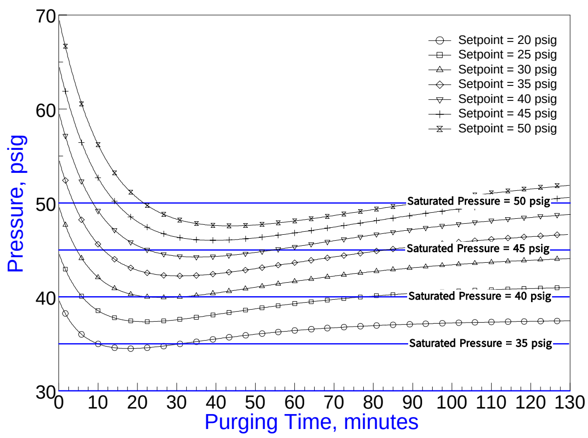

Figure 5. Pump Suction Pressure During Purging Operation With 20 SCFM Nitrogen Supply

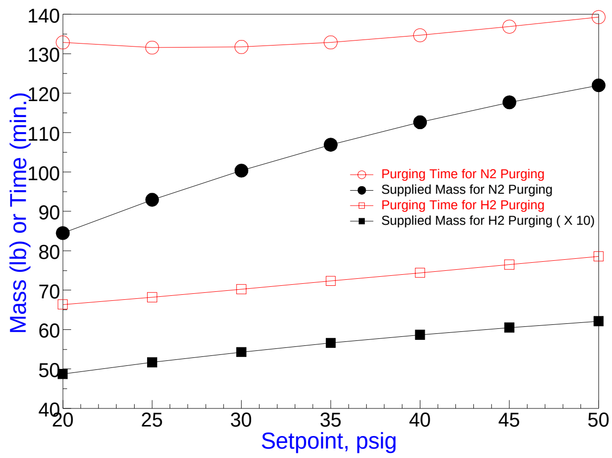

Figure 6. Supplied Gas Mass and Purging Time with the Capacity of 20 SCFM

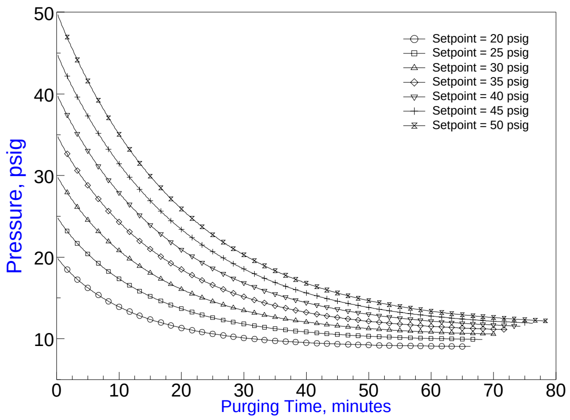

Figure 7. Tank Pressure During Purging Operation With 20 SCFM Hydrogen Supply

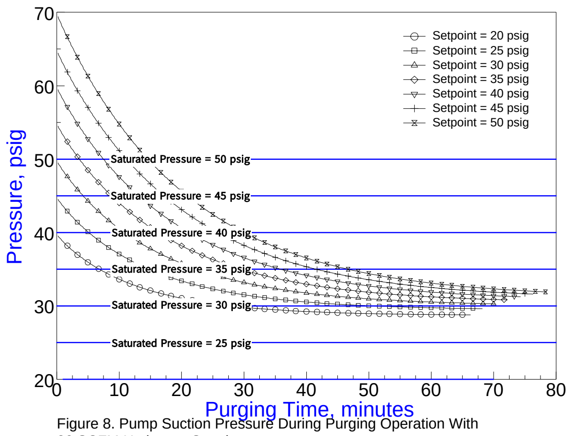

Figure 8. Pump Suction Pressure During Purging Operation With 20 SCFM Hydrogen Supply

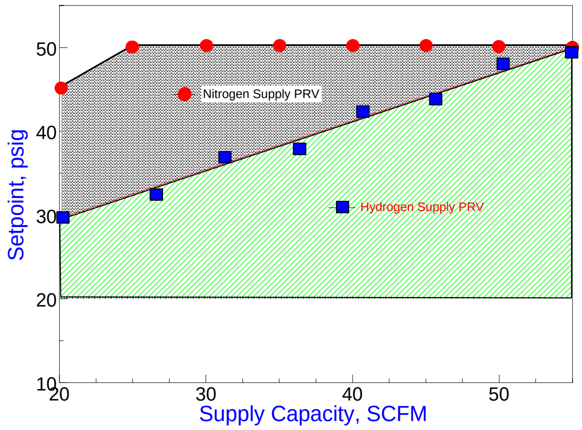

Figure 9. Allowable Setpoint Ranges of PRVs and Their Supply Capacities