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Replacement Gas Management Valve Sizing for the MTF Helium Compressor Skid

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Abstract:

The gas management valves currently in use have been in service for many years. Within the last several years, the valve positioners have required increasing maintenance. Typical problems are cracked bellows and damaged nozzles. The valves have been discontinued, but parts for the actuators are still available. Even so, on-going maintenance resulting from positioner failures due to system vibrations has prompted MTF to plan for a replacement of these valves. This document describes the sizing of these valves and the operational implications of the selected valves.

Introduction

The MTF helium compressor skid includes five gas management valves. During normal operations, these valves are controlled with proportional-integral (PI) control loops programmed in a programmable logic controller (PLC). The purpose of these valves is to control suction pressure, interstage pressure, and discharge pressure either by bringing helium gas from the buffer tanks to the compressor skid, sending helium gas from the compressor skid to the buffer tanks, or recirculating helium gas within the compressor skid. This document tabulates the characteristics of the in-service valves, verifies the sizing of the new valves, and discusses the operational implications of the new valves.

In-Service Gas Management Valves

The in-service gas management valves are Foxboro V1S series stem-guided Stabilflo valves with Foxboro P91V Type C Vernier Valvactor positioners (3-15 psig signal) and Foxboro P25 or P50 pneumatic spring diaphragm actuators. Nameplate data for the five in-service gas management valves are listed in Table 1, and their positions within the compressor system are represented schematically in Figure 1.

Table 1 Nameplate data of the in-service gas management valves.

Valve	**PCV204**	**PCV206**	**PCV210**	**PCV211**	**PCV221**
Control Loop	PIC200	PIC201	PIC201	PIC202	PIC203
Mode	--	Recirculation	Makeup	--	--
Process Variable	PI210 (Discharge pressure)	PI201 (Suction pressure)	PI201 (Suction pressure)	PI206 (Interstage pressure)	PI206 (Interstage pressure)
Nameplate Info					
Model	V1SF-3M5A00A St. A	V1SF-2M1A0ZA St. A	V1SF-2M1A0ZA St. A	V1SD-2M1A00N St. A	V1SE-2M1A00A St. A
Aux. Spec.	V-CEH 1AS-A	V-CEH 1AS-A	V-CEH 1AS-A	V-CEH 1AS-A	V-CEH 1AS-A
Actuator	P50SF-J3 St. A	P50SF-J3 St. A	P50SF-J3 St. A	P25SD-D3 St. A	P50SE-J3 St. A
Ref. No.	76N-53766-1	76N-53766-3	76N-53766-2	76N-53766-5	76N-53766-4
Origin	90 76 50	90 76 50	90 76 50	90 76 47	90 76 50
Body Size	1"	1"	1"	1/2"	3/4"
Material	CS	CS	CS	CS	CS
ANSI Class	300	300	300	300	300
Inner Valve	Stem Guided	Stem Guided	Stem Guided	Stem Guided	Stem Guided
Material	STD 1AO	STD 1AO	STD 1AO	STD 1AO	STD 1AO
Char/C_v	=% 17	=% 17	=% 17	=% 2	=% 10
Temp. F	20 to 406	20 to 406	20 to 406	20 to 406	20 to 406
Packing	TFE V-RING	DBL TFE V-RING	DBL TFE V-RING	TFE V-RING	TFE V-RING
Stroke	3/4"	3/4"	3/4"	3/4"	3/4"
Air to	OPEN	OPEN	OPEN	OPEN	OPEN

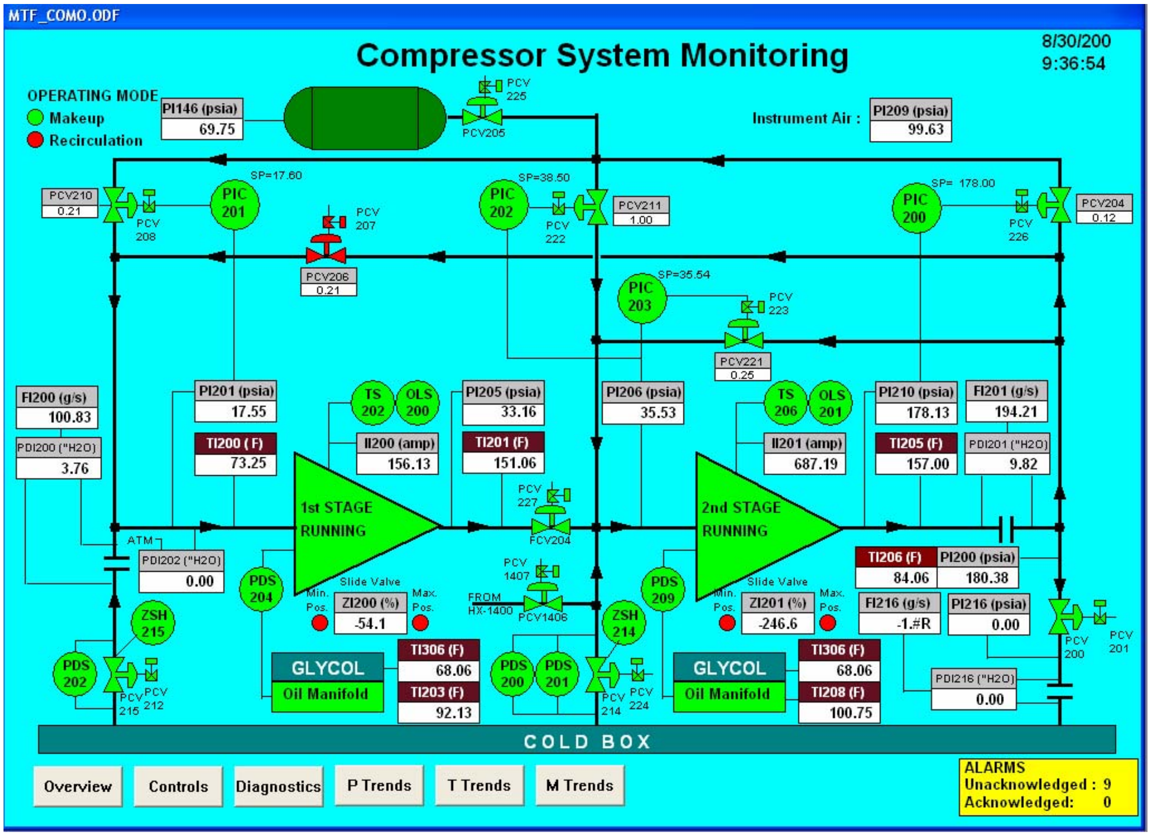

Figure 1 Compressor skid monitoring screen schematically showing the gas management valve positions.

Replacement Gas Management Valves

The replacement gas management valves are Masoneilan 21000 series control valves with Masoneilan 88 pneumatic spring diaphragm actuators, and Masoneilan 4700P pneumatic positioners (3-15 psig). At the time of writing this document, the valves are not yet received so the nameplate data are not available. Table 2 lists information taken from the vendor quote in a format identical to Table 1.

Table 2 Vendor quote information for the replacement gas management valves.

Valve	**PCV204**	**PCV206**	**PCV210**	**PCV211**	**PCV221**
Control Loop	PIC200	PIC201	PIC201	PIC202	PIC203
Mode	--	Recirculation	Makeup	--	--
Process Variable	PI210 (Discharge pressure)	PI201 (Suction pressure)	PI201 (Suction pressure)	PI206 (Interstage pressure)	PI206 (Interstage pressure)
Nameplate Info					
Model	88-21624	88-21624	88-21624	88-21624	88-21624
Aux. Spec.	--	--	--	--	--
Actuator	88, Size 3	88, size 3	88, size 3	88, size 3	88, size 3
Ref. No.	--	--	--	--	--
Origin	--	--	--	--	--
Body Size	1"	1"	1"	3/4"	3/4"
Material	CS	CS	CS	CS	CS
ANSI Class	300	300	300	300	300
Inner Valve	Stem Guided	Stem Guided	Stem Guided	Stem Guided	Stem Guided
Material	A276 type 440C, 304SS, A564 gr. 630	A276 type 440C, 304SS, A564 gr. 630	A276 type 440C, 304SS, A564 gr. 630	A276 type 440C, 304SS, A564 gr. 630	A276 type 440C, 304SS, A564 gr. 630
Char/C_v	=% 12	=% 12	=% 12	=% 3.8	=% 12
Temp. F	--	--	--	--	--
Packing	TFE Dual V-Ring	TFE Dual V-Ring	TFE Dual V-Ring	TFE Dual V-Ring	TFE Dual V-Ring
Stroke	0.8"	0.8"	0.8"	0.8"	0.8"
Air to	OPEN	OPEN	OPEN	OPEN	OPEN

Sizing Verification for Replacement Gas Management Valves

For operations, the important difference between the in-service valves and the replacement valves is the change in the flow characteristic C_v. The full-open flow characteristic $C_{v,max}$ of the replacement valves is smaller for the three valves controlling suction pressure and discharge pressure ($C_{v,max}$ = 12 vs. $C_{v,max}$ = 17) and larger for the two valves controlling interstage pressure ($C_{v,max}$ = 3.8 and 12 vs. $C_{v,max}$ = 2 and 10).

At a given valve position x (x = 0 is a closed valve, x = 1 is a fully-open valve), the flow characteristic of an equal percentage control valve is given by Equation 1:

$$C_v = C_{v,max} \left(\text{Char}\right)^{x-1} \qquad (1)$$

where Char is the equal percentage characteristic of the valve, typically either 50:1 or 100:1. This characteristic describes how quickly the C_v of the valve changes with valve position. For a 100:1 equal percentage valve, the C_v changes 100x faster near the fully-open position than near the fully-closed position. This is shown in Equations 2-3.

$$\frac{dC_v}{dx} = C_{v,max} \ln\left(\text{Char}\right)\left(\text{Char}\right)^{x-1} \qquad (2)$$

$$\frac{dC_v / dx|_{x=1}}{dC_v / dx|_{x=0}} = \frac{(Char)^0}{(Char)^{-1}} = Char \tag{3}$$

Knowing the C_v at a given valve position, the mass flow rate $\dot{m}$ [g/s] through the valve can be calculated with Equation 4 using the upstream pressure P [psia] and the upstream density ρ [g/cm^3]. This equation is for sonic flow through the valve, which is valid for typical operating pressures of the compressor skid and buffer tanks.

$$\dot{m} = 34.7\, C_v \sqrt{\rho\, P} \tag{4}$$

Using Equations 1 and 4 in conjunction with archived MTF operating data allows the mass flow rate through each in-service gas management valve to be calculated. The required valve position of the replacement gas management valve can then be calculated. An undersized replacement valve is indicated by a required valve position of greater than 1. For each valve, approximately six thousand data points spanning six months of continuous operating data from late July 2004 to mid-January 2005 were used to compare the in-service valve position with the estimated replacement valve position.

Figure 2 compares the logged and calculated positions of gas management valve PCV210 (buffer to suction). The calculated position of the replacement valve is generally 10% further open than the logged position of the in-service valve, and the replacement valve is not fully open for any of the logged operating conditions.

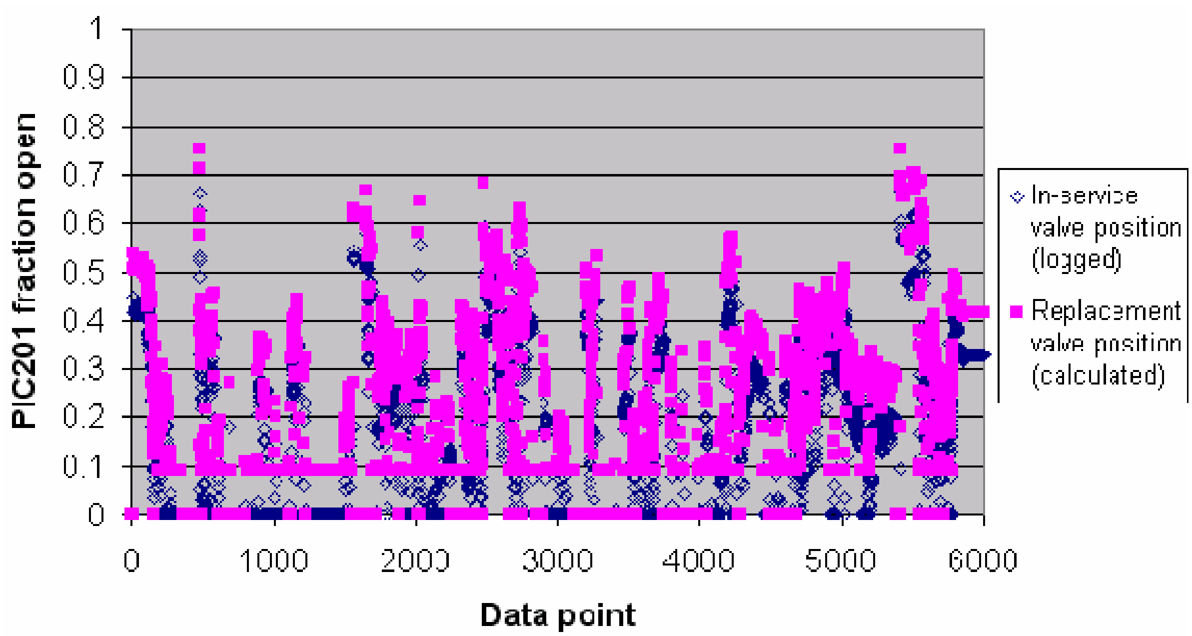

Figure 2 PIC201 requested valve position for in-service and replacement valve PCV210.

For the gas management valves PCV204, PCV211, and PCV211 controlled by control loops PIC200, PIC202, and PIC203, respectively, there is more interaction among the valves. With the in-service valves, PCV211 is always open 100%. PCV221 opens as necessary to maintain the interstage pressure, and PCV204 opens as necessary to maintain discharge pressure. Under some combinations of buffer pressure and compressor loading, the requested discharge pressure cannot be achieved because so much helium must be recirculated to the interstage through PCV221.

Using a larger PCV211 (C_v = 3.8 vs. C_v = 2) will help eliminate this problem by reducing the required recirculation from discharge to interstage. It provides another degree of freedom which could be useful for advanced refrigerator control strategies. The position of PCV211 can be controlled to ensure that the desired discharge pressure can be achieved.

With this in mind, Figures 3 and 4 plot the in-service valve logged position and the replacement valve calculated position with PCV211 86% open (C_v = 2) for PCV204 and PCV221, respectively. Figure 5 and 6 plot the same quantities for PCV211 95% open (C_v = 3), and Figures 7 and 8 plot these quantities for PCV211 100% open (C_v = 3.8). PCV221 progressively closes in Figures 4, 6, and 8 as PCV211 opens and more helium is taken from the buffer to interstage. PCV204 progressively opens in Figures 3, 5, and 7 as less helium is recirculated to the interstage. For none of the data points are the replacement valves undersized.

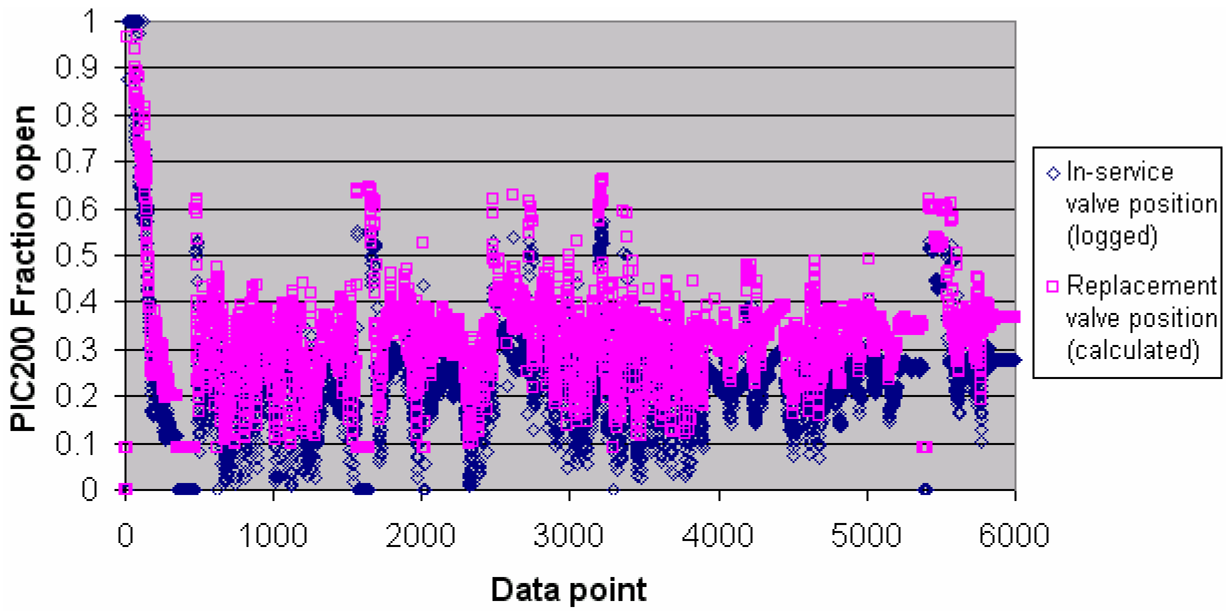

Figure 3 PIC200 requested valve position for in-service and replacement valves PCV204 with PCV211 86% open (C_v = 2).

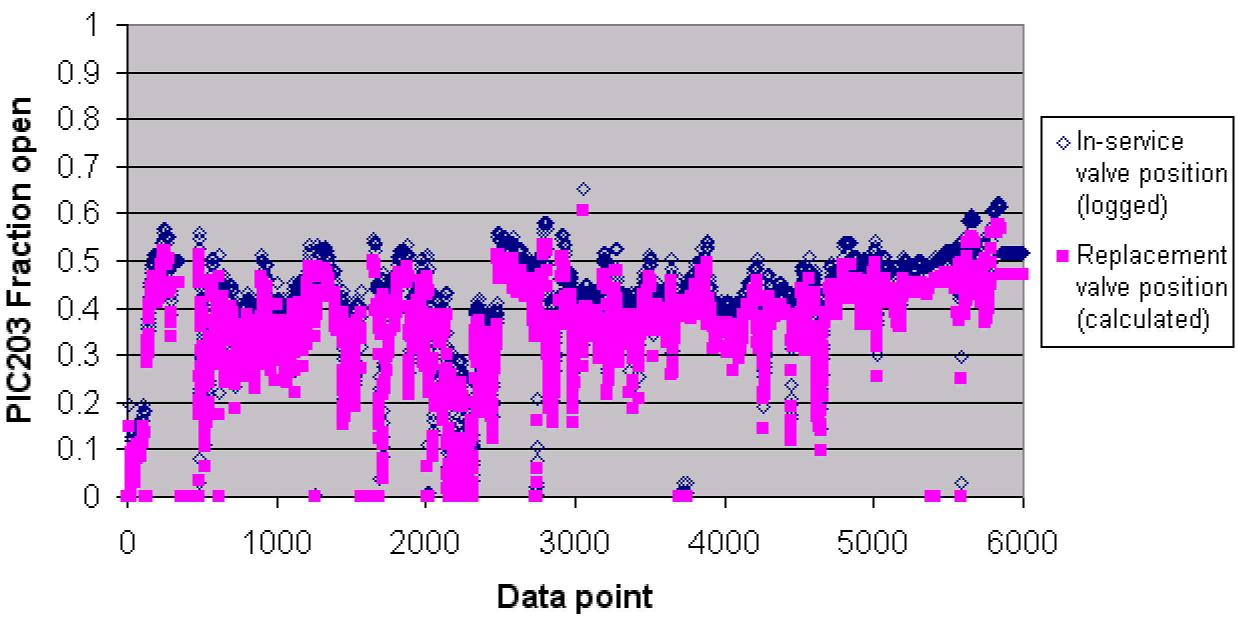

Figure 4 PIC203 requested valve position for in-service and replacement valves PCV221 with PCV211 86% open ($C_v = 2$).

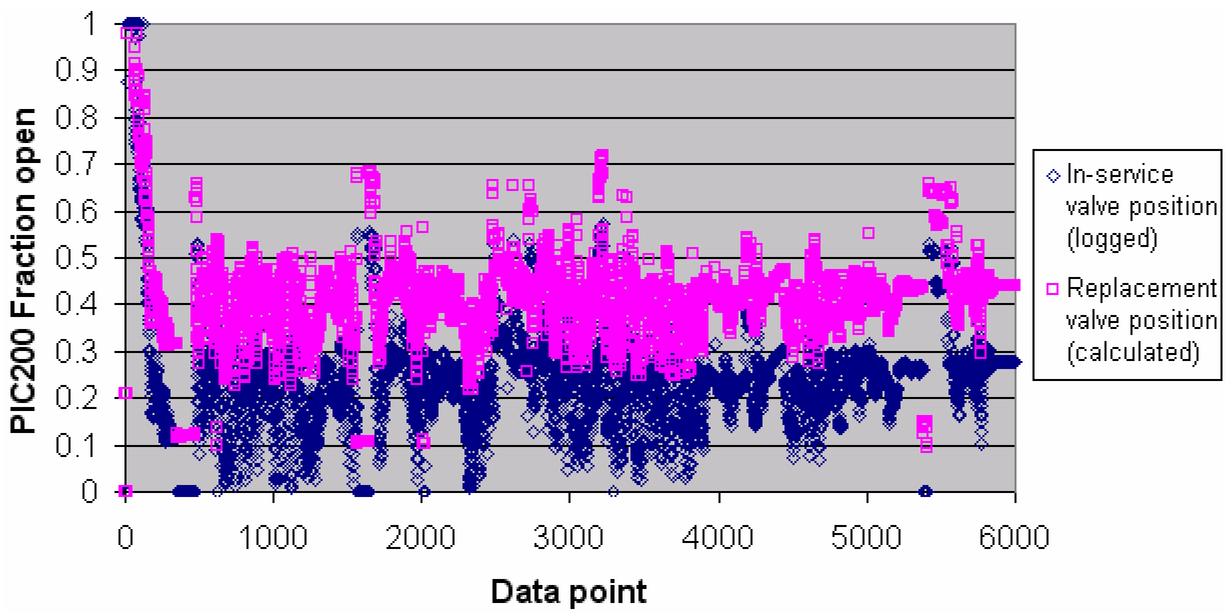

Figure 5 PIC200 requested valve position for in-service and replacement valves PCV204 with PCV211 95% open ($C_v = 3$).

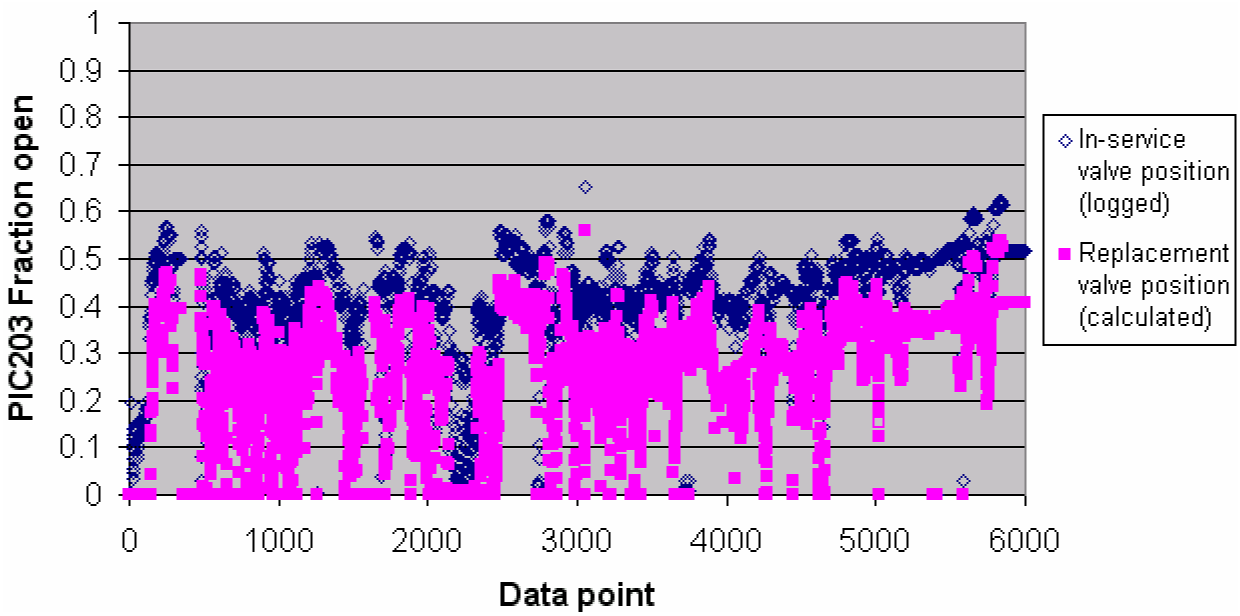

Figure 6 PIC203 requested valve position for in-service and replacement valves PCV221 with PCV211 95% open (C_v = 3).

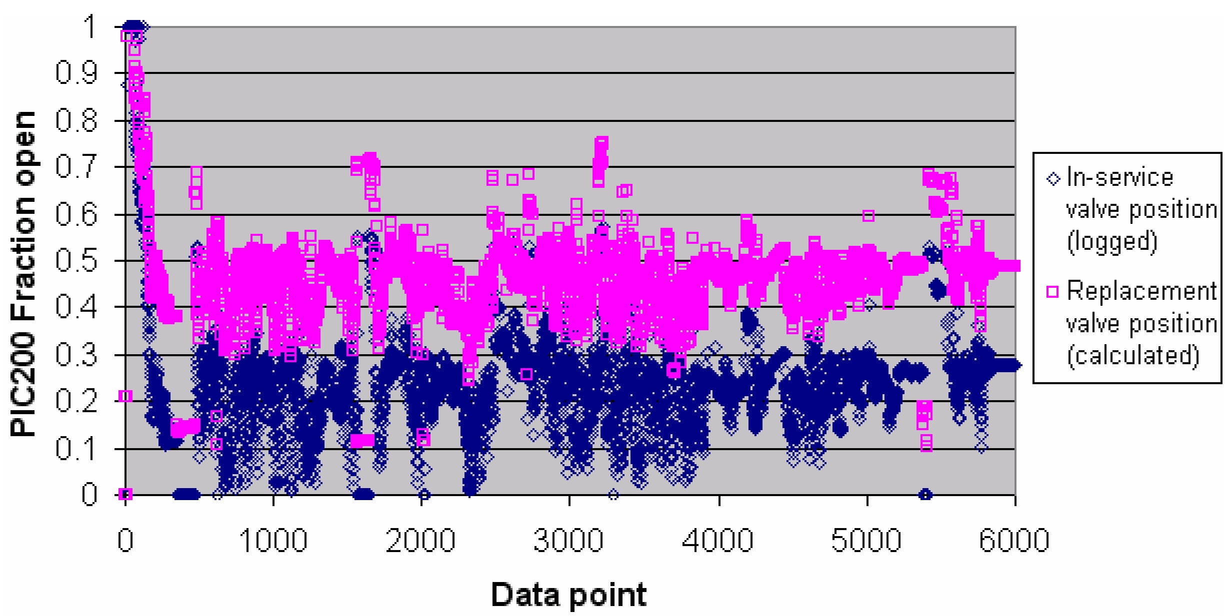

Figure 7 PIC200 requested valve position for in-service and replacement valves PCV204 with PCV211 100% open (C_v = 3.8).

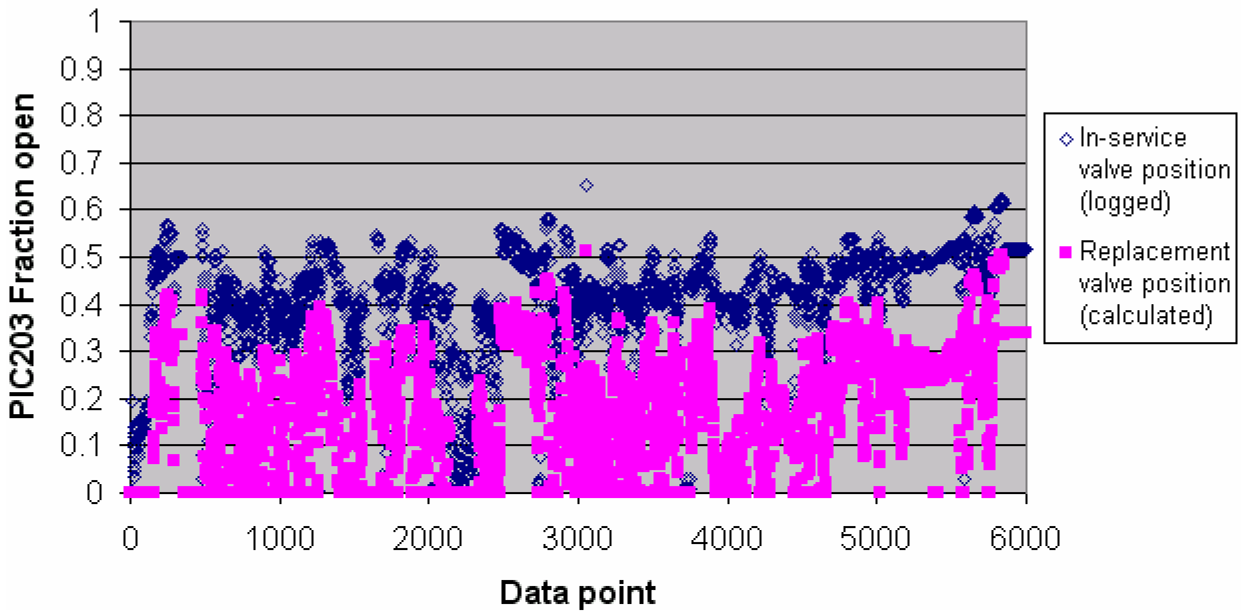

Figure 8 PIC203 requested valve position for in-service and replacement valves PCV221 with PCV211 100% open (C_v = 3.8).

Control Loop Tuning Parameters

The replacement valves have been shown to be properly sized. The control loop parameters must now be modified in order to provide stable system pressures. The present tuning of the in-service gas management valves provides stable system pressures. The control loops will need to be retuned with the replacement valves to provide the same rate of mass flow change as the valve position changes. This is described by Equation 5:

$$\frac{d\dot{m}}{dt} \propto \frac{dC_v}{dt} = \frac{dC_v}{dx}\frac{dx}{dt} \qquad (5)$$

The first term, dCv/dx, is a function of the valve itself. The second term, dx/dt, describes the rate at which the valve opens or closes and is defined by the control loop parameters. For the PI control used at MTF, the control equation used by the PLC [1] is reduced to Equation 6:

$$M_n = K_c\, e_n + K_c \left(\frac{T_s}{T_i}\right) \sum_{j=1}^{n} e_j$$

where M_n = output at sample time n
K_c = proportional gain (%/%, 0.01 – 100.00 range)
e_n = error at n^{th} sample
T_s = sample rate
T_i = reset or integral time (minutes, $0 < T_i \leq \infty$)

The dx/dt term can then be described by Equation 7:

$$\frac{dx}{dt} = \frac{M_{n+1} - M_n}{T_s} = K_c \left[\frac{(e_{n+1} - e_n)}{T_s} + \frac{e_{n+1}}{T_i} \right] \tag{7}$$

Equations 2 and 7 can now be substituted into Equation 6:

$$\frac{d\dot{m}}{dt} \propto \frac{dC_v}{dx}\frac{dx}{dt} = \left[C_{v,max} \ln(Char)(Char)^{x-1} \right] K_c \left[\frac{(e_{n+1} - e_n)}{T_s} + \frac{e_{n+1}}{T_i} \right] \tag{8}$$

Equation 8 indicates that in order to keep $d\dot{m}/dt$ constant, the product of the valve's fully-open flow coefficient $C_{v,max}$ and the proportional gain K_c should be constant. The proportional gain for the replacement valves can then be calculated by Equation 9.

$$(K_c)_{replacement} = (K_c)_{in\text{-}service} \left[\frac{(C_{v,max})_{in-service}}{(C_{v,max})_{replacement}} \right] \tag{9}$$

This relation assumes that the in-service valves and the replacement valves have a similar characteristic (50:1, for example). Based on data collected during bench testing of the in-service gas management valves, this appears to be a valid assumption. A 50:1 characteristic provides a reasonable fit to the data.

Table 3 presents the calculated tuning parameters for the five gas management valves. These values represent starting values; additional fine-tuning will likely be required.

Table 3 Calculated tuning parameters for the in-service and replacement gas management valves.

Valve	**PCV204**	**PCV206**	**PCV210**	**PCV211**	**PCV221**
Control Loop	PIC200	PIC201	PIC201	PIC202	PIC203
Mode	--	Recirculation	Makeup	--	--
In-service valve					
$C_{v,max}$	17	17	17	2	10
K_c [%/%]	10.00	0.20	0.20	0.11	1.30
T_i [min]	0.60	0.05	0.05	0.01	0.16
Replacement valve					
$C_{v,max}$	12	12	12	3.8	12
K_c [%/%]	14.17	0.28	0.28	0.06	1.08
T_i [min]	0.60	0.05	0.05	0.01	0.16

Conclusions

The sizing of the replacement gas management valves has been verified. Calculations using data points taken from several months of typical MTF operating data showed the replacement valves are neither undersized (valve fully-open for extended periods) nor oversized (valve nearly fully-closed for extended periods). The larger PCV211 (buffer to middle stage) presents another degree of freedom and should allow better control of compressor discharge pressure under all combinations of buffer pressure and compressor loading.

The proportional gain for each control loop was recalculated based on the current control loop tuning and the relative flow characteristics of the in-service and replacement valves. The calculated values should be a good starting point to retune the control loops once the gas management valves have been replaced, although some additional fine-tuning will likely be required.

References

1. SIMATIC 545/555/575 Programming Reference (Siemens), pp. 9-6 & 9-22).