ZEVAC

The Importance of Liquid-Readiness in Cross Compression and Flaring Applications

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In cross compression and flaring applications for piping system maintenance, there is a high probability and high consequence of liquids and debris being encountered. It is therefore very important that compressors and flares have a high degree of readiness to encounter these liquids. This paper highlights the importance of liquid readiness through the framework of risk reduction:

Risk = Probability x Consequence

- ZERO Consequence of liquids: ZEVAC Compressors
- High Probability of encountering liquids during maintenance
- High Consequence of liquids: Flaring (Flare carryover)
    - What happens if liquids enter the flare system?
    - How do equipment operators protect against this today?
- High Consequence of liquids: Traditional Compressors (Failure)
    - What happens if liquids enter the compressor system?
    - How do equipment operators protect against this today?

(HIGH)	ZEVAC		FLARE, COMPRESSOR
Probability of Liquids			
(LOW)			
	(LOW)	Consequence of Liquids	(HIGH)

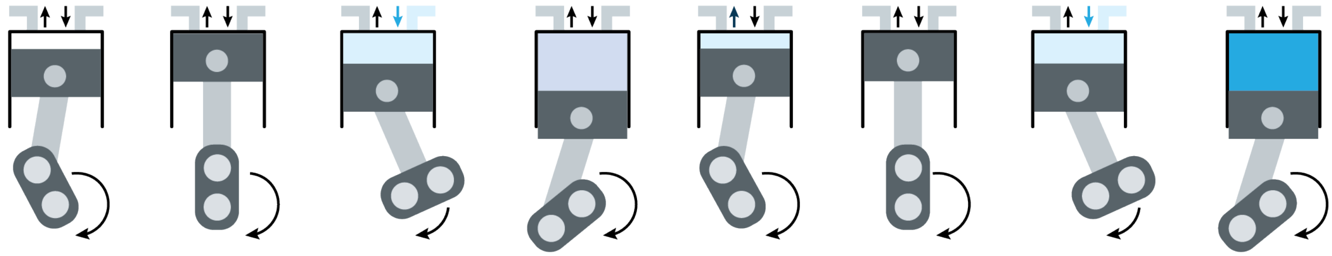
Zero Consequence of Liquids: ZEVAC Compressors:

ZEVAC compressors were first created to solve 2-phase blowdowns in the wet gas gathering environment, where various equipment contains up to 100% liquids, but can also be 100% gas or any mixture in between. The ability to safely handle liquids, gases, and mixed phase fluids is derived from the unique nature of the drive train and compression system.

ZEVAC compressors are Linear Positive Displacement Compressors. As opposed to rotary equipment (traditional reciprocating and centrifugal compressors), linear compressors are highly tolerant of liquids due to the compressibility of the air within the drive train. By contrast, a traditional compressor's rotary drive train has both 1) the pistons connected directly to the crankshaft coupled directly to the prime mover and 2) high speed and inertia, so that a sudden stoppage of the piston due to liquid ingress immediately creates incredibly high hydraulic forces in the compression cylinder. This in turn stops the piston instantly, which transfer shock loads through the connecting rod, to the crankshaft, and back up the drive train until the weak point is found and failure occurs. In this same scenario, a ZEVAC compressor cylinder becomes filled with liquid, but the lack of inertia in the drivetrain and the compressibility of the prime mover (compressed air), the piston stops, and the air pressure will rise, which will functionally cause the ZEVAC to act as a positive displacement "pump" until the cylinder is cleared of liquids. At this point, the ZEVAC is undamaged, the liquids have been processed in and out of the ZEVAC unit, and the gas transfer can resume (or additional liquids can be transferred).

ZEVAC

Typical Reciprocating Compression (Gas)



1100 rpm

1 Top Dead Center

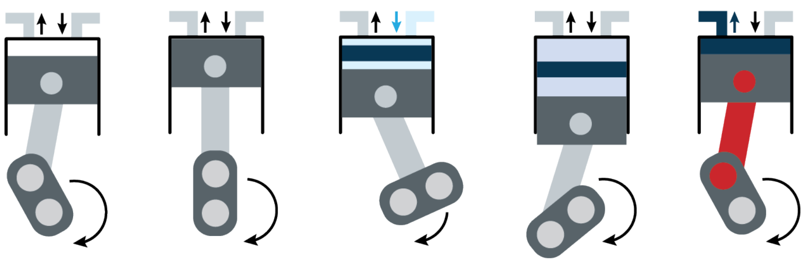
2 Gas is drawn into the cylinder

3 Gas is compressed as a piston rises

4 Gas is discharged when cylinder pressure> backpressure

5 Cycle repeats at crankshaft rpm

Typical Reciprocating Compression (Liquid Encountered)

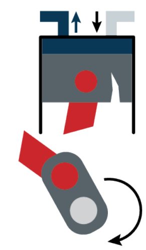


4 When the piston attempts to compress the incompressible liquid, exterme hydralic forces are created in a near instantaneous shock

5 Shock load propagates through the piston, connecting rod and crankshift until the weakest link fails

6 After drivetrain failure, high pressure gasses and liquids are released

7 Part ejection and cascading failures are typical

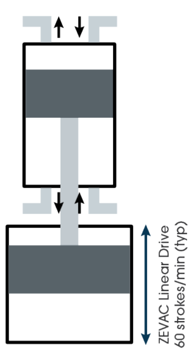


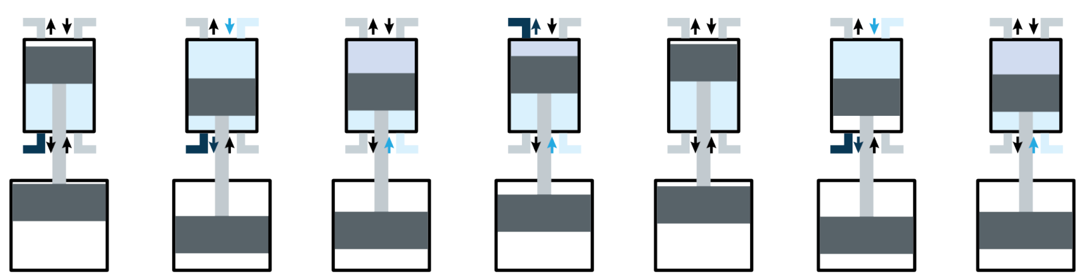
1 Top Dead Center

2 Gas and incompressible liquid is drawn into the cylinder

3 Gas is compressed as piston rises

ZEVAC Linear Compression (Gas)





1 Top Dead Center

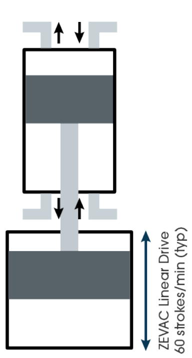
2 Gas is drawn into the cylinder (while back side is compressing)

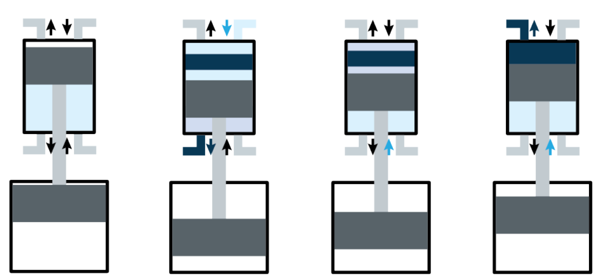
3 Gas is compressed as a piston rises (while back side is drawing gas in)

4 Gas is discharged when cylinder pressure> backpressure (while back side fills with gas)

5 Cycle repeats as fast as the drive can be supplied with air

ZEVAC Linear Compression (Liquid Encountered)



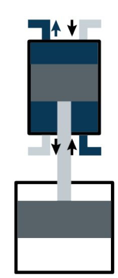


4 When the piston attempts to compress the incompressible liquid, the linear drive will function as a “pump” and continue to slowly stroke as the fluid is discharged

5 As the cycle repeats as fast as the linear drive can be powered, up to 100% liquids can be processed.

6 When the liquids cleared, the gas transfer process resumes normally.

7 Two phase and condensable flow are also commonly handed by ZEVAC in wet gas applications.



1 Top Dead Center

2 Gas and incompressible liquid (while back side is compressing)

3 Gas is compressed as a piston rises (while back side is drawing gas in)

High Probability of Encountering Liquids During Maintenance:

'Cross Compression' aka 'Vent Gas Recovery' and 'Flaring' are two commonly accepted methods of reducing voluntary blowdown emissions. The normal process for these two methods involve a common overall project flow:

1. Isolate the pipe system being "blown down"
2. Connect temporary equipment (flare or compressor)
    a. Flare = Drawdown connection only
    b. Compression = Drawdown and Discharge connections
3. Activate temporary equipment to remove pressurized product from the pipe

Both methods involve bringing the pressure on the system "vented" down to a safe level so that maintenance can proceed. In these pre-maintenance depressurization applications, there is a near certainty that some degree of liquids will be encountered. The following table outlines some of the liquids that are commonly found during maintenance operations on pipelines and distribution piping systems.

Liquid	Note
Water Vapor	Pipeline quality gas allows for up to 7lbs of water vapor for every 1,000 mcf of gas.
Water	Water is commonly found in pipelines at low points (usually water or other crossings). Water can enter the pipe during hydrotesting, a leak, or condensation of the water vapor in the gas. Free standing water can (and does) exist in pipelines, but are only occasionally detectable at the delivery point.
Ethane	While the majority of natural gas is methane, various other hydrocarbons are always found in the gas stream. These other gases have lower vapor pressures (and therefore higher vapor temperatures). Depending on the conditions, these products can be in either the vapor or liquid phase in the gas lines.
Propane	Propane is commonly found in virtually all natural gas systems. At high pressures, the propane remains liquid. During flaring or cross compression, the propane can vaporize, but this creates a very low temperature environment which can in turn cause other liquids to remain in their liquid state even at atmospheric pressure.
Butane	Similar to propane, butane will be present in some amount in most gas systems. Butane will typically be a liquid under any pressure above atmospheric, and butane will remain a liquid even in open atmospheres at temperatures below 31 deg F.
C5+	"Natural Gasoline", and all other NGLs can be found in gas systems. These products are typically passed at very low concentrations into the pipelines and distribution piping, but over years and years, they can build up.

Liquid	Note
Glycol/Methanol	To "dry" the gas, certain liquid chemicals such as glycol and methanol are introduced. These chemicals act to prevent hydrate formation. While many operators attempt to recover and recycle these chemicals, there is some inevitable "slip" that ends up as liquids in the pipelines.
Compressor Oil	Traditional compressors in all stages of the natural gas value chain have some degree of lubrication and oils present in their operation. While many operators attempt to recover and recycle lube oil from the compressors, there is some inevitable "slip" that ends up as liquids in the pipelines.
Solvents	Due to buildup of solids, waxes, and other contaminants in the pipe systems, operators commonly clean the pipes with solvents in a process called "chemical cleaning".
Biocide	To prevent corrosion due to biological processes and microbes, biocides are commonly used to treat pipe. These liquid biocides will be present in most pipelines
Corrosion Inhibitor	To prevent corrosion in general, inhibitors are used to coat the inside pipe walls of pipe to ensure long life. These corrosion inhibitors will generally exist as a liquid film on the inside wall of the pipe, and eventually these chemicals will migrate and pool, hence the periodic reapplications performed by operators.
BTEX	BTEX is not one chemical but are a group of the following chemical compounds: Benzene, Toluene, Ethylbenzene and Xylenes. BTEX are made up of naturally occurring chemicals that are found mainly in petroleum products such as gasoline. BTEX chemicals are considered toxic and are commonly found in trace amounts within natural gas systems.

* **Note regarding upstream applications:**

E&P, Gathering, Processing, and other stages of the natural gas supply chain before transmission have much higher liquid contents (up to 100% liquids). In those applications, even more care must be taken to consider the volumes of liquids that may be encountered.

** **Note regarding solid contaminants:**

The line between liquid and solid contaminants is not always easily defined. Pipe scale, rust, wax, paraffin, sand, and thick "sludge" may behave as liquids in some conditions while appearing as solids in other situations. The consequences of solids on a compressor or a flare system are similar to liquids and similar precautions should be considered. Filtration is typically used to remove solids contaminants, but if filtration is not present, tremendous caution should be given to the high probability that solids will also be present in the gas stream.

Specifications for Pipeline Quality Gas

Major Components	Minimum Mol%	Maximum Mol%
Methane	75	None
Ethane	None	10
Propane	None	5
Butanes	None	2
Pentanes and heavier	None	0.5
Nitrogen and other inerts	None	3
Carbon dioxide	None	2–3
Total diluent gases	None	4–5
	Trace components	
Hydrogen sulfide	0.25–0.3 g/100 scf (6–7 mg/m^3)	
Total sulfur	5–20 g/100 scf (115–460 mg/m^3)	
Water vapor	4.0–7.0 lb/MM scf (60–110 mg/m^3)	
Oxygen	1.0%	
	Other characteristics	
Heating value (gross, saturated)	950–1,150 Btu/scf (35,400–42,800 kJ/m^3)	
Liquids	Free of liquid water and hydrocarbons at delivery temperature and pressure	
Solids	Free of particulates in amounts deleterious to transmission and utilization equipment	

Source: Engineering Data Book (2004).

High Consequence of Encountering Liquids During Flaring:

In flaring operations, the contents of the pipeline are combusted to remove them. For these purposes, flaring is extended to also include thermal oxidation, both enclosed and open flares, as well as any other combustion driven process. The hazards of flaring have been studied extensively, and well documented in the wake of several severe accidents. In these studies, liquid overflow is routinely cited as the #1 hazard related to flaring.

Flare disposal systems have been involved in a number of major accidents – the most notable incidents in the UK include two fatalities at BP Oil Refinery Grangemouth in 1987, and the explosion and fires at the Texaco Refinery, Milford Haven in 1994. There are numerous additional examples world-wide such as in Mexico, in 1984, where around 500 people were killed in the PEMEX Mexico City disaster when the site ground flare was the ignition source for a released vapour cloud.

Hazards of liquid overfill & liquid slugging

Liquid overfill of flare vessels and liquid slugging in flare pipework can result in a number of hazardous events including – liquid rain-out from the flare tip, loss of containment due to liquid hammer, overpressure of upstream vessels trying to relieve into a partially blocked/liquid filled relief path, low temperature embrittlement and hydrocarbon release from the flare system into site effluent system via the seal water system.

A wide range of initiating events can and have led to liquid overfill, but in essence the initiating events for this hazard can be divided into two categories i) ingress of liquids from process equipment which relieves, vents or is blown down via the flare system ii) liquid accumulation in pockets, low points, dead-legs in flare laterals, sub-headers and main headers.

Prevention of the hazardous events listed above include the following prevention layers; effective level measurement and alarms in the flare knock out drum(s); automatic pump out of knock out drums to storage/slops on high level and knock out drums adequately sized for foreseeable events which provide operations personnel sufficient time to troubleshoot and identify and isolate the source of liquid ingress to the flare system.

Should the prevention layers fail and liquid overfilling or slugging occur, a hazardous event such as loss of containment occur, a number of mitigating layers may reduce the consequences to people, the environment or the commercial impact to the duty holder, though these may be less effective than preventative layers. Mitigating layers against the consequences of liquid overfill or liquid hammer include; siting of knock out drums at the edge of a plot or well away from other process units, process design allowing in the worst case overflow into seal water drums, overflow from knock out drums into seal water systems into sumps in preference to blocking the relief path as liquid accumulates up the flare stack.

One such incident where liquid overfill from the upstream process resulted in a loss of containment in the flare system is the fires and explosions at Texaco Refinery, Milford Haven, 24 July 1994 (UK HSE, 1997). A simplified overview of this incident, is illustrated in Figure 5, which summarises the accident path in terms of the protection layers present, how each protection layer was defeated to result in the accident and the post-accident measures put in place to improve upon the reliability and effectiveness of each protective layer.

Hazard	Accident Location and Country	Year	Description	Consequences
Flaring toxic streams	Poza Rica, Mexico (Mannan.S, 2005)	1951	A flare stack connected to a sulphur recovery unit at a natural gas processing facility developed a malfunction and flamed out for over 20 minutes resulting in a toxic plume containing approx. 16% v/v hydrogen sulphide in the unflared vent stream drifting off-site in foggy and calm conditions.	22 persons living off-site in the vicinity of the facility were killed by the toxic effects of the release and a further 320 were hospitalised for loss of smell, severe nausea, headache and unconsciousness. rigger) killed.
Working on flare systems	Refinery Grangemouth, United Kingdom (UK HSE, 1989)	1987	Flash fire formed and ignited followed by pool fire/jet fire following a sudden release of hydrocarbon vapours and liquids when removing a spacer from a flare line whilst replacing a cross-over valve - line was thought to be free of liquids and at residual pressure.	2 contract workers (fitter and rigger) killed 2 further workers suffered extnesive burns. Company prosecuted and fined £250,000.
Liquid overfill & liquid slugging	Pembrokeshire & Refinery & Cracking slugging Complex, Milford Haven, Wales (UK HSE, 1997)	1994	Following a lightning strike a unit was restarted and due to factors including, alarm flooding, the operations personnel did not detect and prevent liquid overflow from the process to the flare knock out drum. The knock out drum in turn overfillled and a liquid slug caused a rupture at an elbow of a 30 inch flare header.	Loss of containment and release of approx. 20 tonnes of hydrocarbon liquid and vapours. An initial explosion resulted which then led to further fires and explosions. 26 on-site injuries (all minor). Damage and losses of $140 Million (in 2013 prices)
Blocking the relief path	Petrochemical Plant, Augusta, USA (US CSB, 2002)	2001	Trapped pressure in a dump tank, which vented to flare, was not detected on account of vent lines and pressure indicator sense line filling up with molten polymer which then solidified with the result that when the dump tank cover was removed to empty the vessel of solids that it blew off with explosive force.	3 Maintenance workers killed by effects of the blast and subsequent fires.

Figure 1: http://www.icheme.org/media/8462/xxv-paper-15.pdf

Figure 2: Flare carryover igniting liquids which are falling back to ground

Additional hazard examples:

https://www.youtube.com/watch?v=SV-GOR9V35c
https://www.youtube.com/watch?v=35JpGjstasE
https://www.youtube.com/watch?v=I8rcwvHGplQ
https://www.youtube.com/watch?v=CITaS1hDAlQ

*** Note regarding other flaring hazards:**

Flaring, by its nature, presents many hazards beyond liquid carryover, which are beyond the scope of this discussion, but should be considered by all flaring operators.

- Hazards of liquid overfill & liquid slugging
- Hazard of flame out
- Hazard of flaring toxic streams
- Hazards of air ingress
- Hazards of blocking the relief path
- Hazards of heat and cold
- Height and other hazards
- Working on flare systems
- Hazards particular to offshore systems
- Environmental hazards and consequences

Preventing Flare Carryover:

In the design of flare systems for facilities with controlled environments and known process conditions, a variety of protections exist to prevent liquid carryover in the flare. In field maintenance environments with uncontrolled sites and unknown process conditions, experienced flare providers will provide very large and/or redundant protections for their flare systems. However, to great risk, it is commonly observed that in field flaring conditions, protections against liquid carryover are not utilized at all. It should be noted that even in the presence of liquid knock-out protection, slug flow and thermal effects can “get past” the typical separator systems and result in flare carryover.

High Consequence of Encountering Liquids During Cross Compression:

The consequences of liquids entering a traditional compressor are high, often resulting in catastrophic compressor failure. The problems with liquids in compressors are well understood, as evidenced by the extensive collection of publications as well as the existence of an entire industry of "knock-outs" and "filter separators" and "inlet scrubbers" that exist to prevent liquids from passing into compressors, which are found at nearly all stations.

> Compressors are intolerant to liquids. In reciprocating compressors with inherently large volumetric displacement rates, all modes of liquid ingestion pose a serious problem and can even result in catastrophic failures.

> Reciprocating compressors are positive displacement machines which are unable to handle substantial amounts of liquids. Significant amounts of liquids entering reciprocating compressors are known to cause reliability problems or even catastrophic failures.

The GPSA Data Book provides this summary: "Reciprocating compressors should be supplied with clean gas as they cannot satisfactorily handle liquids and solid particles that may be entrained in the gas. Liquids and solid particles tend to destroy cylinder lubrication and cause excessive wear. Liquids are noncompressible and their presence could rupture the compressor cylinder or cause other major damage."

Heinz Bloch's book on Reciprocating Compressors list four categories for foreign materials that destroy compressors and give clues of what to look for:

1. Liquid carryover (slug flow, carryover from interstage coolers, flow changes)

2. Dirty gas (solid particles act as grinding compounds and interference debris)

3. Carbon formation (high temperatures, oils, and gases make carbonaceous debris)

4. Corrosive elements (corrosion, erosion, and complex failure modes occur)

Additionally, most compressor systems rely on inlet regulation which are not designed to encounter liquids or debris, as well as fuel gas and other control systems that are intolerant of anything other than dry clean gas. Failure of these components (such as an inlet regulator) can result in overpressurization of the compressor and other components normally protected by the regulator and controls.

Prasad, B. G. S. (August 6, 2002). "Effect of Liquid on a Reciprocating Compressor ." ASME. J. Energy Resour. Technol. September 2002; 124(3): 187–190. https://doi.org/10.1115/1.1491981

EFRC Liquid Guidelines How to avoid Liquid Problems in Reciprocating Compressor Systems| 3rd edition 2018 https://www.ogj.com/home/article/17221442/special-report-liquids-entrainment1-changing-operating-conditions lead-to-compressor-damage
https://www.amacs.com/wp-content/uploads/2012/09/Ask-AMACS-Compressor-Suction-Drums1.pdf

In many cases of compressor failure due to liquids injestion, the failure of the compressor results in a release of process gas and liquids. These gas and fluids escaping through unplanned paths pose two additional hazards: First, a fire hazard exists as soon as the gas is released after compressor failure, because that gas may be in close proximity to electronics, engine, or other hot parts. Second, the gas release within non-pressure containing equipment is likely to cause secondary projectiles which may cause additional injuries or property damage.

Preventing Compressor Carryover:

Most compressor stations are so concerned with the possibility of liquids that they employ multiple lines of defense against liquids.

Station Inlet - Slug Catcher - Separator - Suction Filter Separator - Compressor

In addition to the bulk liquids protection a station will employ, the compressor unit itself will commonly have another additional liquid knock-out separator immediately in front of the compressor frames as a last line of defense against liquids.

As discussed in the prior flare design discussion, the compressor facilities that are shown here are permanent facilities with known process conditions. Somewhat paradoxically, in many cross compression applications (during which process conditions are highly unknown), and during which the presence of liquids is nearly guaranteed, we commonly see no protection against liquid carryover at all.

Figure 3: ZEVAC performing liquid butane bullet tank emptying in a port

Figure 4: ZEVAC pumping Y-grade from a filter-separator at a pipeline facility

Figure 5: ZEVAC in use in cold environments where liquid formation is very common

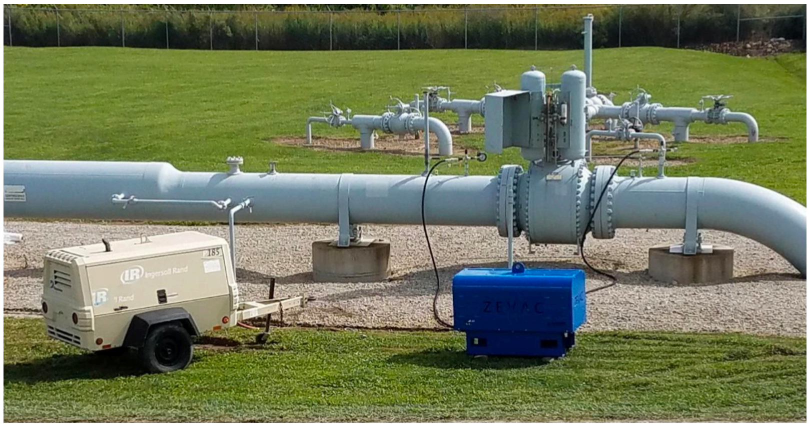


Figure 6: ZEVAC in use at a pigging receiver that is susceptible to receiving high levels of liquid and solid debris.

Figure 7: ZEVAC in use during a pipeline repair involving old pipe that has significant water and oily sludge inside the line.

Conclusion

Unlike traditional compressors, which require very carefully considered protection from liquids to avoid catastrophic failure, ZEVAC is designed to handle up to 100% liquid flow. ZEVAC is routinely used in NGL, condensate, butane, and propane applications in addition to standard natural gas.

Background:

Voluntary venting is estimated to account for nearly 10% of annual methane emissions in the natural gas industry. Blow and purge is a large source of unsteady emissions and accounts for approximately 30 Bscf of methane emissions annually. Blow (or blowdown) gas refers to gas that is vented due to maintenance, routine operations, or emergency conditions. A piece of process equipment or an entire site is isolated from other gas-containing equipment and depressurized to the atmosphere. The gas is discharged to the atmosphere for one of the following reasons: I) Maintenance Blowdown - the gas is vented from equipment to eliminate the flammable material inside the equipment, thus providing a safer working environment for workers that service the equipment or enter the equipment. 2) Emergency Blowdown - the gas is vented from a site to eliminate a potential fuel source. For example, if an equipment fire begins at a compressor station, the station emergency shutdown and emergency blowdown system blocks the station away from the pipelines and discharges the gas inside the station, thus reducing the fuel that could feed the fire.

TABLE 4-2. BLOW AND PURGE EMISSION RESULTS

Industry Segment	Annual Emission Factor	Activity Factor	National Annual Methane Emission Rate, Bscf
Production:			
Gas Wells Unloading	49,570 ± 344% scf/well	114,139 ± 45% wells	5.66 ± 380%
Compressor Blowdowns	3,774 ± 147% scf/comp.	17,112 ± 52% compressors	0.065 ± 173%
Compressor Starts	8,443 ± 157% scf/comp.	17,112 ± 52% compressors	0.144 ± 184%
Pipeline Miles	309 ± 32% scf/mile	340,000 ± 10% miles	0.105 ± 34%
Production Vessels	78 ± 266% scf/vessel	255,996 ± 26% vessels	0.020 ± 276%
Completion Flaring	733 ± 200% scf/completion	844 ± 10% completions	0.0006 ± 201%
Well Workovers	2,454 ± 459% scf/workover	9,329 ± 258% workovers	0.023 ± 1,296%
PRV Releases	34 ± 252% scfy/PRV	529,440 ± 53% PRVs	0.018 ± 289%
ESD Releases	256,888 ± 200% scf/platform	1,115 ± 10% platforms	0.286 ± 201%
Dig-ins	669 ± 1,925% scf/mile	340,000 ± 10% miles	0.23 ± 1,934%
Gas Processing	4,060 ± 322% Mscf/plant	726 ± 2% plants	2.95 ± 262%
Transmission and Storage:			
Stations	4,359 ± 322% Mscf/station	2,175 ± 8% stations	9.48 ± 263%
Pipeline Miles	31.6 ± 343% Mscf/mile	284,500 ± 5% miles	9.00 ± 236%
Distribution:			
PRV Releases	0.050 ± 3,914% Mscf/main mile	836,760 ± 5% miles main	0.04 ± 3,919%
Dig-ins	1.59 ± 1,922% Mscf/mile	1,297,569 ± 5% miles	2.06 ± 1,925%
Blowdowns	0.102 ± 2.521 Mscf/mile	1,297,569 ± 5% miles	0.13 ± 2,524%