Performance Application Limits

Critical Projects

Critical Projects are those projects that are more complex and have a greater potential for operational issues if special attention is not applied early in the project. Ariel would like to assist in the review of critical projects and therefore has included a flag in the performance software identifying the projects that fall in this category.

Critical Projects are defined by a review of:

Application Type:

- Gas Transmission
  - Wide Range of Operating Conditions
  - Wide Range of Capacity Control Steps including Single Acting Cylinders
  - Large drivers
  - Difficult Valve Selection due to the Wide Operating Range
  - Complex Acoustic Responses
- Storage Injection and Withdrawal
  - Higher Pressures
  - Attention to Cylinder Lubrication
  - Water cooled packing cases
  - Wide Range of Operating Conditions
  - Difficult Valve Selection due to the Wide Operating Range
- PRC (Petroleum / Refinery / Chemical)
  - Industrial Gasses
  - More Stringent Specification Limitations
  - New Customer base

Equipment Type:

- Large Frames
  - KBU, KBZ, KBB and KBV
  - Some JGC, JGD and JGF
  - Large Two Throw Frames
  - Requiring Special Tools for Maintenance
- Pipeline Cylinders
  - High Flows with Large Piping
  - High Frequency Components
  - Large, Low Natural Frequency Cylinders
- VS Forged Steel Cylinders
  - High Pressure
  - Lubrication

  - Water Cooled Packings
  - Available Tailrods

Driver Type;

- Electric Motor
  - Unique Installations
  - Shaft Sizing Restrictions (see Packager's Standards)
  - Always Requiring Torsional
  - Often Requiring Torsional Detuning Devices (flywheels, detuners, special couplings...)
- VFD (Variable Frequency Drive)
  - Unique Installations
  - Shaft sizing restrictions
  - Always Requiring Torsional
  - Often Requiring Torsional Detuning Devices (flywheels, detuners, special couplings...)
  - Wide range of speeds, often with blackout ranges due to torsional response
- Large Gas Engines
  - High horsepower - high excitation forces
  - Longer drive trains
  - Often Requiring Torsional Detuning Devices (flywheels, detuners, special couplings...)
  - Some larger engines designed for power generation may require special couplings and attention to torsional results
- Gear Boxes
  - Difficult to detune torsionally
  - Most often requiring special couplings
  - Axial and Lateral Alignment Concerns including Thrust Limitations

Location:

- Offshore and FPSO
  - Limited Access
  - Limited Space for Maintenance
  - High Visibility
- International Destinations
  - Less Support Infrastructure in some Regions

Other:

- Sour Gas
  - Proper Materials
  - Purge and Vent Systems
- Pneumatic Fixed Volume Clearance Pockets
  - Supply and vent lines
  - Complex controls

Project Reviews

Many Critical Projects can be successful with a comprehensive review of the system during different phases of the project:

1. Budget and Quotation Phase
   - Regional Sales Managers and Applications Engineering can provide assistance in selection
2. Order Phase
   - Order Entry can provide assistance with scope of supply
   - Applications Engineering can provide assistance with documentation, including torsional data
   - Tech Services can provide assistance with packaging design for maintenance support and vibration avoidance
3. Installation and Start-Up Phase
   - Tech Services can provide assistance with installation review, start-up checklist review, review of vibration concerns

Torsional Providers

The success of the torsional analysis depends heavily on the modeling of the equipment and operating range of the compressor. A torsional provider must be familiar with moderate to high speed reciprocating compressors and must be provided with the full range of operation of the compressor. The operating range is to include part load cases, cases with single acting cylinders and speed variations. Familiarity with Ariel compressors is quite helpful in understanding aux end amplitudes, the availability of the torsional data (mass elastic data, torque effort data and fourier coefficient data) and availability of specific flywheels, detuners and internal flywheels.

Acoustical and Mechanical Providers

Familiarity to moderate and high speed reciprocating compressors will aid in the successful acoustical and mechanical analysis. Some larger skids and many platform mounted skids may require a skid analysis to ensure vibration levels and stress levels of skid, piping and vessels are acceptable.

Torsional and Acoustical analyses may have interfering recommendations. More complex the operating ranges have a greater chance of interference between the torsional, acoustical and mechanical systems.

High Discharge Pressure

Applications with high discharge pressures (greater than 1500 psig) have several design details to consider:

Higher pressure applications will require special review of the cylinder lubrication oil selection as well as lubrication rates. Separate lube oil supply and heavier lube oils will be required. Refer to Packager Standards Section 6: Lubrication.

Higher pressure applications may have gas condensates between stages, or operate close to critical points or dense phase regions. This will require special considerations for interstage temperature controls. The Heavy Gas, CO_2 and Sour Gas topics can provide further information on this topic.

Higher pressures may require water cooled packing cases, or limitations on piston speed. The Packager Standards and the performance software will help guide the application for water cooled packings and pressure versus speed limitations.

Much higher pressure applications will utilize forged steel cylinders. A closer review for crosshead pin reversal across the operating speed range must be made to ensure sufficient reversal.

The use of the higher pressure forged steel cylinders will require a closer review of hydrogen sulfide content. Not all of the forged steel cylinders are suitable for operation with hydrogen sulfide content.

Low Suction Pressure

At suction pressures below 10 psig it is difficult for the end user to predict what the actual supply pressure will be within 1 to 2 psi and/or for the packager to predict pressure drops within a fraction of a psi. These variations in inlet pressure and pressure drops can result in a significant change in horsepower and flow, either upward or downward, depending upon the actual suction pressure.

Ariel recommends that compressor cylinders in this application be oversized between 5 to 10% and equipped with variable volume clearance pockets or high clearance valve assemblies to produce the desired flow. The effect of the actual suction pressure being 1 to 2 psi higher or lower should be considered when selecting the driver horsepower rating.

Vacuum Suction Pressure

Vacuum suction pressures can be applied to Ariel cylinders. The sensitivity of changes in suction pressure should be reviewed, as in the above Low Suction Pressure paragraph. Additionally, the mean cylinder pressure should be maintained above atmospheric pressure. If the mean cylinder pressure is less than 5 to 10 psig, air may be pulled into the cylinder and into the gas stream through the packing cases. If operating below 5 to 10 psig mean cylinder pressure, a purged packing can be applied, using sweet gas for the purge gas. This provides process or fuel gas to be drawn into the cylinder across the packing, rather than air. Consider installing an oxygen sensor downstream of any negative suction pressure equipment.

Maximum Allowable Discharge Temperature

The discharge temperature limits are presented as both an application limit and a maximum discharge temperature shutdown set point. The Ariel Performance Software provides a blue and red flag on discharge temperature. The blue flag represents a guideline for applying a selection. The red flag represents the maximum discharge temperature shutdown set point. The maximum discharge temperature shutdown set point is listed in the instrumentation section of the Packager Standards.

Table: Discharge Temperature Flags and Limits by Service

Service	Application Limit	Max Shutdown
Lubricated	330 °F (165 °C)	350 °F (177 °C)
Non-Lubricated	275 °F (135 °C)	325 °F (163 °C)
PRC	275 °F (135 °C)	325 °F (163 °C)
Hydrogen Rich	275 °F (135 °C)	300 °F (149 °C)

The Ariel performance software will provide a red flag if the discharge temperature exceeds the maximum allowable discharge temperature shutdown limit. A blue flag will be provided when the discharge temperature exceeds the application guideline, a warning as the discharge temperature approaches the maximum allowable level. A warning will also be displayed when the average of the suction temperature and discharge temperature exceeds 285 F (140 C).

The discharge temperature calculated by current version of the Ariel Reciprocating Performance Program, is based on suction temperature plus cylinder pre-heat and internal compression ratio. The equation is as follows:

$$T_D = \left[\left(T_S + 460 \right) x\, R^{\frac{(k-1)}{k}} \right] - 460$$

or

$$T_D = \left[\left(T_S + 273 \right) x\, R^{\frac{(k-1)}{k}} \right] - 273$$

for metric units

TD = Discharge Temperature, °F or °C

TS = Internal Suction Temperature, °F or °C

R = Internal Compression Ratio , pressure discharge / pressure suction

k = Ratio of Specific Heats

High discharge gas temperature shutdowns should be set as close as practical to the operating temperature.

Maximum Allowable Working Pressure

The maximum allowable working pressure is the maximum continuous pressure for which Ariel has designed the cylinder when handling the specified fluid at the maximum temperature. Relief valves shall be provided and set to operate at no more than the Maximum Allowable Working Pressure. The MAWP is based upon the minimum of the following considerations:

- Burst test pressure (adjusted by a safety factor which is dependent on cylinder body material)
- Allowable bolt loading
- Flange rating
- Alternate cylinder bolting (17-4PH bolting). Current cylinder MAWP are not reduced in most cases when "Sour Gas" bolting is used. The NACE MAWP are listed in the DataBook for the exceptions (17-7/8K:T:C:D:Z:U Class cylinders).

The Ariel DataBook lists only current MAWP ratings. Many cylinders have been uprated over time. Always check the cylinder nameplate for the MAWP when calculating compressor performance for existing equipment.

Maximum Allowable Internal Gas Rod Load

Ariel gas rod load ratings are based upon calculated internal gas rod loads. The maximum allowable gas rod load of a given frame shall not be exceeded at any operating point. Refer to Ariel Calculation Method for internal gas rod load equations.

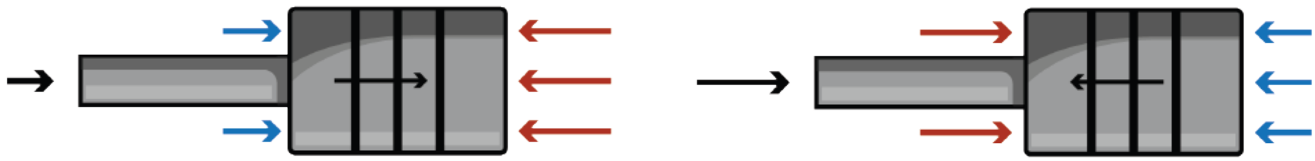
Gas rod load is best monitored for alarm and shutdown with the use of a differential pressure switch across each cylinder at the flange (cylinder discharge pressure minus cylinder suction pressure). The performance software and the rod load charts from the DataBook are available to assist in determining the differential pressure settings.

If the operating conditions are to include the relief valve set pressure, the compressor gas rod load must be maintained within the gas rod load limit, either by not exceeding the gas rod load limit at relief valve set pressure or by applying a shutdown switch on differential pressure across the cylinder. The relief valve is meant to protect the pressure equipment from exceeding system pressure ratings. Relief valve set pressures are discussed in the Packager Standards Section 4.

The Ariel DataBook lists gas rod load ratings for both current and inactive frames. Always check the frame nameplate or contact the Ariel Response Center for the maximum allowable internal gas rod load when calculating compressor performance for existing equipment.

Minimum Allowable Pin Load Reversal

Crosshead pin reversal is a reversal of compression and tension loads at the crosshead pin to connecting rod bushing. Without proper reversing loads, the bushing will not be provided with sufficient lubrication and bushing failure will occur. Pin reversal is defined by two components, degrees and percent. These represent the duration of the reversal and the magnitude of the reversal. Both of these values must meet or exceed minimum values. Ariel’s requirements for reversal are 30 degrees of crank rotation, and 25% magnitude. The percent magnitude is defined by the smaller of the tension or compression force divided by the larger of the two. The combined gas plus inertia loading at the crosshead pin is used for the reversal calculations. The inertia load component includes the weights of the piston and rod assembly, balance nut and crosshead with crosshead bushings.



Some smaller frames are rated for lower reversal values, 30 degrees and 15%.

Ariel's Reciprocating Compressor Performance Program provides the reversal values and will flag upon insufficient reversal. A full review for reversal will need to include the range of speed, pressure and any single acting conditions. The multi-run function is an invaluable tool in reviewing reversal values.

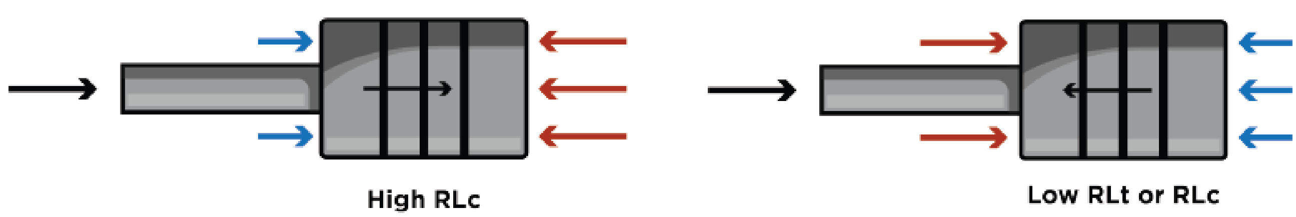
The ratio of compression to tension gas rod load can indicate reversal may be of concern. If compression gas rod load is much higher than the tension gas rod load, reversal may be a concern and should be reviewed.

There are several specific situations and configurations that should be reviewed in the multi-run function across the full range of speed, pressure, and load steps for sufficient reversal. These include:

High Pressure Service:

High pressure on smaller bore cylinders operating at lower compression ratios can see a notably higher compression gas rod load than that in tension. Possible solutions include selecting a larger cylinder bore, selecting a tail rod cylinder configuration, or increasing the balance weight (crosshead and balance nut).

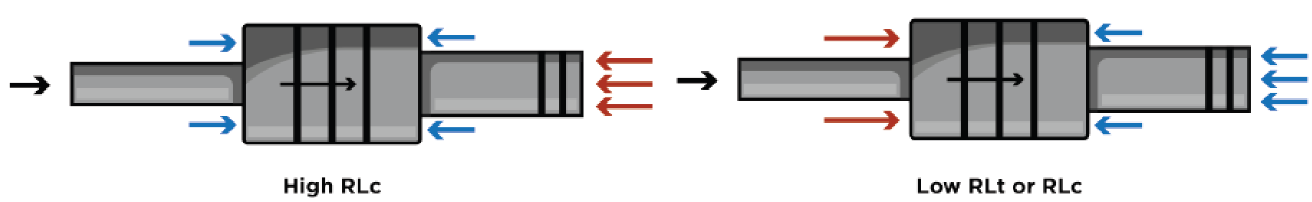
High Pressure - Small Bore



Tandem cylinders:

Tandem cylinders may see sufficient reversal at the maximum and minimum speed, while insufficient reversal somewhere in between. Adding balance weight will move this dip in the reversal curve, but not often completely out of the operating speed range. Possible solutions include selecting a larger crank end cylinder bore (then add clearance if needed), increasing the balance weight, or limiting operating speed.

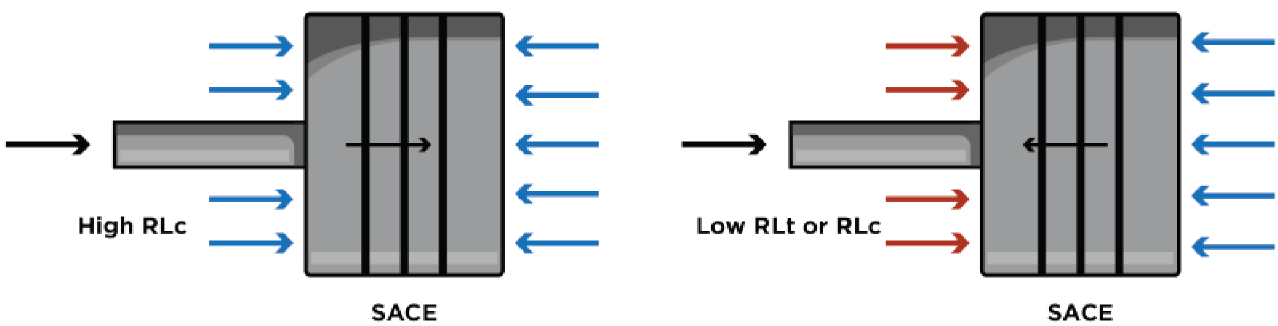
Tandem Cylinders



Single acting cylinders:

Single acting at lower compression ratios results in longer periods of gas rod load in compression. At lower speeds reversal can be insufficient to offset the gas compression load. Possible solutions include increasing the balance weight or limiting the lower end of the speed range.

Single Acting Cylinders



Maximum Allowable Reciprocating Weight

Each compressor frame has a maximum allowable reciprocating weight limit. This weight is based upon the total combined weight of the connecting rod assembly, crosshead assembly, crosshead nut and piston / rod assembly. The maximum allowable reciprocating weight limits are included in the limitations set within the Ariel performance program.

Reciprocating weight will affect the inertia load, and therefore the combined rod load. Ariel publishes internal gas rod load limits, and maximum allowable reciprocating weights, rather than combined rod load limits.

Ariel's performance program will monitor maximum reciprocating weights versus rotative speed and provide application limitations within the weight balance section.

Refer to Ariel Corporation Electronic DataBook Cylinder Details for rotative speed limitations for the various frames and cylinder classes.

Rated Speed (Maximum Allowable Rotating Speed)

Each frame has a rated (maximum allowable rotating) speed. This is the highest allowable rotating speed for continuous operation. The driver overspeed shutdown must be set no higher than 10% over the rated speed of the compressor.

Some large bore cylinders are limited to a maximum operating speed that is less than the frame rated speed. See the Ariel Corporation DataBook cylinder details for rotative speed limitations.

See Also Rated Speed (Minimum Allowable Rotating Speed)

Rated Speed (Minimum Allowable Rotating Speed)

Many factors affect how slow the compressor can be operated. These include oil supply pressure to the frame, crosshead pin load reversal, valve dynamics, and torsional / acoustical considerations.

Ariel Compressor frames are designed to have adequate frame oil supply pressure down to one half their rated rotating speed. If operation at less than half speed is desired, the addition of a motor driven auxiliary lube oil pump is required to maintain adequate lube oil pressure and flow. The additional flow of the auxiliary oil pump will maintain the frame oil pressure required for proper operation. Removal of the main frame oil pump is not necessary.

Lack of adequate crosshead pin load reversal can limit the minimum operating speed. An analysis of the crosshead pin forces must also be performed to ensure that the proper amount of pin force reversal is present at all operating speeds and load steps.

Compressor valves are selected for a specific operating condition with some flexibility for variations for speed and operating conditions. A general rule of thumb for valve selection is that a single selection can be operated within a 2:1 maximum speed range. Varying suction pressures, discharge pressures and gas analyses can further limit this speed range. Low lift valves may be necessary for speed ranges outside a 25% variation.

Speed ranges must be considered in the torsional and acoustical analyses. Wider speed ranges in combination with wide ranges in operating conditions and load steps may result in black out speeds due to natural frequency interferences.

All applications requiring rotative speeds that are lower than one half the rated speed of the frame, must be reviewed by Ariel Corporation Applications Engineering.

Also See:

Frame Driven Lube Oil Pumps

Rated Speed (Maximum Allowable Rotating Speed)

Maximum Allowable Piston Speed

Ariel compressors are designed to be operated at full speed for most natural gas applications. Slower piston speeds may be necessary based upon the application. Factors that affect lowering the operating piston speed include gas mole weight, higher discharge pressures, desire for better efficiency and client preferences.

Piston speed can be calculated with the following equation:

$$PS = \frac{2 \ x \ Stroke \ x \ RPM}{12}$$

PS = Average Piston Speed, feet per minute

This equation calculates average piston speed, which is the basis for piston speed related ratings. Instantaneous piston speed is different, since the piston accelerates from zero velocity at the end of the stroke, and obtains a maximum velocity during the stroke.

Some larger bore cylinders have limited piston speeds due to the higher inertia. For maximum piston speed see individual cylinders in the DataBook.

For non-lube applications, allowable piston speeds are reduced. See application guidelines for non-lube applications for more information.

Frame Horsepower Limits

Ariel Compressor frames are not horsepower limited. Ariel compressor frames are limited by internal gas rod load. The published horsepower ratings are guidelines to be used in applying each compressor frame. The horsepower ratings may be exceeded, as long as other application limits are not exceeded. A torsional analysis should be performed to confirm vibratory torque limits are not exceeded.

Some frames carry a power limit on each throw. This limit is flagged separately, and is speed dependent. The KBK:T frame includes a power per throw limit.

Minimum Volumetric Efficiency

Volumetric Efficiency (VE) is the ratio of the actual delivered gas volume to the swept volume of the cylinder. For additional information refer to the compressor theory

The minimum allowable suction volumetric efficiency for any cylinder end at a proposed operating point is 15%. These limits are set to allow proper valve dynamics.

It is recommended to allow a usable margin to this minimum VE for operation outside normal operating conditions. A 30% VE at normal operating conditions will allow some margin for unforeseen operating conditions or clearance pocket usage.

Low volumetric efficiencies will result in higher than expected discharge temperatures, higher than expected horsepower per million and lower than expected capacity. Low volumetric efficiencies will result in poor valve dynamics leading to possible early valve failure.

Discharge volumetric efficiency must be measured in time rather than percent. Refer to Discharge Event for information and limits on discharge volumetric efficiencies.

Pseudo-Q Value

(Courtesy Hoerbiger Corporation of America)

The "pseudo-Q value" is a term used at Hoerbiger which is an indicator of the "adequacy" of a valve. In other words, is there enough or too little valve for the application?

The pseudo-Q value is a dimensionless value developed by Hoerbiger and Ariel to indicate the adequacy of a compressor valve. It is defined as the average pressure drop through the valve divided by flange pressure, expressed as a percentage. The pseudo-Q value must be between 1% and 15%. With high and low pseudo-Q values the compressor calculation model is not able to accurately predict the horsepower losses, preheating of the gas during the intake event or the volumetric efficiency (capacity).

On the suction valves the Q - value is the pressure drop across the valve in percent of line pressure:

$$q = \frac{\pi^2 \rho_s V^2}{8P_s} = \frac{\Delta P}{P_s}$$

where *Ps* = gas density

Ps = suction pressure

V = mean valve velocity (calculated with equivalent area)

Ariel and Hoerbiger require Pseudo-Q values between 1% and 15%

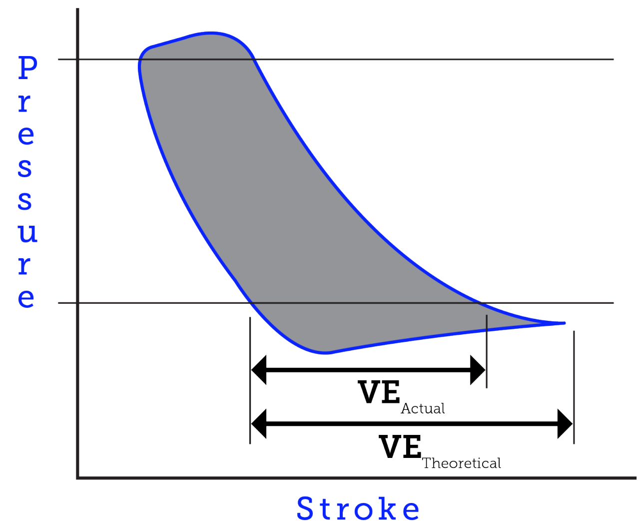
- Pseudo-Q value less than 1%

  If Q drops below 1%, it becomes difficult to achieve good valve dynamics, since the pressure drop which the valve springs work against is too low and a tendency towards valve flutter is great. This is what is commonly referred to as having “too much valve”. This can happen when compressing low molecular weight gases (hydrogen, helium, etc.). The solution is to lower the valve lift, lowering lift area and equivalent area, and creating a larger pressure drop across the valve.

- Pseudo-Q value greater than 15%

  If Q is 15% or higher, the pressure drop across the valve is too high for the cylinder pressure to recover to line pressure at the end of the suction stroke. The valve does not close at the end of the stroke as designed. Gas backflows through the valve as the piston is beginning the compression stroke, which slams the valve closed. Volumetric efficiency is also reduced since the cylinder does not have a full charge of gas (due to a backflow out of the cylinder bore), in addition to the high horsepower losses associated with the large pressure drop across the valve. High q-values can occur when compressing high molecular weight gases(CO_2, propane, etc.). In most cases, lift cannot be added to valve without sacrificing durability. Slower rotating speeds will lower q-values by decreasing piston speed and gas velocity through the valve. Selecting a different cylinder may result in lowering the pseudo-Q value due to valve flow areas differences., etc.).

Figure: Theoretical vs. Actual VE

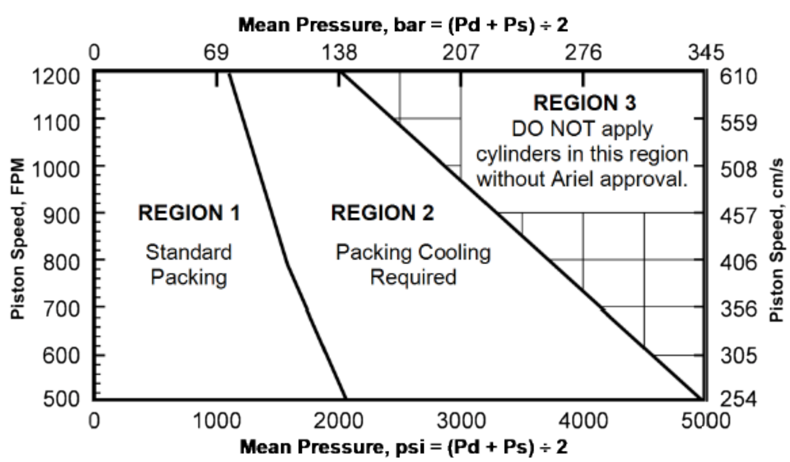


Water Cooled Packings

Cooled packing cases are required for compressor cylinders based upon the average piston speed and average cylinder pressure. Cooled packing cases are supplied to help remove the heat generated as the piston rod/ packing friction increases with the higher pressures and piston speed.

Please refer to the Packager Standards Section 7: Cooled Packing for further information on this topic. The following chart is an excerpt from the Cooled Packing topic:

Figure: Packing Cooling Application Guidelines

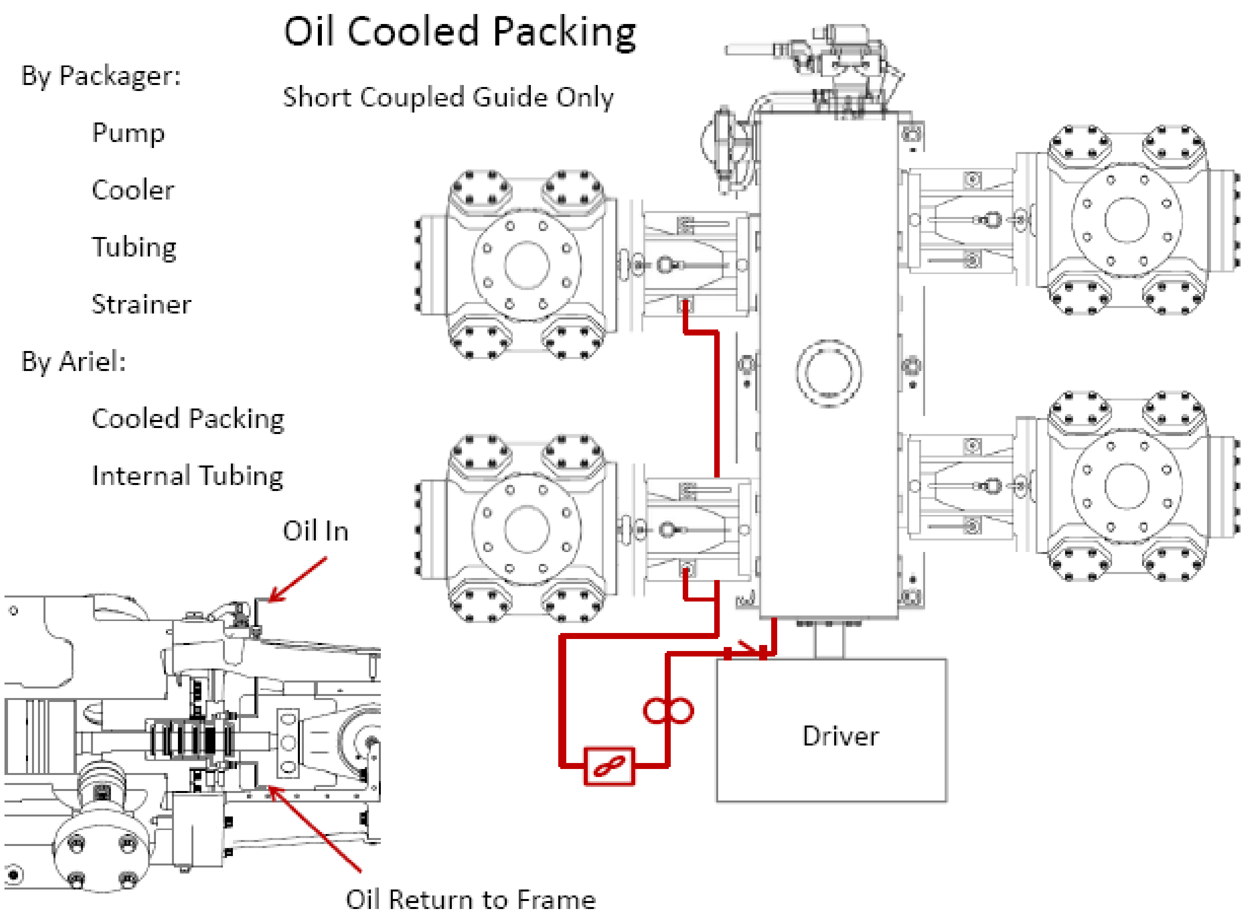


Notes:

1. The Ariel Performance Software will indicate when operating conditions fall within Region 2 or Region 3.
2. All forged steel cylinders have cooled packing as standard and must be connected to a cooling system.
3. All non lubricated cylinders have cooled packing as standard and must be connected to a cooling system.
4. Any deviation from the packing cooling requirements must be reviewed and approved by Ariel Applications Engineering or Technical Services.

Cooling with oil is not as effective due to the lower heat transfer ability and higher pressure losses due to viscosity. In some circumstances, oil can be used as a coolant in the packing cases. This is limited to lower heat load conditions and smaller compressor frames. The advantage of applying oil cooling in the smaller frames, is the ability to use frame oil, making it possible to cool the packing case with the short coupled distance piece. Oil will be taken from the frame oil system, and returned internally, directly into the crosshead guide.

If one packing case is oil cooled on the smaller frames, the oil will be taken from the pressurized frame oil system. This is a closed loop and all tubing provided by Ariel. If more than one packing is oil cooled, a separate oil loop will need to be provided by the packager. Oil can be taken from the sump at the drive end of the frame, through a pump, cooler, and into the packing. The packing return will be internal, directly into the crosshead guide. Below is a schematic showing oil cooling on more than one packing case.



Non Intercooled

At times, more commonly with refrigeration units, interstage gas cooling may not be necessary due to low discharge temperatures from the low gas k-value. Operating without an interstage gas cooler can be done with special considerations.

The suction temperatures to each stage, and mean cylinder gas temperatures must be limited as noted in the Suction Temperature topic.

All considerations for condensation must be reviewed and confirmed to avoid condensation at the interstage. Condensate considerations include periods of shutdown / cool down and compressor cylinder lube oil carry over. Interstage liquid removal should be considered.

A bottom suction cylinder arrangement may be possible on some applications to allow interstage piping routing from the top of one stage to the top of the next stage, avoiding areas that can trap liquids on the interstage.

All non-intercooled applications must be reviewed and approved by Ariel Mount Vernon prior to quotation.