APPLICATION GUIDELINE FOR CENTRIFUGAL COMPRESSOR SURGE CONTROL SYSTEMS

RELEASE VERSION 4.3

April 2008

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Application Guideline for Centrifugal Compressor Surge Control Systems

Foreword

The following guideline was developed through research funding provided by the Gas Machinery Research Council and industry co-funding from BP and Exxon Mobil. The intent behind the development of the guideline is to provide an objective viewpoint on the design requirements and functionality of a centrifugal compressor surge control system. Within the natural gas industry, many different philosophies govern the design of surge control systems, including designing for surge prevention, designing for limited surge occurrence under specific “low energy” conditions (based on previous experience), risk-based evaluation of surge control systems (based on a set of risk criteria), and design based on the predictions of transient models (using the results of a transient model to assure adequate protection of the compressor through the surge control system performance). All of these methods are acceptable depending on the installation and provided that the disadvantages of each philosophy are recognized. This guideline does not attempt to prescribe a specific philosophy, but instead to present the necessary information required to make the most suitable choice for the operating company, manufacturer, or designer.

The objectives for the surge control system application guideline are twofold. First, the guideline provides a common reference on the required functionality of the surge control system components in different operations. This type of reference is needed because a better understanding of the surge control system design would benefit the user, system designer and compressor manufacturer alike through enhanced protection of the compressor and cost effective selection of components. Second, the guideline provides the reader with methods of evaluating surge control system performance against recommended design criteria. This allows the compressor operating company to determine if the existing or future surge control system will meet expectations. Evaluation of the surge control system against design criteria should prevent unexpected costs (i.e. addition of a hot gas bypass valve or piping redesign late in the project) or unexpected surge of the compressor (which may lead to compressor overhaul, reduced mechanical integrity or reduced operational flexibility). The additional understanding of surge control systems can be used by the operating company to design a risk-based approach for compressor station evaluation. Several “high risk” factors are provided in the final section of the guideline.

The surge control system acts as an integral part of the compressor station controls. However, the required functionality differs based on the operating environment. Three distinct operations for the surge control system occur during start-up of the compressor, normal process control operations and shutdown of the compressor. Due to the competing factors in the design of the compressor station, the optimal choice of piping layout, check valve, recycle valve or control algorithm is not always available. The surge control system designer does not always hold the decision-making for the entire compressor station layout and component selection. The surge control system designer must overcome these factors by designing against the limitations of the compressor station.

The guideline recommendations should not serve as a claim against the recommendations of a particular manufacturer. The methods presented for designing surge control systems and verifying performance will provide adequate background in order to apply the design strategies to a particular installation. Different centrifugal compressors and various piping layouts should be expected to perform differently under surge. Thus, user experience with a particular compressor unit or station installation is extremely beneficial in applying the concepts presented in this guideline.
Application Guideline for Centrifugal Compressor Surge Control Systems

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Definitions

1. **Anti-Surge Valve:** Otherwise known as the recycle valve for the surge control system; acts in conjunction with surge control system in recycle loop piping to relieve downstream pressure and return flow to the compressor suction side.

2. **Compressor Operating Point:** The operation of the compressor defined in terms of any two of the following three parameters: Head, Flow or Speed.

3. **Compressor Surge Control System:** The surge detection device (either head or flow sensor), additional recycle loop, bypass valve, actuation system and controls which encompass the entire surge control system and act together to protect the compressor.

4. **Compressor Surge Point:** The capacity below which the compressor operation becomes unstable, as flow is reduced and the compressor backpressure exceeds the pressure developed by the compressor.

5. **Control Algorithm:** The algorithm used in the surge control system to determine how the control signals are sent to the recycle valve based on the compressor operation and the surge control line.

6. **Emergency Shutdown (ESD):** A critical condition for which immediate shutdown of the gas turbine and compressor is required and delayed shutdown options are not acceptable because of the danger posed to the compressor station, human life or physical damage to the equipment.

7. **Flow Coefficient:** A dimensionless parameter for a valve, defined as the compressed mass flow rate divided by the product of inlet density, rotational speed, and the cube of the blade tip diameter.

8. **Lowest Allowable Surge Margin (LASM):** The minimum allowable margin between the surge line and the surge control system line for which the compressor is permitted to operate.

9. **Peak Head:** The maximum compressor head available on the compressor system, defined by the surge control line and the maximum operating speed.

10. **Performance Map:** A representation of all of the available compressor operating points for a particular centrifugal compressor, showing the maximum allowable flow rate (and speed) and the minimum operating point (surge point) as well as the surge margin.

11. **Reduced Flow:** The non-dimensional form of the compressor flow rate, used to represent compressor flow without gas property effects.

12. **Reduced Head:** The non-dimensional form of the compressor head used to represent the compressor enthalpy ratio (head) without gas compositional effects.

13. **Surge Control Line:** The control line used by the surge control system as the point at which surge control should be implemented. The control line follows the actual surge line plus an offset termed the surge margin.

14. **Surge Cycle:** The typical cycle undergone by the compressor when reversible flow occurs and the pressure is reduced, which causes forward flow to occur again.

15. **Surge Detection System:** A detection system using flow or pressure transmitter measurements of dynamic pressure pulsations to determine if a compressor is near or in surge. Offers redundancy as a separate system apart from the surge control system and can open the recycle valve in the event that the surge control system fails.
16. **Surge Margin:** The difference between the actual compressor surge line and the surge control line used by the surge control system to avoid surge.

17. **Turndown:** The allowable operating range for the centrifugal compressor between the design point and the surge line at any given speed for a fixed compressor head.

18. **Valve Flow Capacity:** The available flow rate for a particular valve based on its physical dimensions and the manufacturer specifications.

### List of Variables and Subscripts

- **C** = flow coefficient for DP flow meter
- **c_v** = valve flow capacity
- **d** = bore diameter of orifice meter
- **E** = expansion factor
- **F_p** = piping geometry factor
- **H** = compressor head
- **L_d** = length of piping between compressor discharge flange and check valve
- **J** = rotating inertia of the compressor
- **k** = proportionality factor
- **n_p** = polytropic exponent
- **N** = compressor speed (in rpm)
- **P** = total (stagnation) pressure of gas at suction or discharge side
- **P_c** = compressor power
- **q_m** = mass flow rate
- **Q** = volumetric flow rate on suction or discharge side of compressor
- **s** = speed of sound
- **S_G** = specific gravity
- **t** = time
- **T** = temperature of gas at suction or discharge side
- **T_c** = torque delivered to compressor
- **V** = volume of gas in piping system on suction or discharge side
- **Y** = expansion factor
- **Z** = compressibility of gas at suction or discharge conditions
- **h** = enthalpy of gas at suction, discharge or isentropic conditions
- **Δp** = differential pressure measured across orifice plate
- **φ** = flow coefficient
- **ρ** = density of gas determined at suction or discharge conditions
- **v** = specific volume of gas at suction, discharge or isentropic conditions
- **ψ** = head coefficient
- **ω** = shaft speed in radians per second [rad/sec]

### Subscripts:

- **d** = discharge side
- **s** = suction side
- **p** = polytropic condition
- **v** = valve
- **c** = compressor
1.0 Introduction

The following guideline was developed for designers, manufacturers and users of centrifugal compressor surge control systems. The necessary surge control system components and their impact on the performance of the surge control system are provided, as well as methods of evaluating surge control system performance. The guideline is intended to define the surge control system functionality and the requirements for each control system component. The functionality is based on the operating environment of the surge control system, which can be divided into three distinct operating cases. These are described in Sections 1.4. Control system operation in the three functioning environments is provided in the guideline, as well as methods of optimizing performance.

The intent is for the guideline to be used as a reference for the natural gas industry to provide guidance on the selection, installation and operation of surge control systems. Specific compressor systems and operating companies will require different control system design philosophies and operational methods. This guideline provides an objective view of the design and selection of centrifugal compressor surge control systems without requiring that specific components or design methodologies be used.

A surge control system should be implemented according to the user requirements and the manufacturer specifications. The surge control system performance should protect the compressor system over a range of “high risk” conditions, which may encompass the entire range or a subset of the operating range of the compressor.

Various design philosophies are also provided through the use of surge control system design criteria, which allow the performance of the surge control system to be evaluated. The actual choice of design philosophy rests with the operating company and compressor manufacturer – and may be based on experience with a particular compressor or station. The following design philosophies are discussed in the guideline:

1. Design to Avoid Surge: The philosophy requires control system design criterion based on a calculated allowable discharge system volume. The allowable discharge piping volume should be determined by simple or more complex transient models of the compressor system.

2. Design to Permit Surge Under Specified Conditions: The design philosophy acknowledges that due to operational changes to the compressor station or cost-based decisions, the compressor may not be fully protected by the existing surge control system. The criteria require that the surge control system function to avoid surge at the identified “high risk” or “high energy” conditions. Evaluation of the surge control system using a simple transient model is recommended to evaluate the occurrence of surge against the design criteria. An example of suggested evaluation criteria is provided in the guideline.

3. Design Based on Risk Evaluation: The surge control system is evaluated against a set of risk factors developed for a particular compressor and dynamic simulation is not necessarily required because of previous modeling efforts or experience. These type of economic and risk based analysis models can be used to determine the overall design and operational risk of the surge control systems within the compressor station. The models must be based on known risk probabilities, safety factors/requirements, and equipment repair/replacement costs. As
this information is specific to an individual operator and site, the risk-based evaluation must be customized for the application.

1.1 Description of Surge

Surge is defined as the operating point at which the compressor peak head capability and minimum flow limit are reached. The compressor loses the ability to maintain the peak head when surge occurs and the entire system becomes unstable. Under normal conditions, the compressor operates to the right of the surge line. However, as fluctuations in flow rate occur, or under startup / emergency shutdown, the operating point will move towards the surge line because flow is reduced. If conditions are such that the operating point approaches the surge line, the impeller and diffuser begin to operate in stall and flow recirculation occurs. The flow separation will eventually cause a decrease in the discharge pressure and flow from suction to discharge will resume. This is defined as the surge cycle of the compressor—see Figure 1.

The surge cycle will repeat itself unless control systems are installed or operational changes are made to bring the compressor out of the surge cycle. The surge cycle may result in a small or large flow reversal period depending on the discharge gas volume and the pressure ratio. Chronic surge is characterized by intermittent periods of small flow reversal that may not cause severe damage to the machine. Acute surge is more pronounced, usually due to a rapid transition across the surge line. Any surge event can cause severe damage to the thrust bearings, seals, and the impeller. The extent of the damage due to surge occurrence is somewhat a function of the compressor design.

![Example of Surge Cycle at 100% Design Speed](image)

**Figure 1. Typical Compressor Surge Line on Performance Map**

A surge control system should be capable of monitoring the operation of the compressor continuously. The function of the surge control system is to detect the approach to surge and provide more flow to the
compressor through opening the recycle valve to avoid the potentially damaging flow reversal period and surge cycling. The surge control system should be designed for the three surge environments (which may have competing demands) and the compressor operating parameters as well as manufacturer specifications.

1.2 Function of Surge Control Systems

Surge is a relatively common yet costly phenomenon in centrifugal compressors. The surge control system is an important element in the compressor system because it protects the compressor from surge over the range of compressor operations. Protection of the compressor through the surge control system should be viewed as necessary cost expenditures, in order to avoid considerably more costly repairs or overhauls due to damaging surge conditions. Control systems may be implemented using a variety of methods and philosophies. However, the primary objective of any surge control system should be to predict and prevent the occurrence of surge so as to reduce possible damage to the compressor and assure a safe working environment for all station personnel.

The principle of a centrifugal compressor surge control system is based on ensuring that the flow through the compressor is not reduced below a minimum flow limit at a specific head. The majority of surge control techniques restrict the operation of the compressor to flow rates above a defined surge control line based on the surge margin for a particular compressor. Restriction of the operating window of the compressor in order to avoid surge because of mistakes in the surge control system design should be avoided. A properly designed surge control system can allow the operational range of the compressor to be extended based on the response of the surge control system.

At a minimum, the control system should actively measure the compressor head and flow through the compressor system controls and determine the resulting operating point. The recycle valve should be opened in a specified time to a valve set point determined by the control system. This signal to the valve is based on the compressor operation, its proximity and its movement (rate) relevant to the surge control line. Opening of the recycle valve in the surge control system effectively avoids surge by providing more flow and reducing compressor head, to move the compressor away from its surge point.

1.3 Views of Surge

The surge region of the centrifugal compressor may be viewed in terms of flow, head or speed. These three descriptions affect how the surge region responds to changes in gas composition. The surge line will change based on gas composition if the surge line is represented by variables that are calculated based on gas properties (enthalpy, density, or entropy). The different views of surge are more advantageous to particular operating environments.

Three views of the surge line are shown in Figure 2. Viewing the surge line in terms of speed versus flow rate provides an estimate of proximity to surge within a flow rate range or surge margin. As the compressor speed increases, the surge margin may be reduced. Flow rate changes based on density effects (or changes in the gas composition) will affect the surge margin and surge line in this view. The surge margin is useful during normal process operation when the flow must be reduced due to pipeline requirements.

The surge line viewed in terms of compressor head versus speed provides an estimate of the head rise to surge. The head rise to surge tells the operator how quickly surge will occur during shutdown operation. If the surge line is more flat, the head rise to surge will be smaller and surge can occur more quickly in an emergency shutdown event.
The third view of surge (shown at right in Figure 2) is the head versus flow representation. This view shows the compressor turndown or operational window. At a constant head, the compressor will operate within the operational region to the right of the surge line. The allowable operational flow range determines the turndown of the compressor. The surge limit model is best represented on a head versus flow map because this representation normalizes the surge line. The compressor head for the performance map is calculated using the measured temperature, pressure ratio and flow across the compressor, as well as the gas properties.

\[
H_p = \left( \frac{P_D}{P_S} \right)^{np} - 1
\]

\[\text{np} \cdot T \cdot SG \cdot Z\]  

(Eq. 1-1)

The reduced head versus reduced flow equation should be used to simplify the equations because the temperature, specific gravity and compressibility cancel out in both the head and flow equations. The reduced head is only a function of pressure ratio and flow, calculated as:
Reducing the head and flow to these variables allows the surge limit model to be used at all speeds and gas compositional variations with minimal shifts in the surge line location on the performance map. The reduced head view is the best representation for the surge control system because the density effects cannot affect the uncertainty in the surge control line. This provides more precision in the surge prediction within the control system algorithm.

1.4 Surge Control System Environments

The design of the surge control system is more difficult than other station control systems because of the high speed of disturbances and dynamic nature of surge. In addition, a variety of control system responses are required, depending on the operating environment and the selected surge control system components. The three primary operating environments for the surge control system are described below.

1.4.1 Start-up Environment

The challenge to the surge control system in the start-up environment is to quickly bring the compressor up to design speed without overheating the discharge gas. For steam turbine or single shaft gas turbines, the start-up period will be lengthened and cooling of the recycle gas may need to be considered. In a typical start-up mode, gas is continually recycled to bring the compressor online. Operating in continuous recycle will cause the process gas temperature to increase until new gas can be supplied from upstream. With the recycle valve fully open and the downstream check valve closed, all compression horsepower will serve as heat input to the recycled gas.

Start-up of the compressor is initiated by equalizing pressure of the compressor with the pipeline. This is accomplished by opening the loading (charging) valve upstream. Once pressure is equalized, the upstream and downstream isolation valves are open, causing the downstream check valve to close. The isolation prevents flow from coming in from the discharge side. The recycle valve is fully opened upon start-up. As the compressor begins to gain speed and flow is increased, the recycle valve is gradually closed. At this point the compressor downstream check valve may be opened.

If the compressor cannot reach design speed in sufficient time, the process gas will cause shutdown of the unit due to high discharge temperature in the worst case. The surge control system must function to gradually close the recycle valve according to the start-up controls. To avoid overheating – three strategies are employed in the compressor station design:

1) **Minimize recycle time for start-up.**
2) **Increase the mass of gas in the recycle loop:** Allows for more heat storage. *This will have adverse effects on the surge protection for emergency shutdown.*
3) **Add cooling to recycled gas:** Use a discharge system cooler or add a suction gas cooler on the downstream side of the recycle valve. (See discussion of layout options in Section 2.3).
Because the second and third strategies may increase the discharge piping volume, which reduces response time of the surge control system in the shutdown environment, the first strategy may be preferred. The surge control system should function to gradually close the recycle valve as the compressor speed increases.

The compressor will not be capable of coming up to full design speed if the recycle valve is not closed to some extent (see Figure 3). This relationship between the recycle valve characteristics and the compressor operating map is typical. The surge control system must act to close the recycle valve in sufficient time and with sufficient precision to attain the full design speed of the compressor. Precision in the control signal is required because closing the recycle valve should not cause the compressor to surge due to a corresponding decrease in flow.

![Figure 3. Example of Recycle Valve Characteristic Curves at Various Opening Percentages.](image)

Note: Figure 3 provides an example of a 70% valve opening percentage used for the maximum design speed. However, more conservative criteria may be used at 40-50% valve opening to provide additional valve capacity at the surge line.

The response time for the compressor to come online is typically designed for normal ambient temperatures. However, at higher ambient temperatures, the process gas will heat up quicker. This will reduce the amount of recycle time available. To avoid this occurrence, the allowable recycle time should have a sufficient margin of safety. This margin will permit start-up of the compressor under higher ambient temperatures.

Restart of the compressor after shutdown should also be considered. The restart may involve higher operating temperatures as well, especially if the compressor is shutdown due to high discharge temperature. For compressors with severely limited startup capability, an additional helper motor should be considered. The motor can also be used to provide additional power for the compressor under normal process control operation. Another viable alternative is to add a discharge cooler to the recycle loop, although this may have other implications for the surge control system in the shutdown environment due to the added discharge volume that must be relieved through the recycle valve.
1.4.2 Normal Process Control Environment

The operation of the surge control system under normal process operation is distinctly different. The surge control system should not limit the operational range of the compressor. Thus, the control system should function over the entire operating range. The shape of the surge control line will determine the response characteristics of the surge control system. A relatively flat surge line equates to higher surge sensitivity to changes in compressor head. A steeper line indicates that the compressor is more sensitive to flow rate changes or uncertainties near the surge line. In either case, the surge control system must provide for smooth operation of the compressor.

The challenge for the surge control system in process control is to match the transition into surge (across the surge margin), which is typically gradual during normal process control, with a gradual increase in flow through the recycle valve. This requires precision control of the valve motion. The control signal and response of the recycle valve for normal process control will differ from the shutdown environment. Different control system gains should be used for the different surge operating environments. The control algorithm should be capable of distinguishing between startup operation, normal process control operation and an emergency shutdown operation. During normal process control operation, lower gain signals should be used for adjusting the flow by opening or closing the valve in a controlled manner.

The response time allowed for the recycle valve in the process control environment is longer and typically not critical. Both functionalities must be met to provide for adequate process control during normal operation and quick response during an emergency shutdown.

Controlled shutdown of the compressor also falls under the process control environment. In the controlled shutdown of a compressor, the surge control system functions to maintain a steady flow to the compressor as power is removed from the unit. As the compressor gradually decelerates, the flow is maintained in proportion to the surge control line so the surge margin is not crossed. The single challenge in the controlled shutdown environment is to not overheat the compressor due to operating in continuous recycle. This is only the case when a discharge or suction cooler is not present or the after cooler cannot sufficiently cool the recycled gas (due to improper sizing).

1.4.3 Emergency Shutdown Environment

The two types of compressor shutdown are defined as follows:

1.) **Controlled Shutdown:** Compressor is shutdown under controlled conditions, where speed and power are gradually decreased. The surge control system functionality for this operation actually falls under the requirements for the process control environment (see section 1.4.2.)

2.) **Emergency Shutdown (ESD):** Compressor is suddenly shutdown and driver power is removed. This operation requires distinctly different functionality from the surge control system, as discussed below.

For the emergency shutdown event, the system should be designed to allow rapid shutdown of the unit and adequate protection of the compressor. Delayed shutdown or slowly decreasing speed is not possible as ESD’s are intended to provide immediate shutdown of the unit due to safety considerations. The surge control system must function quickly to open the recycle valve fully because the coastdown path is not being controlled by the station operator – only by the deceleration of the compressor based on the power train inertia and any residual power in the system. The emergency shutdown requires more demanding control system response and may alter the surge control system design because a single valve may not
provide sufficient flow quickly enough. Additional evaluation of the system may also need to be performed.

The worst case emergency shutdown occurs when the compressor is operating at maximum head at the lowest allowable surge margin. This operating point should govern the design of the surge control system – as the maximum possible differential which must be overcome by the recycle valve flow. Additional discussion of the evaluation of the surge control system is provided in the system design criteria in Section 6. The three surge control system conditions will result in differing demands on the control system components. The resulting requirements for surge control system components are discussed in Sections 3 and in the operational description in Section 5.
1.5 Summary of Surge Control System Environments

Based on the differences in the surge control environments, the following table summarizes the requirements for each of the primary surge control system components in the various surge operations and provides the guideline reference for further discussion of component requirements.

Table 1. Summary of Surge Control Environments and Component Functionality Requirements

<table>
<thead>
<tr>
<th>Surge Control System Environment</th>
<th>Surge Limit Model</th>
<th>Control Algorithm</th>
<th>Recycle Valve System</th>
<th>Instrumentation</th>
<th>Piping System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Start-up of Compressor</td>
<td>Used to develop fixed valve opening in design. See Section 3.3.4.</td>
<td>Not Applicable.</td>
<td>Fixed valve opening used. See Section 3.3.4.</td>
<td>Not Applicable.</td>
<td>Larger piping volume will help to avoid overheating compressor. See Section 1.4.1 and Section 3.5.1.</td>
</tr>
<tr>
<td>Process Control</td>
<td>Non-linear surge line will help to extend operational region of compressor. Accurate line is required to avoid surge. See Section 3.1.3 and 8.1.</td>
<td>Use of lower gain signals is necessary to assure valve control is precise and allows for gradual recycle valve opening and closing. See Section 3.2.3.</td>
<td>Precision in recycle valve position control and minimizing overshoot are required. Non-linear response of valve will affect control and resulting operation. See Section 3.3.3.</td>
<td>For instrumentation requirements - see Section 3.4 and 4.1.</td>
<td>Larger piping volumes will affect control – and response will lag in proportion to size of piping volume. See Section 3.5.2.</td>
</tr>
<tr>
<td>Emergency Shutdown</td>
<td>Not Applicable.</td>
<td>Not Applicable.</td>
<td>Recycle valve size and characteristic (time versus % open) will affect surge avoidance ability of control system. Must assure size of valve and opening time are met. See Section 3.3.5.</td>
<td>Not Applicable.</td>
<td>Minimizing downstream piping volume is critical to maintaining fast response time. Modeling of ESD event should result in a piping volume requirement. See Section 6.1 and Section 3.5.3.</td>
</tr>
</tbody>
</table>
2.0 Surge Control System Applications and Layouts

Typical applications requiring the use of surge control systems are described below to better understand the surge control system operating environments. The primary factors to consider in layout design are summarized in this section to provide the background for decisions concerning piping volume and placement of key elements in the compressor station. A typical surge control system layout is outlined in Section 2.2. Alternative layout options are provided in Section 2.3. With any choice of piping layout, some disadvantages arise due to the competing operational demands on the surge control system.

2.1 Surge Control Applications

A number of applications exist for surge control systems. A brief description of functionality and variations in the primary applications is provided below.

2.1.1 Pipeline Compression Application

Pipeline compression is a typical application for centrifugal compressor surge systems. These installations have a fluctuating pressure ratio across the compressor based on the pipeline. In the pipeline applications, surge events will occur due to flow reductions governed by the pipeline. These will occur over the entire surge line (i.e. over the range of the compressor’s given pressure ratio.) Changes in the gas composition and operating temperature will affect when surge occurs. The surge margin should take these uncertainties into account.

Gas temperature is fairly steady for a given daily period, but fluctuations can occur on a seasonal basis. The gas compositions in this type of application are predominately methane (75-95%) with additional heavier hydrocarbons and diluents such as nitrogen and carbon dioxide. The variations in pressure and composition are slower changes occurring over a period of several hours or more, due to the large volume of gas in the pipeline system, unless multiple machines are used in parallel.

2.1.2 Re-Injection Application

In re-injection applications, the compressor is being used to inject gas back into a potential production field. These applications require a varying discharge pressure based on the gas field pressure requirements (with field pressure changes over time.) The composition of the gas can vary widely due to many sources of gas, which requires a representation of the surge line in reduced head and flow (composition independent) form. Liquid slugs of gas that would cause flow disturbances may be common – and surge control systems may be used to mitigate the disturbances. The pressure ratio is significantly larger in this type of application because the discharge gas pressure can be excessively high (greater than 3000 psig) and typically involves multiple bodies. Excessive temperature fluctuations are not as common in this type of application, but can vary on a seasonal basis as well. Suction flow changes can be sudden due to required valve operations and process disturbances at certain conditions.

2.1.3 Storage and Withdrawal Application

In storage and withdrawal applications, the compressor is being used to inject or withdraw gas from a storage field or reservoir. The pressure of the suction gas varies with time (initially fairly high but declining quickly over time for withdrawal applications or initially fairly low and increasing gradually in injection applications.) Pressure ratio is also based on the storage field initial pressure. The gas composition variations are due to changes in the storage gas. These applications can be particularly
challenging for a surge control system – requiring fast response for the normal process control operation, but a more gradual response as the pressure ratio falls. Hence, the control signals for the recycle valve may need to be more diverse than a typical pipeline application.

2.1.4 Gas Gathering Application

Gas gathering installations collect production type gas mixtures to prepare the gas for processing or transmission pipeline applications. This application may have wide swings in gas composition caused by the types of gas being treated and the level of dehydration, separation and filtration used at one particular installation. These installations may require more extensive modeling or design efforts to minimize piping volumes. Gas mixture variations due to various production fields will cause changes in the characteristic head vs. speed curves for the compressor. The pressure ratios are typically lower than re-injection and storage applications, with discharge pressures maintained below 3000 psig because the discharge gas is typically fed into a pipeline system. Gas temperatures are fairly stable in this application.

2.1.5 High Pressure / Process Compression Application

High pressure compressors vary broadly in the pressure ratios and gas compositions used, depending on the specific application. Higher pressures are typically on the order of 3000-5000 psi in these applications. The processing plant compressor will experience changes in pressure, head and operational conditions – depending on the type of process (LNG facilities, refineries, hydrocarbon processing and NGL removal processes). The gas composition and temperature will vary based on the process requirements as well. Surge control systems should be designed to completely avoid surge during normal operation since the higher pressures will introduce additional risk of compressor damage due to surge.

2.2 Surge Control System Layout

The basic elements of a compressor surge control system are the flow measurement (typically on the suction side of the compressor), pressure measurement, discharge check valve, recycle valve and its actuation system, and surge control system controller. The recycle line should be connected immediately upstream of the discharge check valve and upstream of the compressor flow measurement device on the suction side. The recycle line will typically be upstream of the compressor suction scrubber if the recycle loop is cooled to avoid condensed liquids in the recycle flow. The boundaries for the discharge gas volume are set by the discharge check valve (downstream of the recycle line take off point), the compressor and the recycle valve.

Key issues to address in designing the layout of the surge control system are as follows:

1. **Minimize downstream piping volume**: The volume of gas contained between the compressor discharge flange, the downstream check valve and the recycle valve should be minimized as much as possible. This volume is the mass inventory of the system. The volume determines the rate of relief of the downstream pressure and the requirements for the recycle valve (size, speed, characteristic). The downstream piping volume directly relates to the performance of the surge control system in the shutdown environment.

2. **Use multiple recycle loops as needed**: Compressor trains or compressor systems with multiple sections may require independent or separate recycle loops. The surge controller for each compressor section should assure that adequate surge control is provided for every operating scenario (shutdown of individual units and station as a whole).
3. **Downstream check valve placement near the compressor discharge flange:** Proximity of the downstream check valve to the compressor outlet will limit the downstream volume and increase the required system response time of the surge control system. Placement of the downstream check valves for each compressor section, return lines and recycle take off lines must be carefully reviewed to assure that separate compression loops operate independently.

4. **Use of independent check valves:** Parallel compressor units should have check valves installed to assure effective surge control of each compressor. Isolation valves are also recommended.

5. **If startup period requires considerable time to bring the compressor up to speed, consider adding cooling of recycle gas:** The recycle gas or a portion of the gas in the recycle loop should be cooled to facilitate operation in continuous recycle. Incorporation of hot and cool gas recycle loops will help to reduce possibility of overheating upon start-up or controlled shutdown. Upstream pre-coolers (downstream of the recycle valve) are an option to consider which will help to keep discharge system volumes small (see item 1 above). Installation of the system should consider where the cooler is to be placed and how much flow will be required to be cooled. Suction coolers will minimize discharge piping volume but the hydrocarbon and water dew points should be a design parameter for the suction pressure and cooling expected to avoid two phase flow.

6. **Keep separation vessels upstream:** Liquid separation vessels should be located upstream of the compressor and downstream of cooling elements in the system. Placing these on the suction side will also help to minimize discharge system volume (see item 1 above).

7. **Assure recycled flow reaches compressor quickly:** Recycle piping should enter the suction flow downstream of any throttling valves to assure that the flow reaches the compressor entrance quickly. Pressure relief systems should be limited on the compressor suction side because suction mounted relief systems can cause substantial flow reduction. Alternatively, recycle lines that return upstream of the throttling valve may be considered to help unload the motor upon start-up of the compressor.

### 2.3 Alternative System Layouts

The basic cooled recycle loop (Figure 4) provides a large operating range for the compressor. However, use of a non-cooled recycle loop has some advantages over other arrangements because it minimizes the system discharge volume and allows for a faster response time during shutdown – see Figure 5. Other common arrangements that may be used for more than one compressor unit or for providing more flexibility in operation are given below. These layouts may be necessary due to the operation of other units at the station or the need to increase the recycle valve flow capacity.
Multiple valves may be used in the surge control system to meet the demands of both the process control operation and the emergency shutdown event as the valve characteristic curves / control signals can differ. This will allow for both gradual and rapid changes in the valve coefficient. Multiple valves will add complexity to the control system and any transient modeling efforts, but it is often necessary based on the necessary response time or the flow rate requirements for system discharge pressure relief.

### 2.3.1 Hot Gas Bypass with Secondary Cooled Loop

One alternative design to the basic cooled recycle loop is the hot gas bypass with a secondary cooled loop (as shown in Figure 6). Without an overall cooling loop, the compressor cannot run in the recycle mode for a lengthy period. The hot gas bypass and secondary cooled loop arrangement provides a means to
operate in hot gas recycle with a cooled gas recycle loop as a back-up. The suction temperature can help to adjust the operation if inlet suction temperatures are low enough. By removing the cooler from the inner recycle loop, the surge control system can more quickly respond to operational changes.

For the hot and cool two valve arrangement, the cooled outer loop valve is typically a modulating type, while the hot inner loop valve is a quick opening type of valve. The cooled valve in the outer loop can be sized independently of the hot valve. In addition, the capacity of the cooled valve can be considered with the shutdown valve, allowing the shutdown valve downstream of the compressor to be smaller.

![Hot and Cooled Recycle Valves](image)

**Figure 6. Example of Hot and Cool Recycle Valves in Surge Control System**

### 2.3.2 Suction Gas Cooler for Cooled Recycle

Another alternative configuration utilizes a suction gas cooler downstream of the recycle valve in order to cool the recycled gas only - shown in Figure 7. For installations where the delivered gas must be cooled, this configuration may require two coolers, with a larger secondary cooler downstream of the check valve. However, the recycle gas cooler can be sized fairly small to only cool the bypass loop gas. The advantage of this layout is in its small discharge volume and ability to operate continuously in recycle because of the added cooler.

![Suction Cooled Recycle Loop](image)

**Figure 7. Example of Recycle Loop with Suction Gas Cooling**
\section*{2.3.3 Overall Cooled Recycle with Hot Gas Recycle Loops}

A modification which is possible for multiple units in series is the layout shown in Figure 8. Individual hot gas bypass loops are used inside of an overall cooled loop. This configuration alternative provides good modulating surge control and fast shutdown of the units through the check valve proximity to the discharge side of the compressor. Some redundancy is built into this design, which will provide secondary surge control in the event of a valve failure, but not necessarily at the same flow capacity. The additional components will increase the overall system cost.

Using multiple hot and cool recycle loops is advantageous to the startup operation of the surge control system by adding cooling to the recycle gas. The hot gas loop has advantages to the emergency shutdown operation because the recycle valve (if sized properly) can quickly open to relieve discharge pressure.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure8.jpg}
\caption{Hot Recycle Loops with Added Valve on Cooled Surge Control Loop}
\end{figure}

\section*{2.3.4 Parallel Valve Arrangement}

An alternative arrangement of multiple valves is to use the valves in parallel in the recycle loop (Figure 9). The two valves can be set up in the surge control system to open at different surge margins (the first with a higher surge margin set point than the second). If the progression into surge is slow, only the first valve will open. If the progression into surge occurs suddenly, both valves will open. The parallel arrangement may provide redundancy in the event that one valve becomes fouled or its actuator is not functioning correctly. This requires that both valves individually be capable of relieving the system discharge pressure – which may mean collectively that they are oversized.
The parallel valve arrangement allows for one valve to be a linear characteristic type and one to be a quick opening characteristic (globe or ball valve) type. This provides versatility to the surge control system to respond to both operating environments - controlled recycling for normal process control or surge avoidance for quick shutdown. When two valves are used for throttling, the valves are typically operated in cascade or split range.

2.3.5 Multiple Surge Control Valves

Additional surge valves are necessary for multiple compressor units. Using an overall recycle valve with specific valves for each unit may provide more redundancy for the control system. Another alternative for multiple units is to use one overall recycle loop and a second recycle loop for a larger downstream unit. This configuration (shown in Figure 10) will provide less redundancy but allows for a large second compressor to be controlled independently of the smaller first compressor.

The configuration poses some additional risks to consider in the surge control. If both units are operating near the surge line, the discharge pressure will not be sufficiently reduced downstream of the first unit in this arrangement. The second stage compressor will introduce an additional pressure and flow requirement. The arrangement should only be applied if the outer recycle loop can sufficiently provide recycled gas quickly and if the first unit is much smaller than the second.
3.0 Surge Control System Components

Surge control systems are typically sold as separate, dedicated control systems which operate within the overall station control system or used with a dedicated compressor system controller. The recommended essential components of the surge control system are described in this section. The accuracy of the system’s ability to define the surge line and the location of the operating point relative to that line defines how well the surge control system monitors for surge. Accurately monitoring the operation and the method of controlling compressor operation (recycle valve opening point, actuation speed, signal gain, etc.) determines how effectively the surge control system protects the compressor from surge. The required surge control system components are:

- **Surge limit model:** A description of the surge control line for the compressor, typically provided in the form of a performance map. The surge limit model should be based on experimental testing, either in the factory test or from site verification.

- **System control algorithm:** The algorithm implemented in the surge control system used to determine the signal sent to the recycle valve actuation system based on the measured operating point of the compressor relative to the surge limit line.

- **Recycle valve and actuation system:** The valve and its actuation system are controlled by the algorithm and must be selected to quickly respond to the controller signal. The valve will increase the flow of gas to the compressor suction side and reduce the downstream discharge pressure.

- **Compressor system instrumentation (pressure, temperature and flow):** Required instrumentation for the measurement of the compressor operating point. The flow must be measured in addition to the compressor head to determine the operation proximity to the surge line.

- **Piping system (including suction and discharge volumes and recycle loop piping):** The compressor system piping will determine the response requirement for the recycle valve and the amount of gas mass available in starting up the compressor. Piping volume will also influence the process control operation (speed of response and precision of control).


### 3.1 Surge Limit Model (Surge Control Line)

The surge limit model is required to accurately predict when compressor surge will occur. The surge limit model is essentially a look-up table or performance map showing the actual surge line and the surge safety margin. The surge limit model defines the compressor’s operation in relation to the surge line, using any two of the following three parameters: compressor head, flow and speed.

#### 3.1.1 Implementation of Surge Limit Model

The surge limit model should be implemented in the control system in a reduced head (or pressure ratio) against reduced flow representation because this view provides more accuracy in the surge prediction (see Section 1.3). In addition, this method simplifies the instrumentation required to measure surge and the data reduction effort. The view of surge under the compressor head vs. flow squared (H vs. Q^2) representation will detect small changes in the compressor operation until surge is reached. Flow representations of the surge line will be affected by gas composition - which is not typically updated in the compressor control system. Gas composition effects will influence the surge control line shape and position. Using the surge limit model with reduced head and flow variables will help to minimize the gas composition effects. The non-dimensional head versus flow map allows the operation and proximity to the surge line to be characterized independent of compositional changes.

Different manufacturers have different approaches for determining the actual surge line. The use of a non-linear surge control line is an option to provide an expanded operation of the compressor within an allowable region. The non-linear surge line should be implemented after confirmation of the actual surge points in a factory test. For best results, the actual surge line can be verified by a site surge test (see section 3.1.5).

#### 3.1.2 Choice of Surge Margin

The surge limit model is used in the surge control system to determine the distance between the operating point of the compressor and the surge limit. The model should define a surge control line, which determines the protection margin between the actual surge line (when the compressor will surge) and the point at which the control system should act to open the recycle valve. The protection margin should be as accurate as possible to minimize unnecessary recycle time and maximize operating flexibility and compressor efficiency. The margin allowed between the actual surge line and the surge control line is based on the operating company preference, operating range of the compressor and the uncertainty of the surge line measurement. The recommended margin is 6-10 percent of the actual flow surge limit.

Other characteristics of an installed system will affect the selected surge margin. A system with large time constants (slow overall response) may require additional margin to ensure the machine is protected. Faster systems with small time constants will operate satisfactorily with margins even less than 6-10 percent.

The surge margin choice should consider the amount of uncertainty in the detection of surge within the control system. This includes the uncertainty in the pressure, temperature and flow rate measurements (see Section 4.0). The margin should also consider the imprecision of the transmitters and the dynamic response of the controller and actuator in the recycle valve.
Other parameters besides the direct head or flow measurement may also be used to control the response of the valve. The rate of change in flow is often used as an additional control within the algorithm to determine when the surge limit will be reached.

The model provided by a manufacturer should consider the range of possible operating conditions and gas compositions. The model should be provided to the compressor user in normalized variables as a head versus flow characterization. If speed is used in conjunction with head or flow to predict the surge line—the prediction will be dependent on the gas composition used to generate the surge line. This approach will cause the surge limit model to be more uncertain at other gas compositions.

### 3.1.3 Use of Non-Linear Surge Line in Multistage Compressors

Multistage compressors may have a surge line that corresponds to the product of the individual stage surge lines. The use of a compensated surge line results in a non-linear surge limit model, which may be necessary match the changes in surge operating point for each stage. Typically the first stage surge dominates the surge control line because surge will occur earlier in Stage 1 (at higher flow rates). When a later stage surges earlier than the first stage (see Figure 11), the surge line should be adjusted to compensate for the later stage. This will also prevent surge from occurring unexpectedly due to one stage driving another into surge.

![Surge Line Diagram](image)

**Figure 11. Surge Line Developed for Multistage Compressor**

### 3.1.4 Experimental Determination of Surge Line

A factory test is often used to determine the actual surge line, especially for the manufacturer’s purposes of verifying the location of the surge line. The factory test can utilize natural gas or air. In some cases, controlled hydrocarbon blends (mixed gases) are used as an alternative to provide a close approximation to the gas properties expected in the field. Sometimes, air is chosen because the surge condition is less risky in terms of possible damage to the machine if the surge limit model is under-predicting the occurrence of surge or the control system fails to adequately prevent surge. Any factory test performed
on a non-representative gas mixture (that does not closely mirror the field setting gas) should be viewed with additional uncertainty, due to variation in the surge control line caused by gas composition changes. Representing the surge control line in terms of reduced head versus reduced flow will reduce gas composition uncertainties.

The factory test will provide a good measure of the surge line for the compressor, but the installed field site condition may affect the surge limit because of the changes to system impedance at the field site. The measured surge limit will be influenced by the upstream and downstream piping, coolers, valves, and other equipment (scrubbers, auxiliary coolers, added volumes, etc.) The natural gas mixture will also change the surge control line location (for gas composition dependent surge lines) on the performance map if the factory test was performed on air. In this case, the reduced head and flow variables should be used to eliminate the probable shift in the surge control line due to gas composition.

### 3.1.5 Field Site Verification of Surge Limit

The limit model can be verified using an actual test of the compressor as the operating point moves toward the surge condition. For certain compressors with sufficient operating data, the performance map is well known and field testing is not warranted.

Verification at the field site allows the surge limit model to be tested in its true operating environment and in its installed configuration. As recommended in the GMRC Guideline for Field Testing of Gas Turbine and Centrifugal Compressor Performance, the surge limit model should be verified by testing for the compressor surge point with extreme caution. For the first test, it is best to select relatively low pressure differential and operating pressure (i.e., “low energy”) conditions. If later tests must be performed at high head conditions to verify the surge limit model over the entire head/flow range, these tests should be preceded by tests at low energy conditions in order to characterize the compressor behavior and instrument outputs of incipient surge. Verification in the field entails inherently more risk and the decision on how to verify the model should consider the possible consequences of damage to the compressor.

The other purpose in surge site testing is to verify the actual surge line using the field instrumentation (with its unique uncertainties). The testing should be performed by slowly reducing the flow when the compressor is at or near the design operating speed. The test should be stopped at the expected surge flow or incipient surge point, when the flow signal becomes unstable or the vibrations increase considerably. At this point, the recycle valve should be immediately opened to 100%. For the initial test of the recycle valve, redundancy (such as a surge detection system) is recommended to assure the safety of the field personnel.

Surge site testing is a decision left to the operator, based on experience with a particular machine and its ability to withstand “low energy” surge conditions. The benefits of surge testing in the field include:

1.) Verification that the instrumentation is installed and operating correctly.

2.) Verification of control system function.

3.) Verification and calibration of surge detection systems.

4.) Determination that the surge point is not to the right of the predicted surge point.

5.) Determination if sub-synchronous vibration levels exist to the right of the surge limit.
3.2 Control algorithm

The control algorithm is needed to relate the surge limit model predictions of the compressor operation to the measured data from the compressor. The algorithm develops the control signal to send to the recycle valve. The value of the control signal is based on the measured operating point of the compressor and the surge limit (based on the model predictions). Typically, the pressure and temperature instrumentation is used in combination with a flow meter to determine the operating point (see Figure 12).

The recycle valve opening / closing speed and its position (amount of opening or closing) are provided by the control signal from the algorithm. When the compressor flow rate is below the flow specified for the protection margin at a given pressure ratio, the algorithm should send a control signal to the valve to open. The rate of opening (or closing) should be based on the speed required to protect the compressor. The rate of change in the surge margin over time can be used to adjust the amount of gain needed (i.e. a faster rate of change requires a higher gain signal from the controller).

Various algorithms have been successfully developed by manufacturers and surge control system design companies. The provided representation in Figure 12 is only one example of a viable option that may be considered for the algorithm.

The control algorithm response rate will be much faster than equipment response. Equipment – such as the actuation system and recycle valve - used in compressor surge control system is often not selected by the control system engineer and will typically not provide the optimal response. The recycle valve will often be chosen to match the system design of the pressure and temperature transmitters and not be the ideal choice for valve characteristic needed. In addition, the piping layout will have a large impact on performance and the response time of the control system.
3.2.1 Variation in Control System Gain

The amount of gain on a control signal determines the speed of the response as well as system stability. Various responses based on different gain levels are shown in Figure 13. A sudden change in the control system is illustrated under gain levels – a low gain system, a high gain system and a critically damped (optimum gain) system. The critically damped system produces an initially aggressive response but the response is reduced in time to maintain stability.

Different control system gains should be used for the different surge operating environments. The control algorithm should be capable of distinguishing between startup operation, normal process control operation and an emergency shutdown operation. A control system which can use single and two gain signals (high gain to open the valve plus low gain to close the valve) will be a better choice for shutdown operation.

To effectively avoid surge, the control system must use variable gain to handle the different performance demands for the valve system. The variation in gain will help to overcome many unknowns in design for unknown volumes, instrumentation, etc.

![Gain Too Low](image1)
![Critical Damping](image2)
![Gain Too High](image3)

**Figure 13. Various Signal Responses for Control System.**

3.2.2 Control Algorithm During Startup and Normal Process Operation

During normal process control operation, lower gain signals should be used for adjusting the flow by opening or closing the valve in a controlled manner. The speed of opening and closing the valve is not a necessary requirement for this operation. The same control signals may be used for controlling the recycle valve in the startup operation. Consideration for this environment requires changing the gain used by the control algorithm for the process operation. The control algorithm must also consider the reaction of the recycle valve system. The recycle valve will have a certain amount of overshoot – which should be factored into the control signal in the normal process operation.

The combination of high and low gains is recommended, to provide an initially fast reaction of the recycle valve (for opening) and more gradual response to move the system away from surge (for closing).
surge has been avoided and the compressor again crosses into the protected operation region, the gain should be reduced to offset the inherent instability of a constant high gain system.

### 3.2.3 Response Time Variations

Different surge events will require different response times from the surge control system. It is difficult to provide exact values of required response times because of the many differences in compressor applications, compressor station design, discharge system volumes, and control system design. By far, the emergency shutdown situation will require the fastest response time from the control system and this event should be used to determine required minimum response time. In determining the type of PLC and recycle valve in the surge control system, the manufacturers should be asked for an estimated response time requirement or minimum discharge system volume based on the actual compressor model and installation configuration.

**Note:** During an emergency shutdown event, the recycle valve should be opened as quickly as possible to provide a quick response and protect the compressor. The shutdown operation does not affect the surge control algorithm because the sole function of the controller under the shutdown operation is to fully open the valve as quickly as possible. Signal gain levels for opening and closing the valve do not influence this operation.

### 3.3 Recycle Valve

The recycle valve is a key element in determining the performance of the control system and its protection of the compressor. If the surge control system must be redesigned, the recycle valve should be one of the first elements to consider for system redesign. Additionally, the actuation system and control methods for the valve can influence the behavior of the valve. The choice of actuation system and control method for the overall recycle valve system can be used to provide more protection for the compressor under each operating environment.

The recycle valve flow coefficient or flow capacity should be known (from manufacturer data) as a function of valve position. This defines the valve characteristic. In addition, the valve manufacturer should supply a profile for the valve position as a function of time. The sizing of the recycle valve should have additional flow capacity beyond the flow at steady state which can be used to reduce the backpressure of the compressor in the shutdown environment.

The competing requirements on the valve size, type and response time can result in the implementation of three separate recycle valves for each surge control operation, although this can be avoided through proper sizing and system design. If certain valve requirements were not considered in the initial station design, a secondary valve may be necessary and unavoidable.

The optimal selection of a single recycle valve system can be implemented successfully, if the surge control system requirements are properly matched to the designed recycle valve system. The single valve system requirements are discussed in Section 3.3.6. Use of a single recycle valve has been implemented successfully in many surge control systems and can be less costly than multiple valves, actuators and controllers.

The transient model results can be used to guide the valve selection and system design process. The model should allow the user to vary the valve size and characteristic to determine the size range that meets the control system specifications for surge protection. A valve sizing routine should be developed
to match the control valve and evaluate the valve performance under the three different operating environments – see Sections 3.3.3 – 3.3.5 on recycle valve considerations in each surge environment. The sizing routine should calculate the equivalent valve capacity based on a specified valve size and the range of operating speeds, pipe pressures and temperatures and cooler data, if applicable.

3.3.1 Recycle Valve System Components

Table 2 provides a general description of how the valve design specifications affect the surge control system. The recycle valve should open as necessary to maintain the flow through the compressor at a desired margin above the surge line. A typical recycle valve system is designed according to the following components:

1.) **Controller valve** - The control valve is typically actuated with a solenoid. The solenoid valve can either be controlled with a proportional signal for modulating control (as controlled recycling or throttling events require) or quick opening control (for sudden shutdown events).

2.) **Actuator** - The actuator for the surge control valve is usually a spring-return and fail-open type that uses either a spring and diaphragm or a spring and piston. Double acting piston-type designs are useful in some cases. Spring return valves will not require air pressure, which reduces the complexity and makes these actuator types more reliable.

3.) **Positioner** - The positioner selection should be based on capacity and response time. The positioner should have adjustable minor loop feedback in the servo loop. Spool valve positioners are not recommended due to the potential to become plugged. The valve positioner should be intrinsically safe.

4.) **Pressure Relief (Booster)** - The booster will provide pressure relief to help close the recycle valve. Opening the booster allows for the actuator pressure to be reduced and set equal to atmospheric pressure. Slow reductions in pressure will not cause the booster to open. The booster is mainly needed for large pressure reductions. Quick-exhausts are not recommended in the valve actuation system because they will not work well with the positioner. These will typically lead to non-linear positioner response.

5.) **Tubing** - The tubing should be a sufficient diameter for the volume boosters and actuator connections. Tubing lengths should be minimized as long tubing lengths will affect performance. Reducing the tubing diameter will also improve response time.

6.) **Valve Indicator** - The recycle valve should be equipped with a positive mechanical valve position indicator. Electrical feedback and position switches will help with diagnostics. A visual mechanical position indicator on the valve is critical.

7.) **External volume tanks (if necessary)** – External volume tanks are not recommended because these will reduce reliability. If the volume tanks are absolutely required in the actuation system, the external tanks should include a relief valve, a drain valve, a check valve on the supply inlet connection and a minimum pressure rating of 150 psig. The external tanks should be ASME certified as well.
### Table 2. Control Valve Specifications - Effect on Surge Control System

<table>
<thead>
<tr>
<th>General Control Valve Design Specification</th>
<th>Effect on Surge Control System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Valve Type</td>
<td>Valve characteristic (amount of valve opening vs. time) is based on the valve number and type. A quick opening valve will provide most flow in the fastest amount of time (shortest travel). Equal percentage valve will provide lower flow during initial opening – and more flow towards end of travel.</td>
</tr>
<tr>
<td>Valve Actuation</td>
<td>Valve actuation will affect system response during shutdown operation – where speed requirement is most severe. Normal process operation will require gradual valve motion.</td>
</tr>
<tr>
<td>Size of Valve</td>
<td>Larger valves will provide a better response to equalize pressure faster, but the controllability may be less for throttling purposes during process control operation.</td>
</tr>
<tr>
<td>No. of Valves in Control System</td>
<td>Arrangement and number of valves in the control system affects system response as well as operational philosophy for the surge control system.</td>
</tr>
</tbody>
</table>

Various actuation systems are available for the recycle valve using different valve types. Ball valves, globe valves and needle valves have been used effectively and offer different advantages for the different operating environments. (See Figures 14 and 15 for examples of typical actuation systems for the globe valve and ball valve types). For two recycle valve systems, using a combination of valve types may serve to better meet the dual functionality requirements under different surge environments.

Often the controller and actuation system can affect how the valve is opened. The valve characteristic is not equivalent to the overall controller / system characteristic. A linear valve can be actuated in a manner resembling an equal percentage valve through the use of controller bias. This should be considered in selection of the valve type.
Figure 14. Typical Globe Valve Assembly and Actuation System

Figure 15. Typical Ball Valve Assembly and Actuation System
### 3.3.2 Recommended Recycle Valve Specifications

The performance specifications in Table 3 have been used by manufacturers of surge control valves. The specifications vary based on the operating environment. In addition, the specifications are given in terms of dynamic performance criteria to provide smooth and reliable operation of the valve.

#### Table 3. Recycle Valve – Recommended Dynamic Performance Specifications

<table>
<thead>
<tr>
<th>Performance Criteria</th>
<th>Importance for Operating Environment</th>
<th>Specification</th>
</tr>
</thead>
</table>
| Response Time with Position Controller                            | For process control and start-up environments | Time (sec) \( \leq 0.3 + (0.1d_{\text{port}}^{0.5}) \)  
where \( d_{\text{port}} \) = minimum diameter in inches across the valve |
| Response Time for Solenoid Trip                                   | For Shutdown: Response time for valve full open in shutdown environment is more stringent than process control with position controller. | Time (sec) \( \leq 0.1 + (0.1d_{\text{port}}^{0.5}) \)  
where \( d_{\text{port}} \) = minimum diameter in inches across the valve |
| Flow Capacity                                                     | Key to protecting compressor in shutdown environment. |Valve Flow = (1.8 to 2.2) \( \times Q_{\text{max}} \)  
\( Q_{\text{max}} \) = Maximum surge point flow rate (typically at peak head at LASM) |
| Opening Dead Time                                                 | Required for all operations.           |Dead Time \( \leq 0.4 \) seconds |
| Valve Movement                                                    | Required for all operations.           |No stick / slip motion |
| Large Amplitude Response with Step Change from Baseline           | Important for process control and startup environment – overshoot must be minimized to assure adequate flow control. |Max of one overshoot per step in opening direction < 3% calibrated span. Minimize overshoot in closing direction. |
| Frequency Response with 20% peak-peak input signal centered around 50% of calibrated span | Helpful to quantify valve performance in all environments |Gain and Phase plots should be continuous with no resonant peaks. |
| Maximum Control Signal to Initial Movement off the Valve Seat     | Key to assuring valve motion is confirmed with minimal control signal for process control / start-up where signal may be fairly low (i.e. minimal gain as opposed to shutdown env.) | \( \leq 2\% \) |

Testing of the recycle valve for frequency response, amplitude step response in both directions (opening and closing) is recommended for valves configured with custom pneumatic systems or particularly large recycle valves (> 12 inch diameter). Complicated actuation systems on large recycle valves will introduce new dynamics into the valve actuation system that may cause a departure from linearity in the response. Response time or stroking time of the valve should not be used as the only criterion in selection of the recycle valve because this will impair the controllability of the valve and robustness of the design, needed for the process control environment.
3.3.3 Recycle Valve Considerations for Process Control Environment

Valve actuation system requirements primarily stem from the process control environment – not the shutdown environment. The actuation system for the valve during process operation should be capable of modulating control. In addition, a linear valve should be used for process control but the goal should be to enable a linear system response. The linear characteristic provides precise recycle valve flow control at all valve positions. The response time is not critical to this environment. In this setting, the booster system is only needed to help the valve open because the valve should be capable of closing on its own. A recommended response time criteria for the recycle valve process control environment:

\[
\text{Time (sec)} = 0.3 \text{sec} + (0.1 \text{sec/in} \times \sqrt{\text{portsize (in}^2\text{)}}) \quad \text{(Eq. 3-1)}
\]

The key parameter to the recycle valve in the process control environment is precise control of the valve position. It is necessary to specify the speed for which the valve is allowed to change position and the amount of overshoot permitted. Overshoot of the valve should be determined in a position versus time plot (see Figure 16.) The position of the valve in time defines a triangle of overshoot area based on the amount of overshoot and recovery time. This area should be held to a minimum allowable value – in order to define the performance of the surge control system in the process control environment.

![Figure 16. Recycle Valve Position vs. Time in the Process Control Environment](image)

3.3.4 Recycle Valve Considerations for Startup Environment

In the startup environment, the key criteria is to match the valve characteristic to the compressor performance map to assure that the compressor can come up to full speed as the recycle valve is closed. In startup, the compressor will initially operate with the valve at 100% open. The valve characteristic for 100% open should be sufficiently removed from the compressor operational window when the valve characteristic is overlaid on the performance map (see Figure 17). The surge limit will be equivalent to a particular valve capacity, which should be well below 100%.
As the recycle valve is closed, the valve characteristic should match the operational range of the compressor. A minimum valve percentage opening will lie to the left of the surge line, which defines the range of valve positions that can be used to bring the compressor online. Oversized valves will not provide the sensitivity required for particular operational settings and will restrict the performance of the compressor (the valve characteristic lines will be too far to the right of the operation). Undersized recycle valves will not adequately protect the compressor during a sudden shutdown of the system at the higher flow rates.

![Matching of Valve Characteristic to Compressor Performance Map](image)

**Figure 17. Example of Matching Valve Characteristic to Compressor Performance**

It is important to evaluate the startup environment using different gas compositions that may be expected for the compressor, other than the typical design gas. The recycle valve capacity requirement can vary considerably based on the startup gas composition. Additional capacity at the same flow rates will be needed for a lower molecular weight startup gas because of the reduced compressor head.

**3.3.5 Recycle Valve Considerations for Shutdown Environment**

The key requirements for the recycle valve in this environment are response time and flow rate capacity for the given discharge system volume. For an emergency shutdown, the valve opening time is critical. Typically for the first 1 second period after shutdown, the compressor deceleration will reduce the speed by approximately 30 percent and the head by 50 percent. This deceleration period can take as long as 5 seconds depending on the machine. To maintain flow through the compressor, the recycle valve must begin to open within the first second after the downstream check valve is closed. A recommended response time requirement for the valve is:

\[
\text{Time(sec)} = 0.1\text{sec} + (0.1\text{sec/in} \times \sqrt{\text{portsize(in}^2)})
\]  

(Eq. 3-2)

This is the necessary required time to de-energize the solenoid for a valve which is normally open. The booster on the valve actuation system will help to enable a quick response from the valve. Response time
for initial opening of the recycle valve should be requested from the valve manufacturer. In addition to checking the response time of the valve, the valve opening time should be mapped against the compressor deceleration curve to assure that the valve characteristic will protect the compressor (see Figure 18). The blowdown / deceleration of the compressor system with any residual heat should be mapped over the valve opening time to determine if response time is acceptable.

![Figure 18. NPT Deceleration and Valve Opening Response](image)

Sizing the recycle valve to match the system volume is the second requirement for the recycle valve in the shutdown environment. If the valve meets the necessary response time, it may still not protect the compressor adequately because its flow capacity does not match the system downstream volume. The flow rate capacity of the valve is not sufficient to relieve the compressor head rise in some cases. The overall piping system volume may require more than one valve in a surge avoidance system.

The sizing of the valve can be evaluated in a flow rate versus time plot (see Figure 19). If the compressor is surging early in a flow versus time plot – additional valves should be added to provide more flow capacity in a quicker time period. Changing the one recycle valve to larger diameter will not help in this situation. If the compressor is surging late in the valve profile – changing to a different valve characteristic will help to avoid surge. (See discussion of surge impact criteria in Section 6.2.)
Figure 19. Compressor Surge Occurrence vs. Ideal Control Provided by Recycle Valve

3.3.6 Simplification of Recycle Valve Requirements for Single Valve System

The competing requirements for the recycle valve make use of multiple valve systems appealing. This approach to surge control system design is often not the most cost-effective solution. In addition, the use of multiple valves for each surge control function will require additional testing to assure that the transition into and out of each operation is smooth.

A single valve system may be successfully implemented where the recycle valve is a compromise of the various requirements for start-up of the compressor, process control and emergency shutdown. An example of the selection of a single valve system is compared to valve selections based on each surge environment in Table 4.

The requirements for each surge environment can easily be met with the selection of individual valves. Design of a single valve system requires consideration for all three environments. The single valve system design achieves surge avoidance successfully when the additional requirements of all operations are considered. Requirements that must be modified or redesigned for the single valve system include the opening speed time, the sizing of the valve, valve characteristic and type, and the actuation system.
Table 4. Example of Requirements for Design of Single Recycle Valve System.

<table>
<thead>
<tr>
<th>Valve Requirements</th>
<th>Valve for Start-up Operation</th>
<th>Valve for Emergency Shutdown Operation</th>
<th>Valve for Process Control Operation</th>
<th>Single Valve System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opening Speed</td>
<td>--</td>
<td>Fast</td>
<td>Moderate</td>
<td>Very Fast</td>
</tr>
<tr>
<td>Closing Speed</td>
<td>See (1)</td>
<td>--</td>
<td>Modulate</td>
<td>Moderate</td>
</tr>
<tr>
<td>Sized to Match</td>
<td>Compressor</td>
<td>Volume</td>
<td>Compressor + Volume</td>
<td>Compressor + Volume</td>
</tr>
<tr>
<td>Characteristic</td>
<td>--</td>
<td>Linear</td>
<td>Equal Percentage</td>
<td>(3)</td>
</tr>
<tr>
<td>Style</td>
<td>Ball Valve, (2)</td>
<td>Ball Valve, (2)</td>
<td>Globe Valve</td>
<td>Globe or Noise Attenuating Ball</td>
</tr>
<tr>
<td>Actuation</td>
<td>1/0</td>
<td>1/0</td>
<td>Modulating</td>
<td>Modulating</td>
</tr>
<tr>
<td>Actuation</td>
<td>--</td>
<td>--</td>
<td>Symmetrical</td>
<td>Asymmetrical (4)</td>
</tr>
<tr>
<td>Positioner</td>
<td>--</td>
<td>--</td>
<td>Required</td>
<td>Required</td>
</tr>
<tr>
<td>Solenoid 1/0</td>
<td>--</td>
<td>--</td>
<td>Required</td>
<td>Required</td>
</tr>
<tr>
<td>Position Feedback</td>
<td>--</td>
<td>--</td>
<td>Required for testing only</td>
<td>Required for testing only</td>
</tr>
<tr>
<td>Limit Switches</td>
<td>--</td>
<td>--</td>
<td>Required for testing only</td>
<td>Required for testing only</td>
</tr>
</tbody>
</table>

Highlighted cells indicate compromise on valve requirement for optimal single valve system.

Note 1: Speed of closing must assure smooth transition to process control valve.
Note 2: Capacity and simplicity make ball valve the typical choice, but other types may offer other advantages.
Note 3: Equal percentage valve required to control valve in process control and fulfill capacity requirement for shutdown.
Note 4: Asymmetrical actuation required for single valve system.

### 3.3.7 Noise Attenuation

Recommended maximum noise level for the recycle valve is 85 dBA or less during normal operations measured at 1 meter downstream of the valve and 1 meter away from downstream piping. Noise requirements for the valve during partial or fully recycle may be different from those during a compressor ESD event. Various noise attenuation techniques may also be considered from a system design standpoint.

Noise attenuating ball valves are often sold for this application. Globe valves with noise attenuation tend to get blocked because of the perforation pattern design in the valve trim. Ball valves typically use a noise attenuation system that allows flow and debris in the line to pass through the valve. The drawback to the noise attenuating ball valve is that at a higher percentage opening, the noise attenuation tends to be less. The ball valve will be fully open for a very short time during the shutdown operation. During process control operation, the ball valve will typically be less than 50% open.

### 3.3.8 Dynamic and Static Considerations

For static considerations, the valve actuation system dead band should be limited to 1.0% or less of the valve span. The dead time for dynamic considerations should be minimized and should not exceed 0.4 seconds. The recycle valve system should be tested to conform to the manufacturer specified linearity and input signal resolution. The valve stroke time and step response time should be quantified. Valve overshoot may be allowed, but the opening direction overshoot should be adjustable in the field. The overshoot in the closing direction should be minimized to provide better precision for process control.
3.3.9 Use of Multiple Valves

In many cases, a single recycle valve can be used successfully to protect the compressor during process control, start-up and emergency shutdown. The recycle valve system must meet the different system requirements imposed by the compressor surge events as well as the station operation requirements. For a slow progression into surge (as in process control), the valve should behave as a small valve and produce smooth throttling. For the fast progression into surge (such as the shutdown environment) the valve should behave as a large valve and produce sudden changes in the compressor operation. The quick opening valve is the best choice for the shutdown environment. The process control environment calls for a linear or equal percentage valve.

These competing demands often justify the use of more than one recycle valve if the single recycle valve in the control system cannot meet the requirements of all the functioning environments. But the use of multiple valves is typically used to “fix” the surge control system and required mainly due to improper design / sizing initially. Also, if surge avoidance is the objective in the design criteria, the valve specifications may be more severe compared to a system designed using a set of surge impact criteria (see Section 6.2).

If two parallel valves or two recycle loops are justified, the designer should consider implementing both valve types to suit the different operating environments. Parallel recycle loop valves and the use of hot and cold recycle valves in two recycle loops are options that should be considered to add capacity and reduce valve response time (see Section 2.3 for more alternative arrangements). These options may also add redundancy to the system, which may be advantageous in some cases if the actuation system is not reliable.

The primary reason to employ two valves is to gain more functionality and/or speed from the control system response for the emergency shutdown situation. The multiple valve configurations can also be used if a cooler is needed for part of gas in recycle loop.

A larger linear characteristic valve may be replaced by two smaller quick opening valves for installations requiring faster depressurization. Increasing the number of valves will add significant complexity to the design and should be clearly justified by a notable increase in performance and controllability. The smaller valves will provide a significant increase in opening speed. Comparison of the two options will show that a two smaller quick opening valves can provide more flow capacity in a given length of time (250 ms for example) than a single linear characteristic valve. When operated in cascade, the two smaller valves will provide approximately the same flow capacity as the larger valve if the valves are all of the same type.

3.3.10 Valve Position Uncertainty

The valve position should be known with some degree of certainty based on the valve characteristic models supplied by the manufacturer. This can be accomplished by calibrating the valve or valve position indicator or through field verification. The important parameter in the surge control system is the distance from the surge line. Even if a valve is not performing exactly within its specified position, the surge control system will only depend on the valve’s ability to open or close.

Various sources can lead to uncertainty in the valve flow capacity determination – the valve position indicator functionality, the reference valve characteristic plot or blockage in the valve flow passage. In
diagnosing the surge control system, the valve position should be verified to assure that the surge control system accurately determines the valve flow capacity based on valve position. The surge control system should provide the correct signal to the recycle valve to open or close to the desired valve flow capacity.

### 3.4 Control System Instrumentation

Surge avoidance is based on the control system being able to determine the available surge margin based on the compressor operating point in real time. The determination of the compressor operating point relies on the measurement instrumentation. The key measurements are the suction and discharge pressure, suction and discharge temperature and flow rate through the compressor (see Figure 12). The instrumentation used to determine the operating point of the compressor must be capable of determining the compressor flow, head and speed.

Flow meters (DP type, suction to eye method, or venture type) are routinely used in a surge control system to compare the flow rate surge limit (as a function of compressor head) to the actual flow because this approach has a high sensitivity to detecting surge. The flow rate through the compressor will change quickly if the compressor is approaching the surge line. Measurement of compressor head (i.e. differential pressure across compressor) will not be as sensitive to detecting changes in the compressor operation as the compressor moves toward the surge line.

The choice of instrumentation governs the accuracy of the surge control system and its ability to detect surge. Uncertainties in the flow or head measurement will affect the prediction of surge – see section 3.4.5. In addition, pressure and temperature instrumentation in the suction and discharge lines should be selected based on accuracy and response time. The avoidance of surge is dependent on the response time of the transmitters in the system in detecting the onset of surge.

#### 3.4.1 Flow Measurement

Various flow measuring devices may be used to measure the compressor flow. A comparison of the typical flow measurement methods and tradeoffs associated with each method is given in Table 5. The transmitter in the flow measurement system will typically determine response time.

Differential pressure devices (orifice, pitot tube, etc.) will have an inverse relationship between the differential pressure transmitter range and response time. High differential pressure signals increase the response time of the transmitter, so operating at the high end of the transmitter range is preferred. The selection of flow measurement devices which rely on differential pressure (i.e. orifice meters) must account for the possible flow rates and may require specialized low range transmitters for lower flows. However, low differential pressure transmitters will often have a slower response time than the higher speed transmitters due to the internal diaphragm designs. Orifice flow meter requirements are specified in American Petroleum Institute Manual of Petroleum Measurement Standards (API MPMS) Chapter 14.3, “Natural Gas Fluids Measurement – Concentric, Square-Edged Orifice Meter.”

The pitot tube device is an insertion type of meter that allows flexibility in the installation because extensive piping or customized spool pieces are not required. Differential pressure readings will be similar to an orifice meter. The insertion type devices are slightly less reliable because these devices are more susceptible to damage. Installation near the compressor inlet is also a risk factor to the compressor if the insertion probe is damaged or a fatigue failure causes the element to break off and be ingested by the compressor. All differential pressure flow devices must meet a test protocol standard specified in American Petroleum Institute Manual of Petroleum Measurement Standards (API MPMS) Chapter 5.7, *Testing Protocol for Differential Pressure Flow Measurement Devices*. Specific installation requirements
for DP type meters should be provided by the meter manufacturer and should assure that the meter conforms to API MPMS Chapter 5.7.

Table 5. Comparison of Typical Flow Measurement Methods for Compressor Surge Control System.

<table>
<thead>
<tr>
<th>Flow Measurement Method</th>
<th>Relative Cost</th>
<th>Size of Meter</th>
<th>Reliability</th>
<th>Signal Strength</th>
<th>Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pitot type</td>
<td>Good</td>
<td>Good</td>
<td>Fair: Insertion type device – more inclined to failure / contamination</td>
<td>Fair: Low flow / Low DP will produce less reliable signal</td>
<td>Good / Fair</td>
</tr>
<tr>
<td>Orifice meter</td>
<td>Good</td>
<td>Good</td>
<td>Good / Fair</td>
<td>Fair: Low flow / Low DP will produce less reliable signal</td>
<td>Fair / Poor: Affected by flow conditioning, installation can cause errors</td>
</tr>
<tr>
<td>Venturi meter</td>
<td>Fair: Requires more cost than other tech.</td>
<td>Good</td>
<td>Good / Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
<tr>
<td>Suction to eye</td>
<td>Good</td>
<td>Good</td>
<td>Fair: Placement of taps / dirt will affect performance</td>
<td>Good / Fair</td>
<td>Fair / Poor: Accuracy decreases in critical flow region near surge limit</td>
</tr>
<tr>
<td>Ultrasonic meter</td>
<td>Poor: Typical wetted, spool piece ultrasonic meters are most costly flow meter available</td>
<td>Good</td>
<td>Good / Fair</td>
<td>Good</td>
<td>Good</td>
</tr>
</tbody>
</table>

Suction to eye measurement is basically a differential pressure flow measurement method, where the differential pressure drop across the inlet of the compressor is measured. The square root of the differential pressure is proportional to flow. In the typical mass flow rate equation (see below), the flow coefficient, C, is adjusted for the impeller geometry.

\[
q_m = CE \frac{\pi}{4} d^2 \sqrt{2\Delta p_{ps}}
\]  

(Eq. 3-3)
Suction-to-eye measurement uses the inlet shroud of the compressor as the flow measurement device, but the eye port placement is critical to assuring that the differential pressure measurement is not disturbed by the recirculation area near the impeller. The disadvantage to this method is that it becomes vastly more inaccurate as the compressor approaches surge and the turbulence increases. However, the signal to noise ratio of this method is good because the DP signal is typically higher than an orifice or pitot tube measurement for the same flow rate. The key to measurement accuracy with the suction to eye method is where the manufacturer has selected to put eye port. The port placement should allow the flow induced DP to be measured accurately across the entire flow range. Incorrect choice of the port location will introduce large errors. The advantages to this method are its relatively low cost and the inability to alter the DP reading based on compressor station variations.

Venturi meters (sonic nozzles) may also be used to measure gas flow through the compressor. These meters will have a lower pressure drop than an orifice meter. As with all differential pressure devices, the flow measurement error is sensitive to the measurement of differential pressure across the device. Typical meter accuracy is 0.5 to 1.5% if the differential pressure sensor is calibrated and operating well within its range. Venturi meters and differential pressure (DP) type meters are similar to an orifice meter, in that large installation errors can occur (1 to 5%) if installed incorrectly. Installation guidelines for venturi meters are provided in ISO 5167, Measurement of Fluid Flow by Means of Orifice Plates, Nozzles and Venturi Tubes, and ASME MFC-3M-1989, Measurement of Fluid Flow in Pipes Using Orifice, Nozzle and Venturi Tubes.

### 3.4.2 Pressure Measurement for Compressor Head

The surge control system also requires the measurement of compressor head, based on pressure differential across the compressor. The compressor head is determined by the temperature and pressure measurement in the compressor suction and discharge. If the compressor system uses a “head rise to surge” view of the surge margin, the pressure measurement should be made with high frequency dynamic transducers. In addition, the pressure measurement will not be accurate if the transducer is not installed on the pipe taps properly (see Section 4.0 on installation). Typically, fast response dynamic transducers require frequent calibration and may show drift due to temperature changes in the flowing gas stream.

The instrumentation selection should be based on performance specifications an order of magnitude better than system requirements (i.e. if the gas compressor system has a first time constant of about one second; the related instruments should have a time constant of no more than 100 ms). For a surge control system to discriminate between single digit percentages of surge margin, the pressure and temperature instrumentation must be capable of measuring head to within 0.1 percent. The range of the transmitters should also be carefully scaled in relation to the compressor operating range to provide sufficient resolution, but avoid over-ranging the transmitters in any event.

### 3.4.3 Temperature Measurement for Compressor Operating Point

Temperature measurement is also used to determine the compressor head. Typical temperature measurement instrumentation for the compressor system includes thermocouples, thermistors, and resistance temperature devices (RTDs). RTD’s are recommended for measurement of temperature in the flow stream over a broad temperature range. Thermocouples can be used for high temperature measurements, but below 200°F the resolution will be reduced. Thermocouples tend to drift more than RTDs and will require more frequent recalibration.
3.4.4 Uncertainty in Pressure, Temperature and Flow Measurement

Uncertainty in the pressure, temperature or flow measurement will cause the surge control system to over or under predict the occurrence of surge. If the occurrence of surge is over predicted, then the compressor operation will be limited by more than the allowable surge margin. If surge is under predicted, the surge control system will have less time to respond – which will reduce the protection margin. In either case, the measurement uncertainty should be minimized. Flow measurement uncertainty may be as large as 3-5% if installation bias errors are present (such as an orifice plate immediately downstream of a 90 deg elbow). Large measurement uncertainties on this order will completely remove the protection afforded by the surge margin (typically less than 10%). Additional factors influencing the uncertainty in the compressor surge detection are given in Section 8.3.

Table 6 gives typical values of in-practice achievable uncertainties for the compressor surge control system measurements. For compressor measurements derived from an equation of state (such as enthalpy, isentropic coefficient, and density), there is an added inherent uncertainty, since the equation of state is an empirical model. Unless direct experimental data for comparison is available for the gas composition used in the performance test, it is difficult to quantify the added EOS model uncertainty. The compressor head and flow measurements will be affected by the uncertainty in the EOS model unless the reduced head and flow are used in the surge control system.

<table>
<thead>
<tr>
<th>Measurement</th>
<th>Recommended Uncertainty</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pressure</td>
<td>0.3 - 2.0% Full Scale</td>
</tr>
<tr>
<td>Temperature</td>
<td>0.3 - 4.0 ºC</td>
</tr>
<tr>
<td>Flow</td>
<td>1.0 – 3.0% of value</td>
</tr>
<tr>
<td>(for clean gas)</td>
<td></td>
</tr>
<tr>
<td>Gas composition</td>
<td>0.2 – 3.0% of value</td>
</tr>
<tr>
<td>(Density, enthalpy, isentropic coefficient)</td>
<td></td>
</tr>
</tbody>
</table>

3.4.4.1 Flow Measurement Uncertainty

The flow measurement uncertainty is affected by: 1.) Installation errors: All meter types should follow required upstream length / flow conditioning specifications. If the flow profile is not fully-developed or not flow conditioned, most DP meter types will produce a bias error in the flow measurement. 2.) Range of the flow measurement: Any DP meter type will have a higher uncertainty on the low end of the DP transmitter range. 3.) Pulsation in the flow field: Pulsation adversely affects most types of meters and will add to the uncertainty in the test measurement. However, as most flow measurement instruments provide a low frequency output response, it is often difficult to determine pulsation magnitudes and frequencies.

Orifice meters are susceptible to installation-effects resulting from improperly conditioned flow, insufficient upstream length, upstream bends, elbows or valves, or extreme beta ratios (>0.65). If installed correctly with a beta ratio less than 0.65, orifice meters will provide a flow measurement accuracy of less than 1.5%. Other DP meters will have similar uncertainty. The suction to eye measurement should be considered to have a higher uncertainty, especially for flow points near the surge point where the inlet suction flow will have considerably more turbulence.
3.4.4.2 Pressure Measurement Uncertainty

The precision uncertainty in pressure measurement will depend upon the uniformity of the flow field. If piping vibration or flow-induced pulsations are high at the location of the static pressure measurement, the measurement of pressure will show a significantly higher random uncertainty. Non-uniformities, location, installation, and calibration errors will affect the pressure measurement. The main source of pressure measurement error is incorrect installation and location of pressure probes. The installation should meet the upstream and downstream requirements for pressure probes given in ASME PTC 10. Installation configurations, which do not meet ASME PTC 10, will have significantly higher location uncertainties in pressure measurement.

3.4.4.3 Temperature Measurement Uncertainty

Uncertainties in the temperature originate from the following five major sources of error: (i) location: incorrect position of the thermal sensor in the gas stream; (ii) installation: wall conduction heat transfer to and from the sensor due to inadequate insulation; (iii) calibration: instrument drift, nonlinearities, cold junction, and reference temperature errors; (iv) device: inherent accuracy limitations of the sensor device; and (v) acquisition: amplifier, transmission, noise, read, and analog-digital conversion errors.

Location, installation, and calibration errors may be minimized easily in production or laboratory test facilities. However, for field measurements it is more difficult to minimize uncertainty because of the station installation and configuration. Location, installation, and calibration errors are the dominant factors in the temperature measurement uncertainty, while the device and acquisition errors are a smaller contribution to the total temperature error. The installation should meet the upstream and downstream requirements of ASME PTC 10 for temperature sensor installation. Installation configurations, which do not meet ASME PTC 10, will have significantly higher location uncertainties in temperature measurement.

3.4.5 Transmitter Response Time

A common cause of surge control system response time delays is the instrumentation selection. Transmitter selection will usually not be ideal choice for the surge control system. The transmitter and control system must respond to system changes as fast as the compressor surge rate. The actual surge rate may be determined experimentally, but in general the compressor surge rate can be estimated based on the flow rate through the system divided by the downstream volume:

\[
(Time_{\text{surge}})_{\alpha} \left[ \frac{Q}{V_{\text{downstream}}} \right]^{\beta}
\]  

(Eq. 3-4)

This relationship should guide the overall decision process on the type of transmitters to select for different systems. The transmitter response time should be as fast as possible because compressors can approach surge rapidly.

The response time of a transmitter for the measurement a process variable used by the surge control algorithm should be less than 100 ms. This nominal value is available in many smart / analog transmitters – but transmitters with response times greater than 100 ms should be avoided for compressor control applications. Response time of a transmitter is typically quoted by the vendor specifications for the upper range of the device. Operation at the low end of the transmitter range will add an additional time delay.
For low differential pressure measurements, the design of the transducers require sensitive and loose diaphragms, which will respond more slowly to a change in pressure. A fixed “dead time” also needs to be considered by the designer in estimating system response time for smart transmitters.

3.4.6 Other Considerations for Differential Pressure Measurement

Improving repeatability (and reducing measurement uncertainty) by correct selection of the instrumentation and head / flow measurement devices will allow the compressor to operate closer to the surge line without an increased risk to the surge control system. Reduced measurement uncertainty on the flow or head measurement should also improve the compressor efficiency for the surge control compressor system. The common causes of transmitter error are the following:

- **Ambient Temperature and Humidity Variations**: The ambient temperatures at some locations can vary widely. Typically, the station transmitters are located outside and exposed to all the “real world” elements, including ambient temperature and humidity. The ambient temperature and humidity changes will affect the transmitter reading. At extreme upper or lower temperatures, the variation will be significant on the readings for the DP transmitters.

- **High Static Line Pressure**: High line pressures (>1000 psi) will affect the differential pressure transmitter used for the flow measurement. If the compressor suction flow is being measured at a high static line suction pressure (or discharge flow is measured for a high static line discharge pressure), the DP transmitter should be calibrated for the higher line pressure application.

- **Transmitter Installation**: Installation issues can cause the DP transmitter to give erroneous readings. The most common issue is liquid entrapment in the sampling line. This can be avoided by orienting the transmitter on the line horizontally (so that condensate drops out of the sample line before reaching the inlet to the transmitter.) Volume bottles in the sample line should also be avoided to provide faster DP response.

- **Inherent Damping**: DP transmitters may have damping levels that can be set by the user. The damping level should be minimized for this application to provide quick response.

These factors will cause the transmitter readings to drift and produce an error in the flow measurement / head measurement for the surge control system. The error will typically be more severe at the lower end of the transmitter range.

3.5 Piping System

The arrangement of the downstream check valves and the recycle loop(s) affects the amount of gas volume contained in the piping system. The mass of gas directly relates to the requirements for the recycle valve in the surge control system and the startup time for the unit. The downstream volume will affect performance of the surge control system in the shutdown and startup environment. The downstream piping volume requirements are in direct competition in the startup environment compared to the shutdown environment.

3.5.1 Startup Operation Requirements for Piping System Volume
For startup, a larger downstream piping volume will allow for more time to bring the compressor up to speed because a larger mass of gas will take longer to heat up. Addition of a cooled recycle loop to aid in the startup situation will help to ease the competing factors in the two environments. The minimum and maximum allowable volumes can be calculated to assure the surge control system adequately protects the compressor and that startup is possible given the amount of recycle time. A faster compressor startup time will help to keep piping volumes small.

The effect of piping volume on the discharge temperature rise during startup is shown in Figure 20. The baseline case uses a typical discharge 24” pipe diameter with a hot gas bypass loop. This system allows for approximately 23 minutes of startup time before the high discharge temperature set point is reached. Increasing the piping volume causes the allowable startup time to increase by moving the discharge temperature curve to the right in Figure 20. A decrease in piping volume causes the discharge temperature to rise more quickly. This results in a shorter startup time requirement before the high discharge temperature alarm is reached.

The startup time should be evaluated for the particular compressor and piping layout design. Modeling of the startup operation is discussed in Section 7.2.

![Discharge Temperature Rise During Startup](image)

**Figure 20. Discharge Temperature Rise for Different Piping System Volumes**

**3.5.2 Process Control Operation Requirements for Piping System Volume**

During the process control operation, large piping volumes will influence the amount of response time and control scheme for operating the recycle valve. Larger piping volumes may also require a larger valve size to meet the flow rate requirement for depressurization of the system under the ESD operation. The valve size will affect its controllability – larger valves will be harder to control. Because of the
influence on the process controllability and the requirement to minimize discharge piping volume for the shutdown operation, the piping volume should be as small as possible to meet the startup operation requirements.

3.5.3 Shutdown Operation Requirements for Piping System Volume

For shutdown, a minimum downstream volume is optimal as this will ease the flow rate and response time required for the recycle valve. The valve capacity must match the size of the downstream piping volume in order to be able to protect the compressor from surge. Larger volumes will require more time to equalize pressure (i.e. downstream pressure will be more difficult to reduce if the volume downstream is large). If the operating point is far removed from the surge margin, then piping volume will not influence performance greatly because the required response time has been increased.

The behavior of the system in terms of depressurization is shown in Figure 21 for different piping volumes. If the discharge piping volume increases, the recycle valve will require a longer time to reduce the discharge pressure. For a smaller discharge piping volume, the same sized recycle valve can more easily relieve the discharge pressure. Discharge pressure is reduced more quickly with the smaller piping volume system, which results in better protection of the compressor and better surge avoidance design under the shutdown operation.

![Discharge Pressure Drop for Compressor Deceleration](image)

**Figure 21. Reduction in Discharge Pressure for Different Piping System Volumes**

In calculating the maximum allowable volume based on the shutdown scenario, the piping system behavior is relatively simple to calculate accurately. The rate of deceleration of the compressor is more difficult to predict. A simple dynamic model can be used to study the surge control system performance given an assumed deceleration rate. In the model, the deceleration time can be varied within a typical uncertainty margin to determine the maximum piping volume required to avoid surge in the shutdown environment. The model implementation and design for surge avoidance is discussed in Section 6.0 and Section 7.3.
3.6 Control System Hardware

Surge control system hardware varies depending on the user requirements, station operation and the integration of the hardware with the entire station PLC. Most surge control system operate with similar controller hardware. The surge control system is either integrated with the station controls or as a stand alone surge control system.

3.6.1 Integration of Surge Control System with the Station PLC Systems

The surge control system must have some communication with the station driver, to assure that the surge control system is aware of the driver operation of the compressor. Integrating the turbomachinery control system will add more controllability during reduced or part load operation. In addition, the controls for the station should not interfere or conflict with the surge control system signals. Decoupling of the surge and capacity controllers is recommended to reduce the conflict between the surge control system and capacity control system at low flow conditions. If the surge control system is packaged with the station controls, the integration conflicts are less of a concern. If an older system is being retrofitted with a new surge control system, the user should consider retrofitting the driver controls or at a minimum, reviewing the operation of the PLC for the driver.

3.6.2 Surge Control for Multistage Compressors

Multistage compressors may require dynamic decoupling between compressor stages for smooth operation in the process control environment. Opening the recycle valve for a low pressure stage will cause a reduction in flow to the high pressure stages. To protect high pressure stages, the single control system should open the recycle valves for each stage in a staged control scheme to reduce the impact on the operation and avoid surge on the high pressure stages.

3.6.3 Surge Control System Implementation Outside of the Station Control

A separate surge control system is often installed in addition to the compressor controller. The functionality of the station process controls and the surge controls may require this separation. This arrangement may work better on simple stations without multiple recycle loops or extensive capacity control systems. The non-integrated option will add complexity to the overall interconnections and communication signals. The control system for the station may also have gas turbine startup sequencers, variable speed electric motor drives and process overrides which will need to be considered.

3.6.4 Surge Control System Resolution Requirement

If the surge control system is not packaged with the overall station PLC, the control system may have a resolution limit that differs from what is needed by the surge control algorithm. The designer and station user should always consider the resolution requirements for the controller as a limiting factor in the availability of the signal information sent to the surge control algorithm. If a low resolution control system is used, the surge control system performance will be inhibited. Typically, new controllers will not be limited by resolution, but an older station could be equipped with a minimum resolution controller.
4.0 Installation of Surge Control Instrumentation

The design of the surge control system must consider the location of key components to optimize the response of the surge control and prevent operational problems. In the initial planning stages of designing a compressor system, the station operating company should consider possible locations for the downstream check valve, bypass / recycle loop(s), recycle valve(s), process coolers, cooler tie-in to the downstream piping, and the liquid separation vessels.

The various installation options may be reviewed through a transient analysis of the surge control system to determine the expected response and surge protection for each installation option. The overall volume of the piping, bottles and coolers will determine the system response to change. Since different compressor systems have distinct operations, it is important to consider each installation as distinct. One simple transient analysis method (described in section 7.2) utilizes a maximum allowable discharge system volume to prescribe the system design based on surge avoidance. Additional criteria on the compressor system piping volume may be determined through a transient model as described in Section 6.0.

4.1 Instrumentation

Special attention should be given to the installation of the surge control system instrumentation. The accuracy of the pressure and temperature measurement is dependent upon the selected location and installation. The total temperature and pressure should be calculated based on the pressure losses in between the measurement point and the compressor inlet or outlet flange and the gas stream velocity. All pressure, temperature and flow instrumentation should be calibrated frequently with the actual sensor and transmitter as a combined system, preferably in the actual compressor system installation.

The installation effects will bias the measurement and add to the compressor surge uncertainty. Additional discussion on surge uncertainty applied to measurement instrumentation is discussed in Section 8.3.

4.1.1 Pressure Measurement Instrumentation

The installation of the pressure transmitters, pressure tap size, and symmetry is critical to the measurement accuracy for any of the flow measurement devices requiring DP measurement. ASME PTC 10 provides specific guidelines for correct installation and location of pressure probes. The head measurement also relies on accurate DP measurement. For head or flow measurement applications, the pressure tapping should be inspected prior to installation of the pressure measurement device. Short gage lines should be used to avoid any gage line errors and avoid condensation collecting in low spots.

The tube and static tapping used to make the dynamic pressure measurement should have a constant length to diameter ratio and must be greater than 2. The ratio between the pressure tubing and the pipe diameter should be as small as possible to prevent the pressure measurement from altering the flow pattern. In addition, the wall taps should be exactly perpendicular and flush to the surface. Burrs or slag in the taps are not acceptable and will influence measurement accuracy.
4.1.2 Temperature Measurement Instrumentation

Thermocouple and thermistor devices should be inserted into a thermowell. RTD sensors may be used as direct insert devices. Direct insert RTD’s will provide a faster response time, which is preferred for surge control systems. The temperature sensor should be instrumented to a temperature transmitter, with a fast response time.

The measurement location should assure that the temperature sensor will be relatively insensitive to radiation, convection, and conduction between the temperature sensor and all external bodies. The insertion depth can produce a large error in the temperature measurement if the sensor is placed too deep or too shallow in the flow stream (see Table 7). The manufacturer safety guideline should be consulted on the insertion depth of RTD’s for RTD’s without thermowells or extra long thermowells. Compressor gas velocities can be significantly higher than typical pipeline transmission gas velocity and the thermowell depth will pose a risk to equipment.

<table>
<thead>
<tr>
<th>Pipe Diameter (inches)</th>
<th>Thermowell Depth (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>2.0</td>
</tr>
<tr>
<td>8</td>
<td>2.5-3.0</td>
</tr>
<tr>
<td>10</td>
<td>3.0-3.5</td>
</tr>
<tr>
<td>12</td>
<td>4.0</td>
</tr>
<tr>
<td>14</td>
<td>4.5-5.0</td>
</tr>
<tr>
<td>16</td>
<td>5.0-5.5</td>
</tr>
<tr>
<td>18</td>
<td>6.0</td>
</tr>
<tr>
<td>&gt;18</td>
<td>7.5 minimum</td>
</tr>
</tbody>
</table>

Note: Above 18-inch diameter, a minimum depth of 7.5 inches from the inner wall is enough to avoid pipe influence and breakage.

ASME PTC 19.3 provides further guidance on thermowell installation. Compressor system gas velocities can cause high fatigue stress on insertion devices near the inlet / outlet of the compressor.

4.1.3 Flow Measurement Instrumentation

It is recommended that the flow measuring device should be installed on the suction side of the compressor, but inside the inner most loop in the compressor/recycle loop piping system. If the discharge side is used, the flow measurement should be made downstream of any coolers and with correct temperature and static pressure measurement near the flow measurement point. Installation of the flow measurement device on the suction side of the compressor is recommended because the flow stream is more uniform and the measurement is not dependent on pressure compensation.

The upstream piping configurations at field compressor installation are normally not ideal and result in distorted velocity profiles at the meter. Non-ideal meter piping will result in errors in the flow measurement unless measures are taken to correct the metering configuration. The best solution is to use flow conditioners upstream of the flow measurement device or a sufficient length of straight pipe upstream.
5.0 Operation of Surge Control System

The operation of the surge control system must consider the range of possible operations and surge events. The typical events which can cause a centrifugal compressor to surge are described below. Additional recommendations for the delayed shutdown option are provided as well. The operation of the compressor should be verified in a simulation, as recommended in Section 7.0, prior to actual field site / factor test verification of the control system.

5.1 Typical Operating Ranges

The control system should be designed to work over the entire range of the compressor. The worst case conditions – highest discharge pressure, maximum allowable speed, largest pressure ratio differential and the lowest speed of sound for the gas – will provide the basis for the most demanding performance parameters for the surge control system. Obviously, all compressor operations and installations are not the same. The surge control system should only consider the possible range of operations and installation configurations for its particular station and compressor. For example, an air compressor and its surge control system have a distinctly different range of flow rates and pressure differentials than a natural gas compressor.

5.2 Control system operation under different conditions

The surge control system must be designed for the different surge environments but must always act to protect the compressor against the high fluctuating load on the compressor rotor, bearings and other internal components. During typical operation of the compressor, the surge system can provide process control by actuating the valve to provide additional flow to the compressor in response to the gradual changes. The control of the valve under the startup operation is similar where gradual, fine adjustments of the valve position are needed. The control system must function differently in the event of an emergency shutdown (ESD) where the power to the driven centrifugal compressor is immediately reduced. The surge control system must respond rapidly and cause the recycle valve to open, immediately reducing the discharge pressure.

The operating window for the compressor is defined by the surge limit on the left side of the map and the stonewall (high flow) limit on the right side of the performance map (see Figure 22.) The operation is further constricted by maximum speed or available power at the site and the minimum flow limit for the compressor. The operating window for the compressor is further limited by the uncertainty flow limit since these limits will contain an additional uncertainty depending on the operation, installation and gas conditions. The design of the compressor control system must consider these limits and provide sufficient fine-tuning to maintain the compressor operation within the allowable design window.
The following surge events provide a description of the operation of the surge control system performance that is required for various operations.

### 5.2.1 Typical Operation for Process Control

During normal process operation of the compressor, periods of lower flow will occur where the compressor begins to approach its surge limit and operate in stall. The typical low flow surge event is a slow progression past the protection margin of the compressor, based on steadily decreasing flow over a period of several hours. During low flow periods, the surge control system should act to gradually open the recycle loop. The control signal to the valve should result in a small and slow opening of the valve in this case - the recycle loop flow should be almost unnoticeable.

The normal low flow event is the primary event for most surge control systems, but should not be the only design consideration. Other events can have significantly different effects on the surge control system and its ability to protect the compressor. These events should also be considered in the design stage of the surge control system.

### 5.2.2 Emergency Shutdown or Fast Stops

An emergency shutdown or fast stop will cause the compressor to move towards the surge line more rapidly than a normal low flow operational period. An ESD can cause the compressor to cross over the protection margin suddenly (i.e. the allowable distance from the actual surge event – also known as the surge control line.) This type of surge event is particularly challenging for the surge control system if the compressor is operating at its maximum allowable head and close to the surge margin at the time of the sudden engine shutdown.
The ESD event is more challenging for the compressor when the discharge system volume is fairly large. For larger volumes (typical of a larger compressor), both the compressor inertia and the system discharge pressure will work against the reduction in compressor head. The deceleration of the compressor will require more time, thus the speed will be higher for a longer period of time. The discharge pressure will also tend to decrease slower as the recycle valve is less able to reduce system pressure for a larger discharge volume.

For the surge control system design in this type of event, the algorithm should provide a control signal that quickly opens the valve, even if the process is impacted and the recycle flow is noticeable in the compressor operation. The algorithm should be capable of providing the signal to open the recycle valve prior to crossing over the protection margin. The response of the system to the control is determined by the amount of gain used in the control signal and the recycle valve specifications.

5.2.3 Start-up Process

The selection and design of the surge control system will affect the start-up of the compressor station. During start-up the compressor uses the recycle gas loop to build up sufficient compressor discharge pressure. The design of the surge control system in the recycle loop must assure that the discharge check valve opens quickly once the discharge pressure starts to build. If the gas is continually recycled at 100% through the recycle loop and the discharge check valve does not open, the discharge gas temperature can rise quickly. The compressor will overheat before it reaches pipeline discharge pressure unless an after cooler is present inside the recycle loop.

5.2.4 Delayed Shutdown

The delayed shutdown option allows the control system more time to respond to the surge event by delaying the onset of surge through the compressor control system. **This option should not be used to aid the surge control system in an emergency shutdown event.** Non-critical shutdown events may utilize a turbine trip or delayed shutdown strategy because these events do not require a quick response from the surge control system. Examples of non-critical shutdown events can include high bearing temperature, high process scrubber level or high process gas temperatures.

A properly designed surge control system should protect the compressor, even in the event an emergency shutdown. The emergency shutdown is used to shutdown the compressor operation immediately when a significant danger is posed to the station operating personnel or machinery, outside of the normal operating procedures. In this regard, the surge control system should be capable of responding to an ESD and protecting the compressor by quickly reducing the head and providing more flow through the recycle valve.

If the delayed shutdown option is employed for critical events, the ESD procedure will not be carried out as it is intended to be used (in the event of emergencies outside the normal operation). Using the delayed shutdown option as a standardized procedure allows improperly designed surge control systems to be used and essentially defeats the purpose of the control.

The operating company should determine the definition of a critical shutdown as it applies to a particular installation. A critical shutdown is often determined by events that pose a significant threat to personnel, equipment or the environment. A HAZ-OP study can be used as the basis for categorizing the critical type shutdowns that should be ESD events (i.e. no delay or trip option). The classification of shutdown events as either critical or non-critical can be incorporated into the control system logic to automate the
turbine trip / delay function. This strategy helps to minimize the use of the delayed shutdown but keeps the option open for applicable shutdown events.

### 5.2.5 Discharge System Blowdown

Another option to consider for increased protection of the compressor system is a discharge system blowdown operation. A quick discharge blowdown line will some or all of the discharge system gas to be flared in the event of a sudden shutdown of the unit when operating close to or below the protection margin of the machine. Although this option will add some additional complexity to the control system and valve actuations, it is a relatively lower expense than adding more recycle loops or multiple surge control valves. When considering this option, the transient modeling process should be used to verify the discharge system allowable volume limit based on the surge control system response.

### 2.3.3 Operational Flexibility for Multiple Compressor Units

The operation of the station will be increasingly complicated by the number of compression stages and individual compressor trains. If two compressor trains share the same suction and discharge, the overall compressor head across each train will be fairly equalized. The flow distribution can vary dramatically based on the unit performance curves differing. This unequal distribution will cause one compressor to operate closer to the surge line than the other. Typically, if the compressors are closely sized to each other, the deviation in the performance curves should be small.

Load sharing between parallel units should be considered. Many factors in the station operation can cause the load to differ including varied gas compositions feeding different units and low station throughput. The asymmetry in the gas feed and piping systems can also cause load variation. Load sharing will help to avoid unnecessary recycling and more uniform surge control. Both units will also be capable of handling further reductions in throughput.

In designing the surge control system, operational flexibility should be considered so that one compressor unit can be isolated from the other units at a station. This may require independent bypass loops and quick closing valves at the suction side of each compressor. The quick closing valves will prevent overloading the other units if one compressor is shutdown. The independent bypass loops helps to quickly respond to an ESD event and independently bring the compressors back online.
6.0 System Design Criteria

The surge control system should be designed against a set of system design criteria. These criteria may be based on performance data (either modeled or measured at the field site) or the criteria can be developed based on a risk assessment. The recommended performance-based design criteria include: 1.) Surge Avoidance: The surge control system effectively avoids surge under any operating condition; 2.) Surge Impact Criteria: The surge control system is designed to avoid compressor surge at high energy conditions. Surge at low energy conditions is allowed based on surge impact criteria.

Either of these methods is acceptable, although both criteria rely on surge control system performance data to determine if the system design criteria have been met. Modeling of the surge control system is required to verify the design prior to installation or operation of the compressor. Alternatively, a risk based analysis may be used to determine if the surge control system minimizes risk to the compressor equipment. This type of analysis must be developed by the operating company to identify “high risk” installations based on the company’s tolerance for compressor surge and the avoidance of risk. Key areas to consider in a risk analysis are provided in Section 8.0.

6.1 Surge Avoidance

The emergency shutdown event typically requires the fastest response time and corresponding increase in recycle valve flow. Inlet valve closure, upstream equipment trip and separator upsets can also cause very fast flow disturbances. The rundown behavior of the compressor governed by its rotating inertia during a shutdown event determines how the compressor will transition into surge. To avoid surge, the compressor must respond to the shutdown event (which can occur at any operating point) and open the recycle valve. Surge avoidance is based on ensuring that the surge control system effectively provides recycled gas flow fast enough to avoid surge during an ESD event.

The surge control system has a given response time for an ESD event which can be calculated using a simple transient surge model (see Section 7.0). The surge control system response is a function of the discharge system volume and the “worst case” operating point. The worst case operating point should be selected by the designer as representative of the operation. This may be a typical operating point near the surge margin. Operating points at the lowest available surge margin (LASM) and the highest pressure ratio will require shorter response times.

The Surge Avoidance design criterion requires that the discharge piping system volume be held below the allowable maximum discharge system piping volume. Compressor surge is effectively avoided using this system design criteria because the surge control system will always be capable of avoiding surge so long as the discharge system piping volume is held below the allowable maximum volume.

6.2 Surge Impact Criteria

Due to many operational constraints, it is often not possible to design a surge control system that can completely avoid transient surge over the range of possible operating points of the compressor. An ESD event often causes the transient surge condition to occur when the compressor is operated outside its design window. Most manufacturers will not accept surge of their machines. The surge impact criteria should be applied by the operating company on machines which are viewed as tolerant of surge under low energy conditions.
Instead of requiring the surge control system completely avoid transient surge, an alternative system design criteria is to establish a range of conditions where transient surge is tolerable. For these cases, a set of surge impact criteria should be established. The surge impact criteria should determine the range of transient surge conditions where significant damage to the compressor may be avoided. The surge impact criteria should allow the machine to transition into surge during a shutdown event, but only under “low energy” conditions.

The speed at which surge occurs and the pressure ratio at the time of surge can be predicted by the transient model results (i.e. at what operating point the compressor operation crosses over the surge line in the transient model). These values can be compared to the compressor maximum allowable speed and the maximum allowable pressure ratio at the lowest allowable surge margin (LASM) to determine the adequacy of the protection provided by the surge control. By comparing the occurrence of surge to these decision criteria, the surge control system can be verified as adequate or may require a more extensive design.

Figure 23 shows a typical compressor performance map and defines the pressure ratio at the lowest allowable surge margin (LASM) and the initial operating point when the ESD event occurs. When the ESD occurs, the compressor begins to decelerate quickly and moves toward the surge line. The transitory path of the compressor on the performance map as it decelerates should be predicted by the dynamic model.

Once the actual surge line is crossed, the pressure ratio and speed at the time of surge are compared to the pressure ratio at the LASM and the maximum speed respectively to determine if the system meets the transient surge impact criteria. The normalized pressure ratio (pressure ratio at surge divided by the pressure ratio at the LASM) and the speed at surge divided by the max speed can then be plotted on in terms of the surge impact criteria, as shown in Figure 24.
Based on the surge impact criteria, the normalized pressure ratio must be less than 0.30 and the normalized speed must be less than 0.50 in order to assure adequate protection of the compressor system. For specific compressors, the surge impact criteria should be adjusted based on actual operational experiences and manufacturer guidance. Many compressors can withstand surge at higher than 0.3 critical pressure ratio. The pressure ratio and normalized speed values are provided as a broad example and may be overly restrictive for specific machines.

The surge impact criteria provide a means of assessing the adequacy of the surge protection, if transient surge is permitted during the shutdown event. The criteria should be used in conjunction with a transient model to determine if the designed surge control system protects the compressor. A simplified lumped system transient model or the more detailed fully transient model (both are described in Section 7.0) should result in a similar conclusion. However, the more detailed analysis should be more accurate and is recommended in the case of more complex systems involving more than one unit at a station or more than one valve in the surge control system.
7.0  Modeling of the Surge Control System

A dynamic surge model should be used to design the surge control system based on the particular compressor system. Once the system design criteria have been established, the dynamic surge model should be used to verify the design criteria have been met. In verifying the system design criteria, it is recommended that the dynamic surge modeling consider the most challenging operating case for the surge control system – an emergency shutdown event at the maximum permissible compressor head.

Dynamic modeling of the startup and normal process operation should also be performed to assist the operator in fine-tuning the compressor operation and assuring that adequate control is available in the surge control system. The modeling process and interpretation of results should consider the high uncertainty associated with any numerical transient model and the assumptions governing the compressor surge model. If the transient model predicts the compressor operation to narrowly avoid the actual surge condition, the high uncertainty of the model results should indicate that surge is possible. In this case, the modeling effort would suggest that the surge control system or downstream piping volume should be redesigned.

The dynamic surge model for the emergency shutdown operation may be fairly simple, where a basic “lumped system volume” is used to represent the discharge piping system. One approach using a basic fixed volume model is discussed in Section 7.3. The two types of models typically employed to evaluate startup operation are given in Section 7.2. A more complex dynamic model may also be needed to model more complicated systems with multiple recycle loops or more than one compressor unit. General guidance on using more complex transient models for the process control operation is provided in Section 7.4.

A number of basic empirical rules are used to determine if the surge control system adequately protects the compressor. For example, discharge volumes are typically kept to less than 6 seconds of discharge flow, as a target volume based on flow rate capacity of the recycle valve(s). These empirical rules are not necessarily physics based and only apply to a limited number of compressors and types of systems. A basic fixed volume model can be used in a spreadsheet based application to determine a more accurate system-specific discharge volume.

7.1  Model Requirements

The general information required to implement a dynamic model of the surge control system is outlined below. The guidance provided in the stipulated model input parameters and important physical effects can be used to build any type of transient model of the surge control system. The important parameters apply to any choice of transient model, regardless of the level of complexity in the model.

7.1.1  Minimum Model Parameters

Prior to performing a transient study, the design criteria for the surge control system should be clearly established. The known input parameters for the model and the assumed values based on prior testing or empirical relations should be stated. The complexity of the selected transient model and the accuracy (or inaccuracy) of the input parameters will determine the accuracy of the transient model predictions. The following system information is required as inputs for a basic transient model:
• An accurate compressor flow map, preferably in terms of polytropic or isentropic head versus actual flow rate, including a factory test verified surge control line.

• The expected volumes at the inlet and discharge points of the centrifugal compressor and gas composition (density) range expected.

• Start-up limitations such as typical time to operate in recycle mode without overheating.

• Rotating inertia of the driver component mechanically connected to the load. (The designer should not assume instant reduction in rotation.)

• If the compressor is driven by an electric motor or steam turbine, the time to reduce all power to the compressor should be estimated according to the response time of the driver. Most electric motor driven machines will quickly shut off all power to the compressor and small (<1-2 sec) response times are a valid assumption.

• Control system response to transient condition (including turbine unloading and the inherent time lag between the fuel shutoff and the control valve).

• The location of the check valve and an estimation of its valve characteristic for valves of that type (i.e. time to open and time to close.)

• Stroking times and additional dead time for all valves in the system (including isolation valves.)

• Realistic tuning / configuration parameters for the surge control system including values for step opening of anti-surge valves.

• The volume of the discharge piping system.

7.1.2 Model Uncertainties Influencing System Behavior

The following important physical effects should be accounted in a dynamic model. The choice of how to model these effects and the information required to estimate the physical behavior will influence the model predictions. If correctly implemented, the transient model will capture the physical processes and determine how the flow physics affect the surge control system performance. The primary uncertainty factors in the transient model must be considered in reference to the model results.

Primary Model Uncertainties:

1. Power Shutoff / Rotating Inertia of System:

Because it is often difficult to obtain reliable data on the gas turbine and the rotating inertia of the system, manufacturers may prefer to obtain field data on response characteristics. Some assumptions may be required but the model should avoid assuming an instantaneous loss of power in response to a transient event. This assumption will lead to over designing the surge control system components.

The compressor deceleration rate is governed by its inertia, which is essentially based on the design of the compressor and will vary by manufacturer and model. Depending upon the variation in the actual deceleration rate, the transient model can over or under predict the response time of the surge control system. It is best to assume a margin of error and run the transient model at the upper and lower limits of the inertia estimate.
Once the fuel shutoff valve is closed on the gas turbine, flow from the turbine does not immediately stop. The gas turbine will still provide power to the compressor based on its own inertia and heat storage capabilities. The gas turbine will fit the general compressor deceleration equations only after an initial, somewhat unpredictable period (2-5 seconds after initial fuel shutoff). In addition, a stored amount of volume between the gas turbine and compressor exists at the time of shutdown that can be accounted for as an additional uncertainty term.

2. Check Valve Behavior:

The check valve behavior should be estimated with a delay time built into the transient model based on the speed of sound effects (see item 3 below). In addition, the check valve behavior should include a time-variation in the valve characteristic because the valve does not close instantly. The check valve may not be operating in a fully open position because of the valve design. The check valve may be constructed with an anti-slam feature, which should be added to the time delay in the model.

3. Speed of Sound Effects:

The speed of sound must be considered in the transient model because the pressure wave propagation time will effect when the check valve begins to respond to the emergency shutdown. Commercially available fluid dynamic codes will inherently include this physical effect in the transient processes. Other codes may neglect the transient time for the propagation of the sound wave. For short lengths of pipe, it may be possible to neglect this effect but typically compressor systems will require a relatively long (>20 feet) length of pipe between the compressor discharge flange and the downstream check valve. This time delay should be included in the transient model because delay of the check valve closing will impact the surge control system performance.

4. Recycle Valve System:

The opening of the recycle valve is not instantaneous. The transient model should assume a delay time based upon the recycle valve system specifications. It is safe to assume that valves will take longer to open than what is actually predicted by the valve characteristic response. Factory acceptance tests may be used to determine if the recycle valve meets the designer specifications. The specification can be used to implement a reasonable response time in the model. Besides the valve characteristic model, the actuator and valve position indicator introduce uncertainties in the recycle valve system.

These uncertainty factors should be built into any transient model results as additional overall model uncertainty that can be as high as 5-10%, which should impose additional safety margins. If the transient model predicts a surge control system response near the safe operation of the machine, it is possible that the actual surge control system may not adequately protect against surge.

The dynamic model (either the basic fixed volume model or a fully transient model) should be verified if possible prior to use. It is often difficult to obtain reliable experimental data on the conditions during surge. The modeling process should consider this factor as an additional source of uncertainty in the model results. In addition, the physical limitations of the model should be clearly stated to understand which transient effects are being predicted and which effects are neglected.
Any transient model which is used to guide the design of the surge control system should be described in sufficient detail to understand what assumptions are made in the modeling process and which physical processes are being modeled. Over design of a surge control system will lead to reduced efficiency and restriction of the operating range of the compressor. The control system will provide poor control of the compressor. Under design of the surge control system will cause the model to predict safe operation when the compressor is actually operating in overload or near in surge.

7.2 Modeling the Compressor System for Startup Operation

Two models of the compressor system for the start up operation are typically used:

i.) **Heat Rise Model:** This model is a startup model for the heat rise during compressor startup. The model is used if the compressor system uses a hot gas bypass loop and heat rise is a concern. This model should result in a minimum piping volume requirement and corresponding time requirement for the compressor startup. Reducing the piping volume beyond the model requirements or lengthening the startup time beyond the model predicted startup time should be a warning to the compressor operator that shutdown could occur due to high discharge temperature. This model can be used to evaluate if the piping configuration allows for a reasonable startup time.

ii.) **Surge Margin Model:** This model of the compressor surge margin during the acceleration period for the compressor evaluates the compressor surge margin in relation to closing the recycle valve (to bring the compressor online). The model will help to assure that the recycle valve operation or other startup operational influences do not bring the compressor into surge. The acceleration period should be well-characterized for this model to produce accurate results.

7.3 Basic Fixed Volume Model for ESD Event

Modeling the surge control system in the startup, process control and shutdown environment is recommended. The shutdown case will produce the most stringent requirements for limiting piping volume and maintaining fast recycle valve response. A basic fixed volume model can be implemented to determine surge control system dynamic response in the shutdown environment. A description of the implementation of this model, termed the basic fixed volume transient model is provided below. This model should be used to simulate the compressor and suction control system response under the typically “worst case” scenario of a sudden shutdown of the compressor (such as an ESD event). To run the model for the “ESD worst case” scenario, the starting point for the model should correspond with the compressor peak head under normal operation and at the surge control line. Additional explanation on selection of the starting point for the basic fixed volume model is given below.

The primary system behavior represented in the basic fixed volume transient model includes the deceleration of the compressor and the change in the discharge pressure based on the system volume and flow through the recycle valve over time. This model can also be programmed to include the delay time in the downstream check valve closing in response to the propagation of the pressure wave through the discharge volume and the recycle valve characteristic (valve coefficient vs. time).
7.3.1 **Boundaries for Fixed Volume Model**

The boundaries for the model are the discharge check valve in the compressor discharge line, the compressor and the recycle valve. The volume on the suction side of the compressor is usually orders of magnitude larger than the discharge volume and does not need to be included in the simplified sizing model. The suction pressure can be considered as constant. The simplified system is represented by a volume filled by a compressor and emptied through the recycle valve (see Figure 25).

![Figure 25. Simplified System Model for Surge Control System](image)

7.3.2 **Model Flow Chart and Equations**

A program flow chart for the basic fixed volume model is given in Figure 26. The model should be used to predict how effectively the surge control system avoids compressor surge. A variety of operating conditions may be used in the simplified model but the worst case condition of surge occurring under the highest allowable pressure ratio near the surge control line should definitely be considered in the simulations.
Determine starting point for the transient model. (At least one version of the model should be run with the ESD event occurring near the surge control line at the maximum allowable head - as a worst case scenario.)

Calculate the time \( t_d \) for the check valve to close based on speed of sound. \((Eq.7-1)\)

Calculate speed of compressor \( N \) based on deceleration at time \( t_d \). \((Eq.7-2)\)

Determine new compressor flow rate for new speed, \( N \) at \( t_d \), based on performance map.

Calculate new discharge pressure, \( P_2 \), at next time step. \((Eq.7-3)\). Calculate new pressure ratio, \( P_2/P_1 \).

Calculate next speed \( N \) at next time step. \((Eq.7-2)\)

Determine next flow rate based on new \( P_2/P_1 \) and new \( N \) at next time step using performance map.

Calculate flow through recycle valve at current time step based on ISA method \((Eq.7-4)\) and the valve characteristic, \( C_v(t) \).

Compare operating points for each time step to performance map. Determine when surge line is crossed for surge control system.

Equation 7-1 provides the delay time calculation for the check valve response due to speed of sound effects. The check valve should not be assumed to close instantaneously. The check valve will have a certain time varying characteristic. The self-actuation feature of the check valve will assist the valve in closing quickly and responding to the ESD event. However, for moderate or long lengths between the compressor and the downstream check valve, the speed of sound effects are not negligible. A time delay should be accounted for based on the propagation of the pressure wave to the downstream check valve.

\[
 t_d = \frac{L_d}{s_d} \]  \hspace{1cm} (Eq. 7-1)

For an ESD surge event, the inertia of the compressor, mechanical coupling and power turbine must be considered to assure that the surge control system provides adequate protection. The balance of force
The equation for the torque, $T$, transferred to the fluid is given in Equation 7-2a. The inertia of the system and speed variation over time provide the power transferred to the gas. The derivative is then solved to find the characteristic equation in terms of inertia of the compressor turbine system ($J_{sys}$), the proportionality factor ($k$), and the speed at time $= 0$, for the rundown behavior—given in Equation 7-2b. This equation provides for a deceleration of the compressor over time with a time constant that is proportional to the ratio of $k/J$.

$$P = T \cdot N \cdot 2\pi = -(2\pi)^2 \cdot J_{sys} \cdot N \cdot \frac{dN}{dt}$$  \hspace{1cm} (Eq.7-2a)

$$N(t) = \frac{1}{k} \cdot \frac{1}{J_{sys} \cdot (2\pi)^2} \cdot t - \frac{1}{N_{t=0}}$$  \hspace{1cm} (Eq.7-2b)

The basic fixed volume model predicts the discharge pressure reduction over time using Equation 7-3. This equation is based on the initial discharge volume and proportionality factor, as well as the variation in the discharge pressure, flow through the compressor and recycle valve flow.

$$\frac{dp_d}{dt} = \frac{k \cdot p_d}{V_d}[Q_c - Q_v]$$  \hspace{1cm} (Eq. 7-3)

The flow through the valve can be determined based on the pressure differential across the valve and the valve characteristic using Equations 7-4a and 7-4b. Equation 7-4a is the valve flow equation provided in the ISA method. A large portion of the recycle valve capacity will be consumed in recycling the gas flow from the compressor in the surge control system. Only the remaining portion of the valve capacity can be used to depressurize the discharge volume.

The flow through the recycle valve depends on the suction and discharge pressures. Suction pressure may be assumed to be constant in the simplified model. In addition, the temperature at the discharge condition may be assumed to be constant throughout the short duration of the model, for the purposes of the simplified model.

$$Q_{std} = F_p \cdot c_v(t) \cdot Y \cdot \left[ \frac{p_d - p_s}{p_d} \cdot \frac{1}{SG \cdot T_d \cdot Z_d} \right]^{0.5}$$  \hspace{1cm} (Eq. 7-4a)

$$Q_{v,act} = \frac{Q_{std}}{\rho_d(T_d, Z_d)} \cdot \frac{\rho_{std}}{\rho_d(p_d, T_d, Z_d)}$$  \hspace{1cm} (Eq. 7-4b)

The valve coefficient, $c_v$, will depend on the valve characteristic selected by the user and should be implemented in the model as a $c_v(t)$ function which varies with time (as the recycle valve initially opens). If possible, the valve coefficient function should incorporate the available valve flow as a function of the valve capacity and an inherent delay time based on the surge control system response time. The available valve coefficient may be modeled as a total valve design capacity minus the steady state valve coefficient:
In this approach, the available valve capacity \( c_{v,\text{avail}} \) is the portion of the valve flow rate available to actually reduce the pressure in the piping volume apart from the steady state flow through the valve \( c_{v,\text{steadystate}} \) that is necessary to reduce flow at the steady state operating condition.

The basic fixed volume model may be used to determine the maximum allowable discharge volume (based on Surge Avoidance Criteria) or if a system redesign is warranted for a particular system (based on the Surge Impact Criteria). Through varying the input parameters to the model, the model can be used to size the maximum allowable downstream piping volume. The model may also be used to determine at what point the selected surge control system allows the compressor to cross over the surge line. In this case, the Surge Impact Criteria should be applied. The model of the compressor and surge control system can be used in the design stage to optimize the system through sizing the recycle valve, locating the downstream check valve, and determining the optimum system discharge volume.

### 7.3.3 Starting Point for the Basic Fixed Volume Model

Two basic strategies are typically used to determine which operating condition should be used to start the model transient analysis, assuming an ESD event occurs at the start of the transient process. The first method starts the model at the surge control line and recommended maximum design speed for the machine. This operating point may not correspond to the peak head for the compressor. The second method essentially uses a starting point that is located at the compressor peak head and lowest allowable surge margin (LASM). The second method will result in more stringent requirements for the surge control system. Either starting point is acceptable for the simplified transient model. However, the second method will provide more conservative results for the adequacy of the surge protection system. Operators that operate over a broad range of conditions may want to consider running the more conservative analysis using the maximum operating speed and lower surge margin as a more challenging test of the surge control system.

### 7.2.5 Model Process Results

The operating points should be plotted for each time step to trace the path of the compressor on a performance map in relation to the surge line. When the compressor operation crosses over the surge limits on the performance map, the model predicts the onset of surge. This process can be seen in Figure 23.

The modeling process should result in a relation between the discharge pressure, operating speed and compressor flow at the time of surge compared to the initial operating condition at the time of the emergency shutdown event. The discharge pressure will change depending on the capability of the control valve to release flow at a higher rate than the flow through the compressor. The model should be used to determine if the selected discharge volume and valve size can prevent the compressor from surge. System design criteria should be applied to the model results.

### 7.3 Transient Modeling for Process Control Operation

Many compressor stations will have more than one unit installed with surge control systems acting in parallel or series, though each unit will typically have its own surge control system per driver. In addition, a single compressor can have more than one recycle loop/surge control valve in place. Heating or cooling requirements may require partial cooling of the recycle loop. Emergency shutdowns may
occur for an entire station, or for individual units at a station. For these systems with complex piping arrangements and various simultaneous transient processes, a more detailed model of the compressor process control operation may be required. The basic fixed volume model will not adequately determine the protection offered by the surge control systems for each compressor unit.

To extend the dynamic modeling beyond a lumped mass system, a full model of the actual system should be simulated. Many available commercial software programs can perform the transient analysis on a discretized finite element model of the actual system. Some of these programs may include two or three dimensional flow physics modeling may be required. The extended transient model should be a close replication of the actual surge control behavior. A fully detailed simulation should include the surge control system and compressor control system, the recycle and check valve responses, transmitter time delays, etc. The model should be performed by a user who fully understands the functions of the model and the assumptions that are being made in the modeling process. Commercial software programs may not provide sufficient detail in the description of the program (in a typical software user manual) to understand the assumptions of the model.

The compressor control system and actual surge control system must be well characterized and studied to replicate the same response in the transient model. Results of the extended analysis should be somewhat consistent with the basic fixed volume analysis, if this analysis was previously used to model the same system. As with the simplified model, the results of the fully detailed model should be compared (if possible) to the experimental tests of a similar surge control system to verify model accuracy using non-dimensional parameters.

The detail of this model can be expanded to include valve characteristics specific to the recycle valve selected in the control system. The trim characteristics and valve stroke time may be included to optimize the valve selection. The analysis may include design options such as the use of two recycle valves with different characteristics to expand the range and flexibility of the control system. Additionally, the use of a hot gas bypass valve to assist in keeping the compressor out of surge as opposed to cooling the gas in the recycle loop can be evaluated as another design option in the fully transient analysis. Many of the references provided in Section 9.0 discuss the versatility of the transient model in studying the compressor process control.

### 7.4 Motivation for Surge Control System Modeling

A dynamic model of the compressor surge system is distinctly different from a steady state model. The steady state model will use a mass flow balance across the compressor to predict pressure and flow rates in the system. The dynamic model is a transient study. The model will predict pressure and flow rate based on the mass accumulation in the system because these effects are transient processes. The dynamic model will permit the total mass out to be less than the total mass inflow to the compressor. Dynamic models will predict intermediate process conditions when the flow through the compressor is changed. These are useful in the design of the compressor units for all three working environments. If properly modeled, the dynamic model should provide a resource for the operating company and manufacturer in protecting the compressor prior to the installation of the surge control system.

The dynamic model can also be a valuable tool in the design of a new compressor system installation. Results from the transient analysis should be used to evaluate the system piping design, placement of the downstream check valve and anti-surge valve, and the valve selection. The study should confirm the safe design of the surge control system to adequately protect the compressor from surge. A transient simulation of the surge control system can be used to save time and expense in changing the system after
installation. If the system is properly modeled prior to installation, the dynamic study will be a valuable resource to the operating company and manufacturer.

The transient modeling process should be employed in the design stage of a compressor installation and adapted to suit the range of application needed. Many references in industry (shown in Section 9.0) are available to provide examples on the use of dynamic modeling to optimize or predict the behavior of a surge control system.
8.0 Surge Control System Design Considerations

The primary issues to consider in reviewing the overall surge control system design are provided in the following section. If the surge control system does not meet the system design criteria or if the performance of the surge control system is found to inadequately protect the compressor through actual field testing, system redesign may be required. Surge control systems are difficult to design correctly, especially for complex compressor stations with more than one compressor unit, multiple recycle loops and several coolers. The system design is complicated by the various surge environments. Uncertainty in the surge control system performance will add to the risk of inadequate protection.

8.1 Surge Control Line Accuracy

For any transient model, the surge control line must be accurately represented in the model. The shape of the surge line is critical to the model accuracy, especially for the critical ESD event. Often the shape of the curve is not linear. The surge limit for each compressor system is unique. The manufacturer should work closely with the user to develop the shape of this curve with high accuracy to assure the model results accurately represent the behavior of the system.

The surge control system typically assumes a linear approximation of the compressor surge condition, known as the surge control line. The linear approximation is valid for a single impeller machine. The opening and closing motion of the recycle valve is controlled through the signal sent by the control algorithm in response to the compressor operation. If the system nonlinearities (such as compressor performance curves) are large, the system will not behave in a linear fashion and the surge control system will not adequately prevent the onset of surge. The recycle valve specification should limit the non-linearity in the valve system. Typically, these nonlinearities will be determined through factory testing by the manufacturer prior to the onsite installation.

The head rise to surge will become more flat as the surge line is approached. Even small disturbances near the surge line will cause the compressor to surge. These type of non-linearities should be taken into account by determining an adequate surge margin and assuring that the control system is accurate and responsive to counteract these sudden changes.

8.2 Uncertainty Considerations and High Risk Indicators

The surge control system response depends on its ability to determine the compressor surge condition. Uncertainty in the performance of the compressor surge system is a factor that should be considered in evaluating system performance.

8.2.1 Compressor Surge Primary Uncertainties

The common factors contributing to high compressor surge uncertainty are as follows:

1.) **Compressor flow uncertainty (ΔQ):** In-practice, achievable flow meter uncertainty is typically on the order of 1-3%, although wet gas or non-flow conditioned streams will have an uncertainty on the order of 2-5%. Pressure and temperature measurement uncertainty should be less than 1.0% if the instrumentation is installed correctly and the range of the transducer is correctly matched to the operating condition. Instrumentation that is out of calibration will increase the
flow measurement uncertainty and greatly increase the risk that the surge condition is not
detected at the surge margin, with sufficient time for the control system to react.

2.) **Compressor head uncertainty (ΔH):** The head will be determined based on the measured
suction and discharge pressures and temperatures, the pressure/temperature compensation (based
on correcting the measurement at the test taps for the actual condition at the compressor inlet and
outlet flanges) and the selected equation of state uncertainty. Use of reduced variables in the
compressor surge control system will minimize this risk factor.

3.) **Manufacturer surge line uncertainty (ΔSM):** The manufacturer will provide a surge control
line which approximates the actual surge line, but this line will have an inherent uncertainty based
on some original factory tests and analytical models. The surge control line is not always derived
from a factory test. If a factory test is performed to determine the actual surge line, it is typically
done on air at lower pressures, which should add an uncertainty to the manufacturer predictions
of actual surge in natural gas at high pressures. The typical uncertainty for the actual surge line
of the compressor in natural gas is approximately 2-3%, if the surge line was derived from
analytical methods or a factory test on air.

4.) **Recycle valve uncertainty (ΔRV):** The valve(s) actuation system and valve characteristic should
be reviewed as carefully as possible to assure the valve behaves correctly in response to the surge
control system signals. The valve behavior is often difficult to determine precisely because the
valve characteristics and response times vary based on manufacturer. If multiple gains are used
based on the type of surge event or the surge control system sensor readings, the response of the
valve(s) should be verified for each signal gain expected. In addition, if multiple types of valves
are used in the control recycle loop(s), the combined response of the valves to the different
compressor operations should be reviewed.

The valves and measurement instrumentation are often the critical lags in the system response time and
should be factored into the uncertainty of the surge control system performance

These three primary uncertainty percentages should be added together using the root-sum square method
to estimate the overall uncertainty in the compressor system detection of surge.

\[
\Delta U_{\text{surge}}(\%) = \sqrt{\left(\frac{\Delta H}{H}\right)^2 + \left(\frac{\Delta Q}{Q}\right)^2 + \left(\frac{\Delta SM}{SM}\right)^2 + \left(\frac{\Delta RV}{RV}\right)^2}
\]  
(Eq. 8.1)

The uncertainty should be factored into the evaluation of the surge control system using the selected
system design criteria, based on either method recommended in this guideline (see Section 6.0) or a risk-
based approach developed by an operating company. The surge uncertainty should be used to guide
system design choices for the surge control system.

### 8.2.2 Risk Factors to Surge Control System

This uncertainty formulation can also be regarded as a measure of risk to the compressor surge control
system performance. At high values of uncertainty, the compressor surge control system would have a
greater chance of not adequately protecting the compressor. High values of uncertainty should call for a
larger surge margin, additional analysis (such as dynamic modeling) or possibly redesign. In addition to
the uncertainty factors given above, the following additional factors can be regarded as high risk
indicators. If the surge control system meets any of the high risk indicators, a dynamic model or
extensive evaluation of the compressor should be performed.

High Risk Indicators for Surge Control System Failure to Avoid Surge:

1.) **Recycle valve system fails to meet design specification.** The recommended valve
specifications given in Section 3.3 were developed by leading manufacturers of compressor
surge control valves. These specifications should be used to develop specific valve dynamic
performance criteria. If the recycle valve system cannot meet specifications, this will impose
additional risk to the compressor in the relevant operating environment.

2.) **Recycle valve meets specifications but recycle valve system involves complicated actuation system utilizing volume boosters and custom pneumatic system.** Complicated
valve systems may need to be tested by the valve manufacturer to confirm response to an
amplitude step change in both the opening and closing direction and evaluate positioner
performance.

3.) **Multiple compressor units are installed in series with shared recycle loops.** Additional
compressor units will add complexity to the dynamic response requirements for the control
system. In addition, a single recycle valve may not be able to handle the various
requirements for capacity control of the various units and respond quickly to avoid surge. If
the various compressors have different recycle loops, the effect of one compressor surging
should be evaluated to assure that the single compressor will not drive other units into surge.

4.) **Surge control system is not fully integrated with turbomachinery controls at the station.**
The surge control system will often conflict with the station capacity control and load sharing
of the units at a single station. If the surge control system is implemented on a separate PLC,
these operations will not necessarily be synchronized and surge may occur. In addition, the
operation may not be maximized for efficiency if units are forced to operate in continuous
recycle.

5.) **Gas composition at the station varies greatly from factory test conditions / design condition.** Changes in the gas composition will affect the design operating window for the
compressor. If these variations are significant, the compressor actual surge point will change
and the peak head may differ. These changes will affect the performance of the surge control
system, which was designed for a different operational window.

6.) **Compressor is typically operated close to the surge margin and greater than 70% of its peak head.** Operation near the surge control line at high values of the compressor head will
require faster response from the surge control system, during process control operations or
shutdown of the unit. This will add to the risk of compressor surge.
8.3 Risk Mitigation

Risk mitigation can be carried out using two general types of mitigating measures as described below.

1.) **Use of Prior Experience and Surge Control Guidelines:**

   The installation and set-up of the surge control system instrumentation can be reviewed through a set procedure based on prior experience and surge system guidelines. The recommendations of this guideline and other compressor system manufacturer guidance should be used in a detailed review of the station. The review should consider performance of the control system in the three functioning environments – startup, process control, and shutdown (both controlled and ESD events).

2.) **Dynamic Modeling / System Design Criteria:**

   Simple or detailed modeling will provide the capability to analyze the compressor system performance under varied operations. The model results should be compared against a set of design criteria (see Section 6.0 for examples). This is also recommended when prior experience with a particular unit is not available. Modeling of the system will reduce the chances of improperly sized recycle valves and process control upset.

If the surge control system is not accurately measuring the operating point of the compressor, the compressor surge condition will either be over-estimated (the surge control line will be further removed from the actual surge condition) or the compressor surge will be underestimated (surge will occur before the control system senses the onset of surge.) The common causes of uncertainty in compressor surge measurements should be addressed in the surge control system design as these uncertainties will introduce higher risk to the surge control system performance.
9.0 References


