Compressor: Planning for Hot Gas Bypass Valve Early

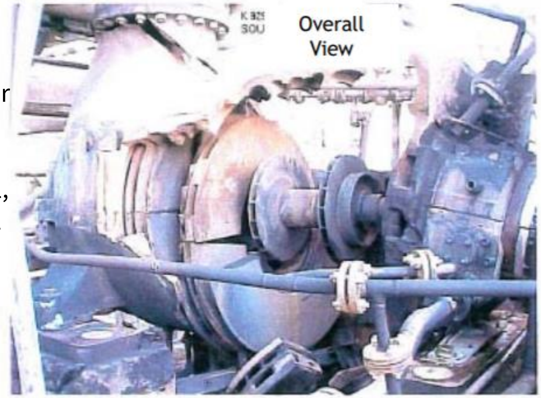
Sachin Anjan,
Probite Design Systems Pvt. Ltd.

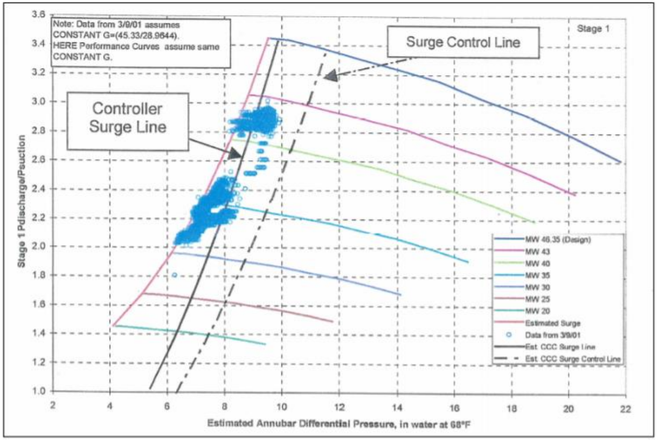
Probite

Compressor Surge Protection

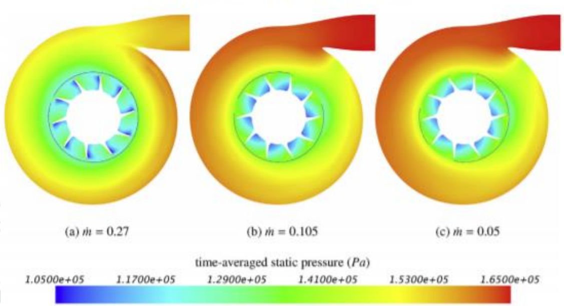
Analysis of all data provided strongly suggested the root cause of the failure is the surging of the compressor without adequate surge protection.

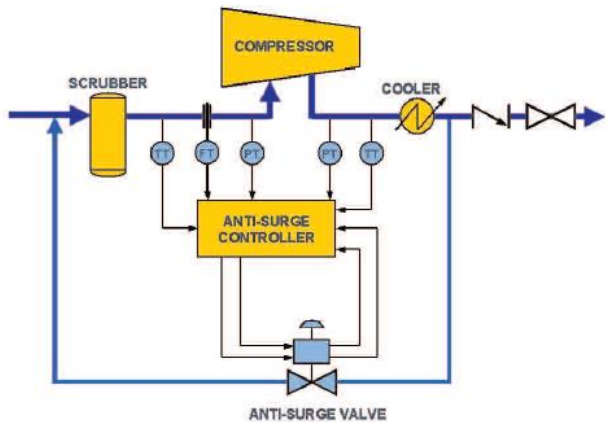
Centrifugal Compressor Failure Analysis, Knight et al, METS, 2011





B. Semlitsch, M. Mihăescu / Energy 103 (2016) 572–587



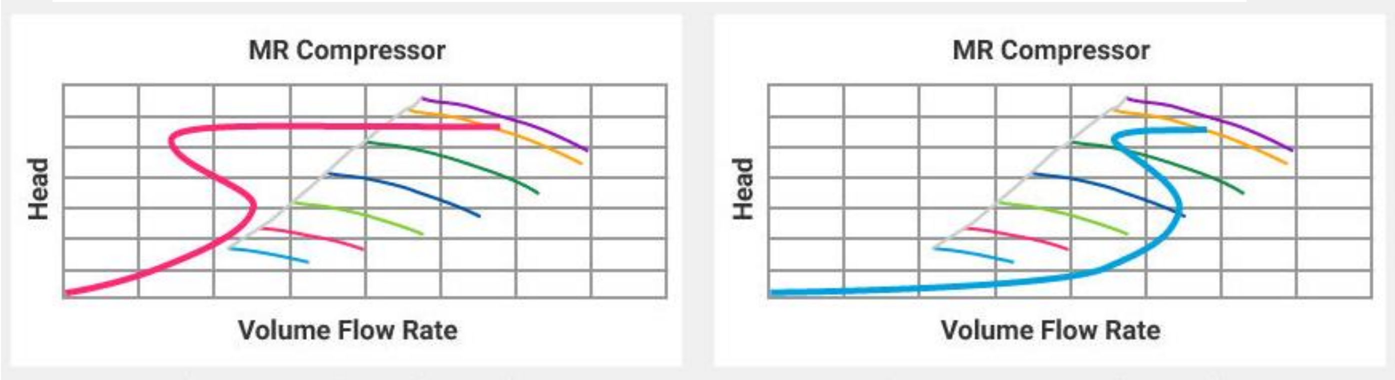


Probite

Compressor Response on Emergency Shutdown

Race between:

- Reverse flow from discharge volume due to decreasing speed and head
- Capacity of anti-surge recycle to evacuate discharge volume



https://www.chiyodacorp.com/en/service/chas/process/

Inadequate size / response time of Anti-Surge Valve (ASV)

Adequate size / response time of Anti-Surge Valve (ASV)

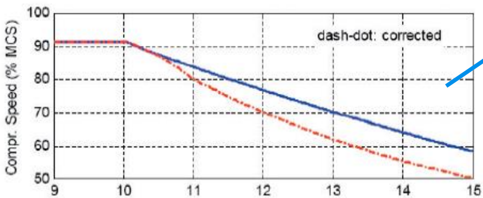
Compressor system design – project cycle:

- Compressor order placed
- Compressor vendor designs compressor / generates curves
- Anti-surge valve sizing
- Dynamic simulation to adequacy check of anti-surge valve

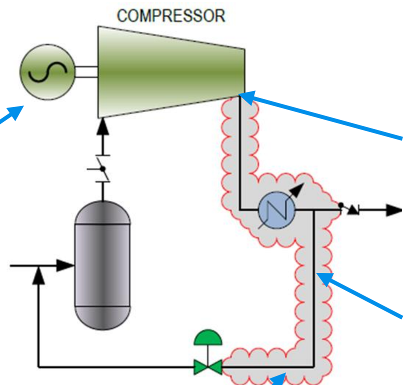
Carried out relatively late in the project life cycle

Why Anti-Surge Valve May not Be Adequate?

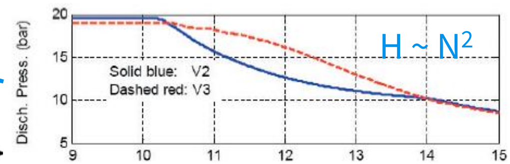
Speed decreasing



Surging forwards in compressor protection, Brighenti et al, HE, May 2005



Developed pressure decreases

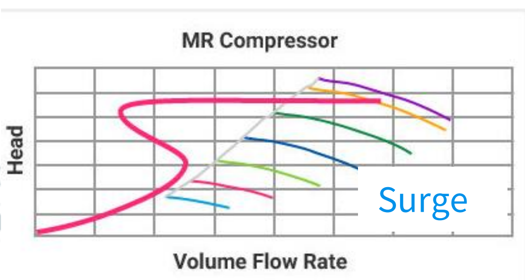


Pressure here is still high → Reverse flow to compressor, but compressor is still rotating; periodic reversing of flow

ASV has to quickly decrease pressure here by removing molecules to suction

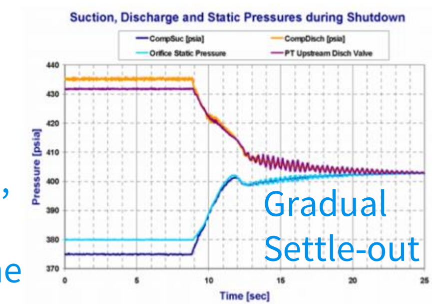
ASV size / response not adequate

ASV succeeds



Which way system goes depends on:

1. Compressor parameters (inertia, head, driver type)
2. Pipe length / volume
3. ASV size / response



Probite

Parameters in Process Engineers Control

In Compressor Vendor's control; Affected by Process design

1. Compressor parameters (inertia, head, driver type)
2. ASV size / response
3. Pipe length / volume

Compressor vendor scope of supply, possible to modify but limited gains beyond a point

- Air coolers installed on piperack; increased piping volume
- Air cooler tube + header volume

Significant piping volume due to:

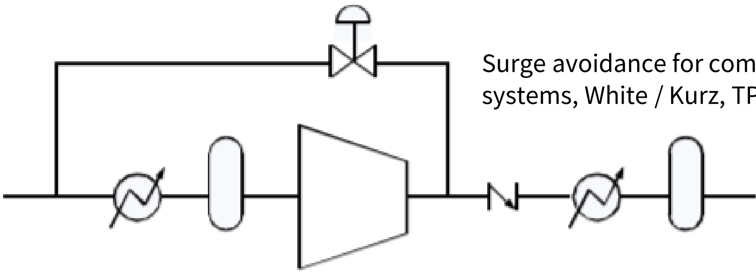
- Anti-surge valve located at high point
- Relief valve located at high point

Process design, piping considerations, engineering guidelines constrain reduction

https://www.gti.energy/wp-content/uploads/2018/12/Materials-6-Siti_Farhana_M_Shaari-LNG17-Poster.pdf

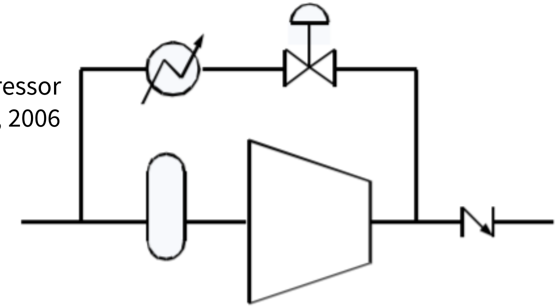
Probite

Improving Surge Response: Options



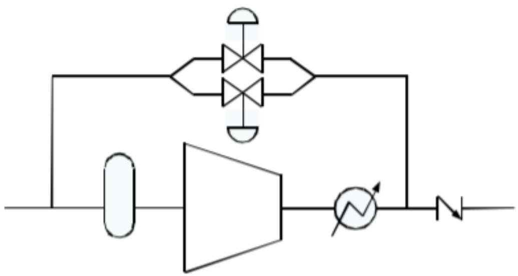
Surge avoidance for compressor systems, White / Kurz, TPS, 2006

Pre and Post Cooling



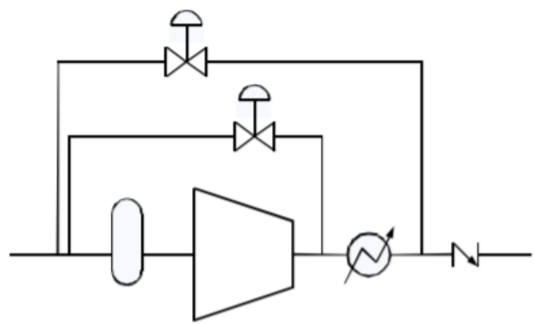
Recycle Cooling

Best Luck convincing Project Team on additional Coolers this late in the project; Even accommodating Hot / Cold Gas Bypasses would be resisted



Cold Gas Bypass Valve

ASV located at high point; Cold gas bypass valve additional space at top resisted



Hot Gas Bypass Valve

Least resistance option

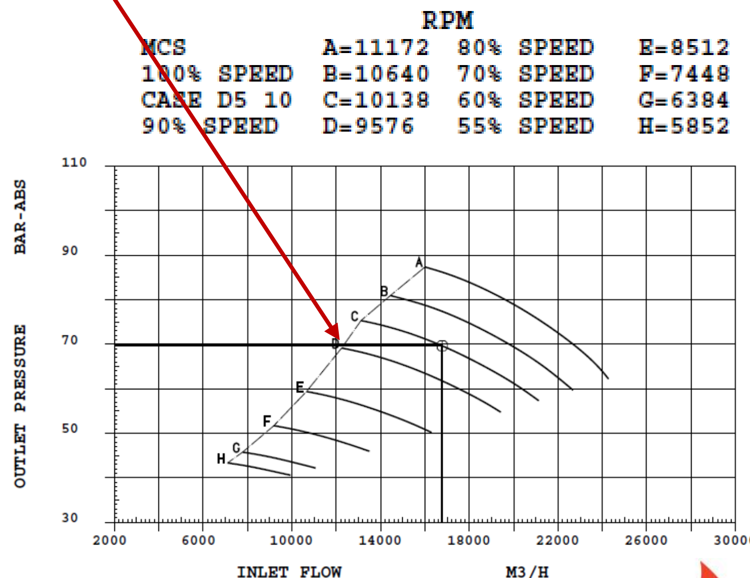
Probite

Sample Case Study

Process Parameters	Export Gas Compressor
Rated mass flowrate, kg/s	92.1
Rated flowrate, m3/hr	15713
Psuction, bara	32
Pdischarge, bara	69.5
Tsuction, deg C	50
k	1.35
MW	17
Zsuction	0.96
Zdisch	0.97
Suction pipe size, in	24
Discharge pipe size, in	20
Suction piping length, m	150
Discharge piping length, m	150
Discharge volume (piping + coolers), m3	60.0

Values that can be decided by Process Engineer or Obtained from Vendor	
Rated head, kJ/kg	134.5
Discharge temperature, deg C	142.3
Adiabatic Efficiency	85%
Mechanical efficiency	95%
Valve pre-stroke time, ms	200

Vendor Data	
Compressor speed, rpm	10138
Total inertia, kg-m2	105
Qso, m3/s	3.33
Hs0, J/kg	135400



Data usually available in Vendor offer before order is placed

Probite

Method 1 – Inertia Number

$$NI = \frac{I \cdot N^2}{m \cdot H \cdot t}$$

I is compressor / driver rotor inertia in kg-m2
N is maximum compressor speed in rpm
m is mass flowrate in kg/s
H is polytropic head in J/kg
t = Valve prestrike time in milliseconds

NI < 3 → Severe surge needing HGBV is likely
3 < NI < 10 → Dynamic simulation needed to confirm HGBV
NI > 10 → HGBV is not likely to be needed

- Original Botros article suggests considering parameters at surge point of maximum speed → conservative basis
- Ajdari et al suggest using normal operating case parameters

Method-1	
Total inertia, kg-m2	105
Polytropic head, J/kg	134500
Inertia Number, NI	4.4
HGBV Needed	Dynamic Simulation

Inertia Number Calculator per Botros article available online at (good webinar too):
http://www.betamachinery.com/knowledge-center/tools/surge-control-dynamic-simulation-calculator

Ajdari et al, HP, August 2010

Centrifugal Compressor Surge Control Systems -Fundamentals of a Good Design, Botros et al, ATPS, 2016

Method 2 –Impedance Characteristics

Compressor operating point does not move till compression wave or expansion wave travels to compressor; occurs at speed of sound

ASV

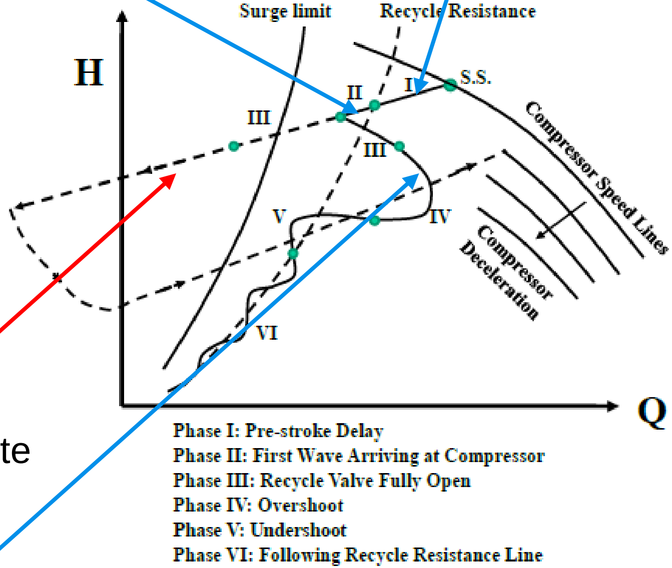
High pressure | Low pressure

Expansion wave to compressor discharge prompting more people to move → compressor operating point change

Molecular communication at speed of sound

Compression wave to compressor suction prompting more people to move → compressor operating point change

Finite limit to how fast ASV can receive signal and respond to it → pre-stroke delay



Path if recycle valve not adequate

Path if recycle valve adequate

Centrifugal Compressor Surge Control Systems -Fundamentals of a Good Design, Botros et al, ATPS, 2016

https://www.pinterest.com/pin/1004 86635411375676/

Method 2 –Impedance Characteristics

$$\delta t_{max} = I\, N_o^2 \left[\frac{S(Q_o - Q_{so}) + (H_{so} - H_o)}{2H_{so} - S\,Q_{so}}\right] / \left[\frac{\dot{m}_o H_o}{\eta_a\, \eta_m}\right]$$

Time for compressor to cross surge line

Greater

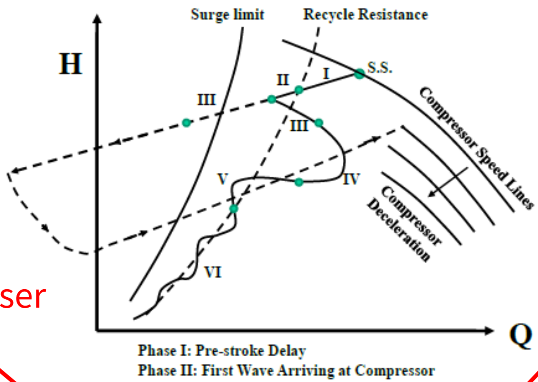
ASV size / response adequate

Lesser

ASV size / response not adequate

Due to:

- Low compressor inertia
- High differential head



Time for ASV pre-stroke delay + expansion / compression pressure wave travel time from ASV to compressor

Lesser

ASV size / response adequate

Greater

ASV size / response not adequate

Due to:

- Large ASV pre-stroke delay
- Longer suction / discharge pipe

Centrifugal Compressor Surge Control Systems -Fundamentals of a Good Design, Botros et al, ATPS, 2016

Probite

Method 2 –Impedance Characteristics

Time for Compressor to go in Surge	
Gas Constant, J/kg-K (= 8.314 / MW)	489.1
Speed of sound at suction, m/s	461.9
Speed of sound at discharge, m/s	514.0
Angular speed (w), rad/s (= N*2*pi/60)	1061.6
Zeta, J/kg	588245.1
S, J.s/kg-m3	3396.7
dNmax/N0	0.017
dNmax, rpm =(dNmax/N0)*Impeller rpm i.e. N0	172.0
m0*H0/na*nm, kW	15333.8
Deltamax, ms	131.0
Time for ASV pre-stroke + Pressure waves to Reach Compressor	
Valve pre-stroke delay	200
Expansion wave arrival time at discharge, ms	291.8
Total time for expansion wave, ms	491.8
Pressure wave arrival time at suction, ms	324.7
Total time for compression wave, ms	524.7
Fastest arrival time, ms	491.8
HGBV Decision	
HGBV Needed	YES

$$Speed\ of\ sound\ (c) = \sqrt{\frac{\gamma \cdot R \cdot T}{MW}}$$

$$where:\ \xi = \frac{Z_{av} R T_1}{\left(\frac{k-1}{k}\right)}$$

$$S = \frac{dH}{dQ} = \left(\frac{k-1}{k}\right)(H_o + \xi)\left[\frac{\rho_1 c_1}{P_1 A_1} + \frac{\rho_1 c_2}{P_2 A_2}\right]$$

$$\frac{\delta N_{max}}{N_o} = \frac{S(Q_o - Q_{so}) + (H_{so} - H_o)}{2H_{so} - S Q_{so}}$$

$$\frac{\dot{m}_o H_o}{\eta_a \eta_m}$$

$$\delta t_{max} = I N_o^2 \left[\frac{S(Q_o - Q_{so}) + (H_{so} - H_o)}{2H_{so} - S Q_{so}}\right] / \left[\frac{\dot{m}_o H_o}{\eta_a \eta_m}\right]$$

= Pipe length / speed of sound

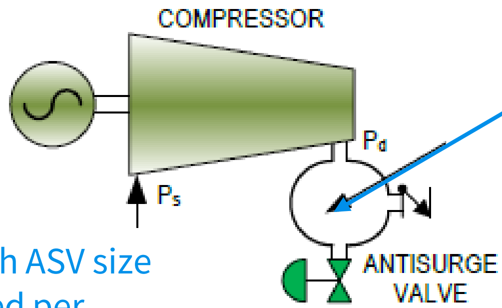
Time for compressor to go in surge < wave arrival time → HGBV needed

Probite

Method 3 – Lumped Volume

On compressor trip, within 1 second:
- Speed decreases by 20-30%
- Compressor Head decreases by 50% →

ASV must decrease pressure here by 50% as well



Compressor discharge initial mass = Discharge volume * discharge density @ 75% of normal discharge pressure

↓

Target mass at discharge after 1 second = 50% of initial mass

↓

Required flowrate = (Initial mass – final mass) / 1 second

←

Calculate ASV size (Cv) @P1 = 75%*Pd

$$Cv = \frac{W_s}{N_8 \cdot F_p \cdot P_1 \cdot Y} \cdot \sqrt{\frac{T_1 \cdot Z_1}{X \cdot MW}}$$

↑

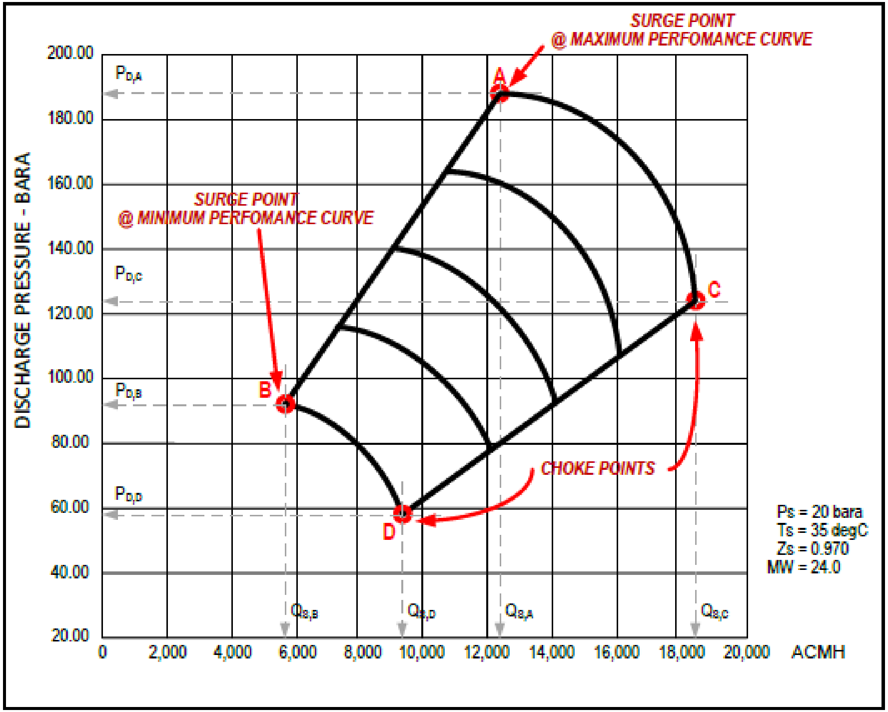
Compare with ASV size (Cv) estimated per conventional procedure

HGBV needed if calculated Cv > Cv from conventional method

Turbomachinery control valves sizing and selection, Medhat Zaghloul, TPS, 2017

Probite

Method 3 –ASV Cv Estimation



Turbomachinery control valves sizing and selection, Medhat Zaghloul, TPS, 2017

$$Cv = \frac{W_S}{N_8 \cdot F_p \cdot P_1 \cdot Y} \cdot \sqrt{\frac{T_1 \cdot Z_1}{X \cdot MW}}$$

- Estimate Cv at these four points A to D
- Cv for surge point = maximum of Cv at A or B
- Selected ASV valve Cv = Cv for surge point * 1.8 to 2.2
- Selected ASV valve Cv < Cv at point C or D

Method 3 – Lumped Volume

Method-3	
Discharge pressure for ASV sizing, kPa	5212.5
Discharge density, kg/m3	27.5
Discharge mass, kg	1647.6
Target mass, kg	823.8
Mass flowrate, kg/hr	2965610.9
Required Cv	4798
Actual Cv of ASV	550.0
HGBV Needed	YES

75% of normal discharge pressure

Normal discharge Z and T

= PM/ZRT

= Discharge volume * discharge density

= 50% of initial mass

= (Initial mass – target mass) / 1 s

$$Cv = \frac{W_s}{N_s \cdot F_p \cdot P_1 \cdot Y} \cdot \sqrt{\frac{T_1 \cdot Z_1}{X \cdot MW}}$$

If required Cv > Actual / estimated Cv of ASV → HGBV needed

Summary of Sample Calculation:

1. Method-1 → HGBV need to be confirmed by dynamic simulation
2. Method-2 → HGBV needed
3. Method-3 → HGBV needed
4. Dynamic simulation and actual construction → HGBV installed

Analysis of Few Data Points

Process Parameters	Export Gas Compressor	Circulation Compressor	Recompressor	Recirculation Compressor	Export Gas Compressor
Rated flowrate, m3/hr	15713	950	37566	4327	1810
Psuction, bara	32	53.5	29	152.3	110
MW	17	19.5	17	3.6	18.5
Rated head, kJ/kg	134.5	14	20.72	158.12	69.5
Compressor speed, rpm	10138	16800	9300	11412	12558
Total inertia, kg-m2	105	5.5	13	52	440
Method-1					
Inertia Number, NI	4.4	57.2	1.4	9.4	98.1
HGBV Needed per Method-1	Dynamic Simulation	NO	YES	Dynamic Simulation	NO
Method-2					
Time for compressor to go in surge, ms	131.9	401540.7	3180.3	106144.9	4532017.5
Fastest pressure wave arrival time, ms	486.4	310.4	308.8	295.9	430.8
HGBV Needed per Method-2	YES	NO	NO	NO	NO
Method-3					
Required ASV Cv (HGBV)	5565	262	5307	483	1716
Actual ASV Cv - Vendor / Conventional Method	695	161	4468	165	145
ASV Cv shortfall as % of ASV Cv	-701	-63	-19	-193	-1081
HGBV Needed per Method-3	YES	YES	YES	YES	YES
HGBV Needed per Dynamic Simulation	YES	NO	NO	NO	YES

Few more data points needed; do you have any?

- Dynamic Simulation is the Best way to decide on HGBV
- Method-2 based on impedance characteristics seems to agree with dynamic simulation except for one data point with large inertia, high suction pressure and low flow
- Method-1 though simple shall be used only for export / feed gas compressors
- Method-3 predicts HGBV need for all data points though difference between ASV Cv and HGBV Cv can be used as an indicator of severity of surge. On this count, this is the only method that works for last example

Probite