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Safety Restraint System for High-Pressure Oilfield Piping

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Abstract

Conveying energized fluid through piping presents a significant hazard with the potential for explosion in the event of a component failure. A method is presented for a simple restraint system that limits the movement of piping to a contained area. Basic practical design equations and considerations useful for piping constraints are presented.

Introduction:

The safe constraint of piping used to convey highly energized fluid is essential for safety, but has proved to be a difficult task to accomplish. This has been especially true for temporary well service applications where piping must be light enough to assemble and remove quickly, and does not usually have the benefit of permanent anchors at the worksite.

Energized fluids, such as pressurized nitrogen or C02, have high explosive potential due to their stored energy. While pressurized liquids present their own kind of danger, a compressed gas has enormous potential for damage if freed rapidly. If a piping assembly fails, the initial forces released are those of the static pressure. Compounding the problem are the acceleration forces created as the stored medium continues to evacuate the piping. Both forces continue as long as any pressurized fluid remains in the system. The acceleration forces are responsible for most of the danger by causing the piping to move violently, placing personnel and equipment at risk.

Testing has shown that constraints with limited elasticity, such as wire rope, perform poorly in high pressure situations. The lack of a constraint's ability to dissipate the discharge energy is a reflection of not only its strength, but also its toughness.

The solution to this problem is a flowline restraint system (FSR), developed by us, that manages to contain the damaged piping within a limited zone of danger.

The FSR system consists of members of tough synthetic loops that are strung the length of the piping and held in place by smaller loops attached at key points along the piping. This assembly is terminated at each end by anchoring to a substantial member such as the wellhead or a pumping truck for land based operations. Suitable structural tie-downs can be substituted for the truck and wellhead in offshore operations. Supplementary restraining loops are normally provided to further minimize flowline movement.

Theory and definitions:

The rapid discharge of energized fluid, such as pressurized nitrogen, will occur if a portion of the conduit piping fails. J.L. Stromberg and J.B. Surjaatmadja[1] found that the forces applied to damaging the piping are proportional to the energy of the discharging fluid. They deduced that the steady state force of ejecting gas supplied by an infinite reservoir can be described by the following equation.

$$F = m_2 \frac{M_2}{g_c} \sqrt{k g_c R T_2} + \left(P_2 - 14.7\right)A$$

Where:

F	=	steady state force value
m_2	=	mass flow rate at exit point of pipe
M_2	=	fluid mach number at exit point of pipe.
g_c	=	gravitational acceleration.
k	=	ratio of specific heats
R	=	gas constant
T_2	=	absolute temperature at exit point of pipe
P_2	=	absolute pressure at exit point of pipe
A	=	cross-sectional flow area of pipe

The first set of terms on the right of the above equation represents the forces generated by the fluid acceleration out of the pipe. The second represents the static pressure force generated over the cross sectional area of the pipe at the exit.

Since the piping will begin to accelerate under this loading, kinetic energy becomes a critical element. Consequently, the reaction forces required to capture and stop the piping can be much higher than the instantaneous force generated by the exiting fluid. We find that the average impact force can be defined by,

$$F_{imp} = \frac{KE}{X} + F$$

Where:

F_{imp} = average impact force
KE = kinetic energy of the system
X = Working distance of the impact
F = instantaneous discharge forces from the exiting fluid.

What becomes quickly evident is that slack in the restraining system will allow kinetic energy to accumulate, creating very high impact loads at the point of constraint. This is especially true if the constraining device is relatively rigid, making the working distance of the impact short. Stromberg and Surjaatmadja found the KE/X value would typically overshadow the instantaneous force value.

Tests to prove the worthiness of the flowline restraint system (FSR) were conducted over a one-year period with somewhat differing systems and various pressures. However, all included the same size (and roughly same length) piping that featured a special separation device. This component could be preset to fail at a specific pressure, closely resembling an actual fracture failure.

During each test, gaseous nitrogen was introduced into the piping until the device failed. At lower pressures, the fluid was supplied by bottles of pressurized nitrogen. As the test pressures increased, nitrogen pumps were used.

After each test, the condition of the restraint system and pipe was documented along with other relevant information.

All of these tests were conducted at full scale and represent a reasonably close facsimile to a real world “well service” operation.

Application of equipment and processes:

The tests were done using 3” nominal piping rated at 15000 psi working pressure. Assembled to the pipe were the FSR “spines”, which ran along the length of the piping, and the FSR “ribs”, which secured the spine to the piping at every union connection. Nitrogen gas was supplied to the piping until the separation device failed.

Fig. 1 illustrates the arrangement for the first test. The system featured a sixty-foot length of piping, and was pressured to 4000 psi before the device failed.

The balance of the tests were conducted at higher pressures and arranged so they more closely resembled an actual well service job. In these cases, a mock pumping truck and wellhead were at opposite ends of the system, along with swivel connections. Knowing in advance that the accumulated kinetic energy would largely determine the behavior of the pipe, a maximum effort was made to assure that all restraints were as tight as practical to eliminate slack. To better resemble an actual job, this was done manually rather than using any special power equipment. Fig. 2 illustrates this arrangement representing tests #2 and #3 with pressures of 7500 psi and 15000 psi, respectively.

Even with higher pressures of Test #3, the piping separation was limited to only a few feet of movement. However, starting with Test #4, a 360’ length of 4” piping was added at the wellhead to create a pressurized gas reservoir that was free to flow back through the failed piping. As a result, there was a dramatic increase in the movement of the failed piping, especially in the direction toward the wellhead. Fig. 3 illustrates the addition of the reservoir piping and Fig. 5 shows the two “anchor” lines which were eventually added to reduce movement of the pipe toward the well.

Characteristics of each test were documented and the actual events were captured on videotape. A walk-through, using video tape and still photos, was conducted at the conclusion of each test. A summary of the six (6) tests can be found in Table 1.

Data and results:

TEST #1:
Test #1 was performed at a failure pressure of 4000 psi and resulted in a small movement of 3 feet between the two sections of pipe. The spine used for this test was rated between 75000 lb and 100000 lb breaking strength.

TEST #2:
Tests #2 was run at 7500 psi with the same restraints as in Test #1, but included a longer pipe (80 ft) with swivels at each end. The released energy from these was greater than the first test, but showed little evidence of taxing the strength of the restraint. The resulting pipe movement was approximately six feet separation and six feet out of alignment.

TEST #3:
Test #3 was run at 15000 psi using heavier spines and ribs rated at between 100000 lb and 150000 lb breaking strength. The movement from test #3 was eight feet separation and six feet out of alignment. One of the ribs located at a swivel was found to have suffered damage.

TEST #4:
Test #4 was reduced to 7000 psi, but featured the addition of 360 feet of 4” piping to act as a flow-back reservoir (see Fig. 3). For this test, we returned to the restraints rating of Test #1.

The ribs, rated at 50% of the spine, were double-wrapped to produce the same capacity.

It was at this test that the full violence of a failure from the piping with a reservoir of compressed gas became evident. The cover of one of the ribs was damaged, but not its load-bearing fibers. The cover is intended to separate at approximately 60% of the breaking strength of the loop; that would have represented a tensile force of 51000 lb.

Because there were swivels at each end of the piping that made several turns, the entire piping shifted approximately 12 feet toward the well. This was true even though the spine and ribs remained attached to the piping. A 30 foot length of the 3” piping on the well side suffered a bend of approximately 30°. It was also during this test that a video camera that had been set up 150 feet away, but in-line with the piping, was destroyed by the dirt debris created by the failure explosion.

TEST #5:
Test #5 was setup identical to Test #4, but with the failure pressure at 12000 psi. While the final location of the piping indicated a 6’ separation and a general shifting toward the wellhead, the video of the event was dramatic, reflecting substantial movement.

With this test, the piping shifted sufficiently towards the well to pull one of the mock pumps from the truck. And once again, the piping toward the well side was bent at about a 30° angle.

Another indication of high loads was that the spine loops at both the pump truck and at the wellhead swivels had separated. A close-coupled restraint that had been attached between the two flanges to negate their separation, also failed.

TEST #6:
Test #6 was done at 15000 psi. As with the previous tests, it included the supplemental 360 feet of 4” piping to act as a reservoir. The spine and rib ratings were increased to the rating of Test #3. Additionally, anchor lines were attached to the crossover anchors at the wellhead swivel and terminated at a trailer hitch (See Fig. 5). Their purpose was to minimize shifting of the piping that occurred in the previous tests. While quite violent, the test results showed all restraint components remained intact and axial shifting and lateral shifting were kept under control. This was true even though there was a secondary unplanned failure and the piping restrained by the anchor lines had again become bent.

Conclusions:
A test by Dowell Schlumberger[2] several years ago clearly illustrated the extent of damage possible in an unconstrained failure when pumping energized fluid. A failure in the line at 6000 to 8000 psi caused large sections of the treating iron to break and fly several hundred feet. Anecdotal information from other sources describe similar experiences with this type of failure.

Messers Stromberg and Surjaatmadja predicted that fluid escaping at 15000 psi in piping similar to ours would generate forces in the range of 56000 lb. And, upon initial review, one could argue that even higher forces caused the damage to the ribs and spines in Tests #3 and #5 (15000 psi and 12000 psi respectively).

However, we believe these forces were the result of the mechanical lever effect in the vicinity of the swivels. As the piping separated and shifted (see Fig. 4) the spine had to stretch to accommodate this displacement. A zone of high load then developed in the spine where it turned a corner. These highly loaded zones resulted in forces much greater than the dynamic forces of the fluid.

By adding the anchor lines illustrated in Figure 5, the reaction to the exhaust forces (always in the direction of the well/reservoir) was dealt with directly. No mechanical advantage came into effect. While the movement was violent, the piping stayed in the confined area, and there was little damage to the restraint system.

The bending of the piping mentioned in Tests #4, 5 and 6 represents a classical case of column failure. With those tests not featuring the anchor lines (Tests #4 & #5), the piping system shifted towards the well until all piping and restraint slack was gone. With a likely abrupt stop, the 30 feet of piping (still ejecting the fluid) had no lateral support and began to fail in column, resulting in an approximate 30° bend. Test #6 used the anchor lines which reduced the shifting problem. But, the loading on the piping ejecting fluid was still the same and the exposed piping suffered the same results.

While damage to the piping was not desired, it likely provided some benefit by absorbing a portion of the energy expended.

The ribs, spine, and anchor lines worked to contain the entire system even though sections of pipe had broken and bent. These pieces of piping were not free to escape, therefore the dynamic forces of the gas had to apply to the mass of entire system rather than separate portions.

With all piping effectively tethered together, there was also some energy dissipated by the piping working against the ground. This is evidenced by the amount of dirt that was disturbed during these higher-pressure tests.

There is no practical way to keep piping completely fixed during a failure. Rigid connections or wire rope restraints would likely be too heavy and expensive to apply. If too light in construction, they would fail catastrophically and add to the material being ejected.

The flexible constraints used in the tests did not keep the piping restrained in one spot. However, they did remain attached to the piping as it thrashed about while spending the energy of the gas. There was a violence zone around the piping that was deadly and must be avoided. However, the danger zone associated with the safety restraint system was generally cylindrical and ran the length of the flow line. While extremely dangerous, the potential danger zone surrounding an FSR-restrained flow line was drastically reduced over an unrestrained flow line.

We believe this process has genuine utility in producing a safer environment around energized fluids.

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Nomenclature:

Anchor: Any practical method of securing the restraint line including earth anchors, large trailer hitches, wellhead, etc.
Anchor Line: Supplement member (same size as the spine) used to keep the system from shifting or wracking.
Crossover Anchor: A short pipe featuring wings to which constraints can be attached. These components are placed at strategic locations in the piping.
Energized Fluid: Any gas (typically nitrogen, or C02) that is pressurized.
FSR: Flowline safety restraint.
Rib: Transverse member attaching the spine to the pipe at key locations.
Spine: Main restraint member running the length of the pipe.

References:

1. J.L. Stromberg and J.B. Surjaajmadja – Halliburton Services"Restraining System To Help Contain Well Flowlines and Equipment During Rupture for Increased Safety", SPE 24619, 67th Annual Technical Conferences & Exhibition of the Society of Petroleum Engineers Washington, DC October, 1992 , Page 779.

2. Dowell Schlumberger documentary film. "There Are No Clowns" Creative Communications, Inc., October, 1979

TEST NO.	PRESS (psi)	PIPE SIZE (in)	PIPE LNGTH (ft)	SWVLS	ANCHOR CRSSOVRS	ANCHOR LINES	4" RES. PIPING	COMMENTS
1	4000	3	60	NO	NO	NO	NO	Approx. 3' separation at failure point. **75000 lb to 100000 lb** spine and ribs used.
2	7500	"	80	YES	"	"	"	Approx. 6' separation at failure point. Same spine and ribs used as Test #1.
3	15000	"	"	"	"	"	"	Approx. 8' separation at failure point. **100000 lb to 150000 lb** spine and ribs used. Sizable depression created in ground. One white rib located at swivel damaged.
4	7000	"	"	"	YES	"	YES	Approx. 4' separation. Same spine and ribs used as in Test #1. Videos showed this to be a violent event. 3" piping towards dummy well bent at 30 degree angle. Substantial amount of debris thrown up from the ground. One video camera in-line with piping destroyed.
5	12000	"	"	"	"	"	"	Approx. 6' separation. Same spine and ribs used as in Test #1. Videos showed this to be a violent event. One blue spine at each end of piping in vicinity of swivels failed. 3" piping towards dummy well bent at 30 degree angle. Substantial amount of debris thrown up from the ground. Substantial shift of entire piping assembly away from truck and towards well -- pulled one pump from truck. Separate closed coupled restraint at failure flange separated.
6	15000	"	"	"	"	YES	"	Approx. 10-12' separation. Same spine and ribs used as in Test #3. Videos showed this to be a violent event. While piping separated more, shifting of piping was minimized. Piping bent at 30 degree, and secondary failure. Restraints held up well.

Table 1. Test Synopsis -- Defining Pressure, Arrangement, and Results.

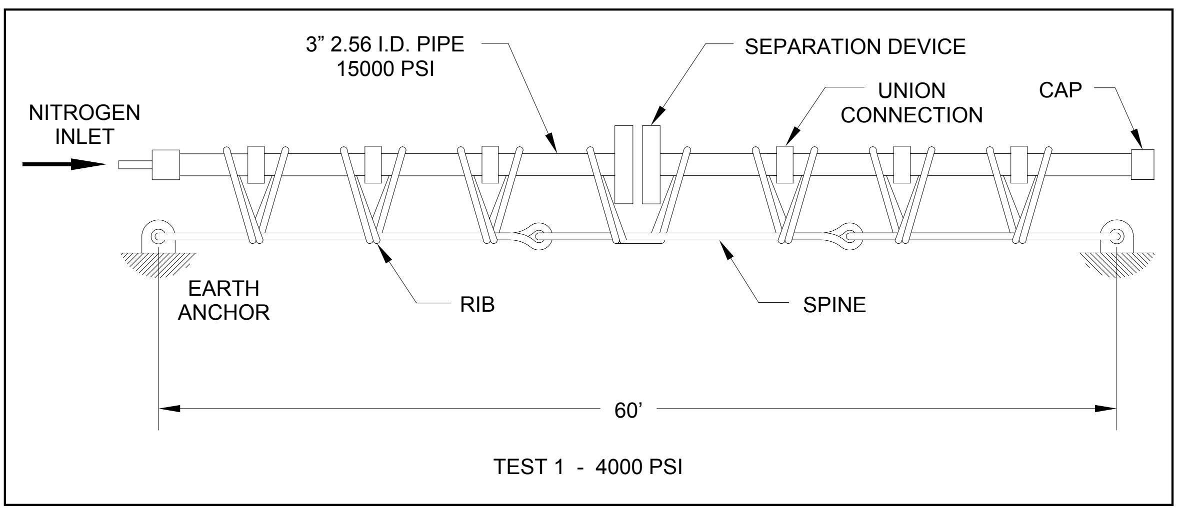

Figure 1. Test #1, Featuring Piping and Constraint Arrangement.

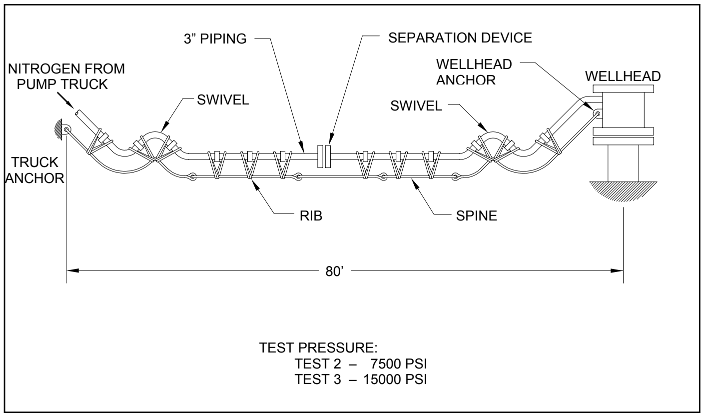

Figure 2. Tests #2 & #3, Featuring Swivels, Well Head and Pump Truck.

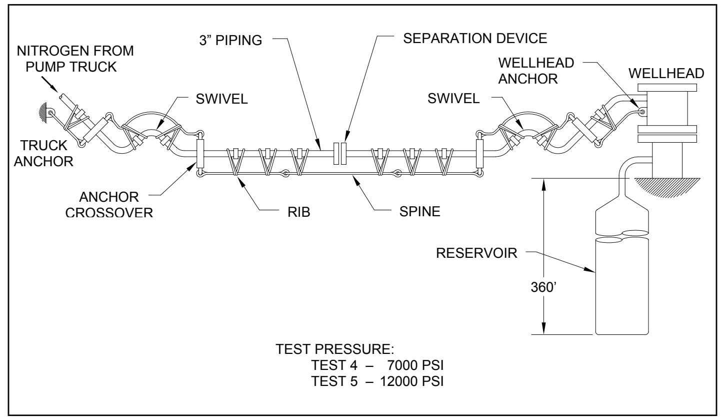

Figure 3. Tests #4 & #5, Featuring Additional Fluid Reservoir.

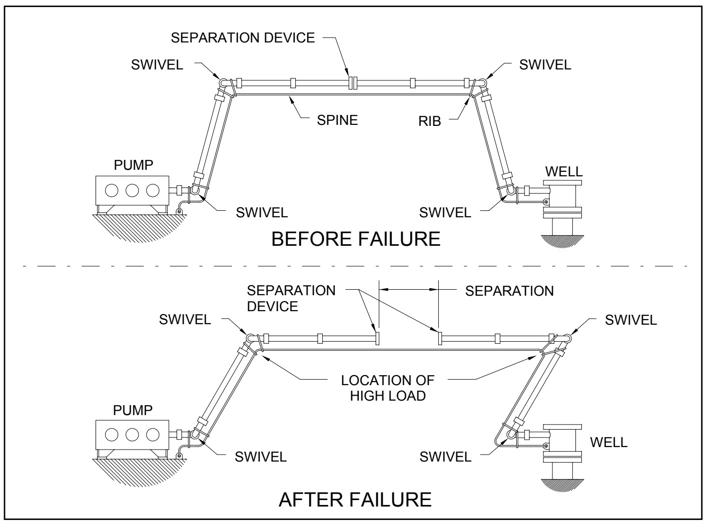

Figure 4. Piping Movement and Location of High Load Points.

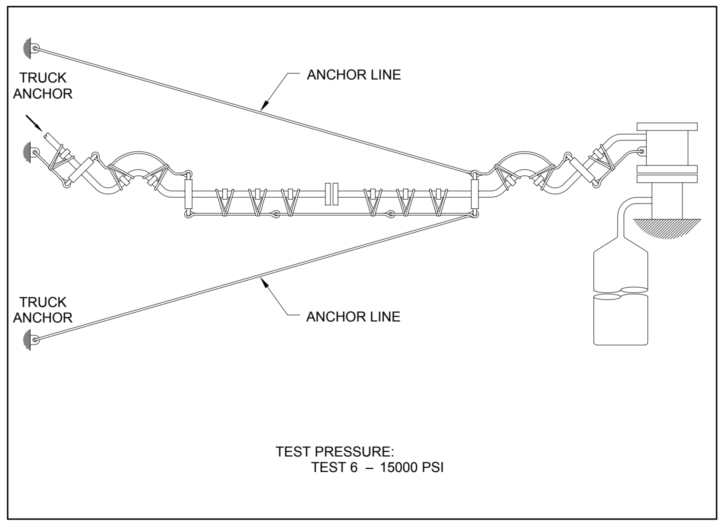

Figure 5. Test #6, Featuring Anchor Line Constraints.