Drilling Rig Catastrophic Hydraulic Component Failure Analysis
For
Shell UK Ltd.

Problem Statement:

What is the velocity of fragments from a catastrophic hydraulic component failure in a system that is at 15000 psi and contains 84 Gallons of fluid? The fragments are from weights of ½ pound up to 5 pounds. Once the velocities of these different size fragments are known; how many layers of Xtegra will be require to safely contain the fragments and fluids ejected in the hydraulic failure? A separate analysis will be conducted for Sea Water, Crude Oil, and Drilling Mud.

Problem Basics:

Hydraulic component failures are different as compared to pneumatic system failures. In Hydraulic system failures, even high pressure systems, the major areas of concern are in high velocity fluid jets, fitting failures, and brittle system failures. Unlike pneumatics systems, hydraulic systems do not have pressure shock wave hazards. The main reason for this difference is that most fluids are not very compressible. Water at 15000 psi is only compressed about 5%, while air would be compressed approximately 100000%. This means that the total expansion for a fluid is very small in a hydraulic system and, thus, does not create the explosive pressure wave of a pneumatic system. It also means that the distance on which a fragment is influenced by the expanding fluid is relatively short. This is the reasoning behind hydraulic testing gas pipe lines and very high pressure gas tanks. A tank or pipeline hydraulic failure might throw some fragments, but the same failure using pneumatics is equivalent a large bomb going off.

Small area failures in hydraulic systems do create the new hazard of high velocity jets of fluid. This jet of fluid can be strong enough to inject fluids deep into human tissue or even lacerate flesh and bone. Under the right conditions, fluid type and particulate matter in the fluid, these jets can even cut through steel.

Important Note:
The above is only true for fluids that are unsaturated. Unsaturated means that no gases are in saturation in the fluid. If a fluid has gas saturation, when the fluid rapidly expands due to system failure, the gas comes out of saturation and also expands. We then have a mixed hydraulic and pneumatic system. Although, not as bad as a pneumatic system, this mixed system still release thousands times more energy than the straight hydraulic system. For this analysis it has been assumed that all the fluids used are unsaturated.

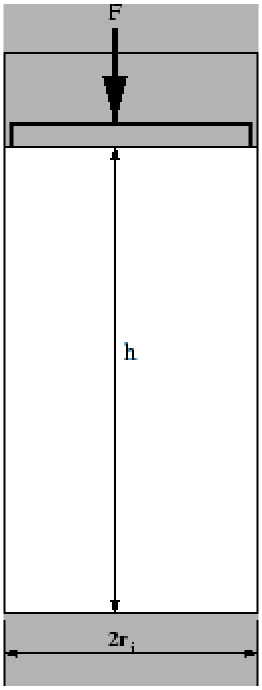
Problem Analysis:

The first step in the analysis of this problem is to determine the amount of energy stored in the system. To do this we can assume that the system is a cylinder that is capped at one end and filled with 84 gallons of the fluid under analysis. On the non-capped end of the cylinder we place a piston. A force is applied to the piston until the working pressure of 15000psi is reached. If we integrate the applied force over the distance the piston moves, we obtain the work done in compressing the water.

$$E = A\int_{h_o}^{h(p)} p\ dh$$

Where;

E is Energy
A is the cross sectional area of the cylinder
h(p) location of the piston at the working pressure
h0 location of the piston at ambient pressure
p is pressure



Because the mass of the fluid is fixed, we can determine the relationship between pressure and piston position.

$$\rho(p)V(p) = \rho_o V_o$$

Thus, we can relate the density of the fluid to pressure.

$$\rho(p) = \rho_o(1 + \gamma p)$$

Where **γ** is the compressibility of the fluid and ***ρ0*** is density of the fluid at ambient pressure and ***ρ(p)*** is the density of the fluid at the operating pressure ***p***.

This leads to two very helpful relationships,

$$p = \gamma^{-1}\left(\frac{h_o}{h} - 1\right)$$

First, where pressure is directly related to the change in piston position and

$$h = \frac{h_o}{1 + \gamma p}$$

Second, where piston position is related to ambient piston position and the working pressure. This then allows us to find, with the help of the Taylor series, a direct relationship between potential energy in the fluid system, the working pressure and ambient volume.

$$E(p) = \frac{\gamma}{2} V_o p^2 \ .$$

The next step is to determine how this stored potential energy is released when the hydraulic system fails.

Failure Modes

There are four failure modes that must be examined;

1. Brittle failure where the object is completely fragmented
    a. Through experimental testing it has been determined that all fragment obtain nearly the same velocity
    b. Fragments will cover a large range of sizes.
    c. Upper bound of fragment velocity can be found by allowing the total stored energy to become Kinetic energy. This Kinetic energy affects all the fragments resulting in all fragments having the same initial speed.
    d. We know this is a conservative upper bounds as some of the fluid will flow out between particles.
    e. The distance over which the fluid expands is small. Water is only compressed 5% at the test pressures of 15000 psi.

Note: Pressure vessels are generally not constructed of brittle materials. But this type of failure can occur if a material is used at an operating temperature that is to low or causes embrittlement of the base metal. Work hardening in some metals can lead to a more brittle material.

2. Ductile failure either complete object failure of major section failure
   a. Complete object ductile failure will lead to a small number of large fragments.
   b. Partial ductile failure will also be a small number of fragments but of smaller sizes than the complete ductile failure.
   c. Ductile failure in a liquid filled system leads to rapid pressure decay, because this type of failure opens large areas around the fragments.
   d. The amount of stored energy that can be turned into kinetic energy is related to the fragment size verses the total failure opening size.

3. End cap, Fitting or plug failure
   a. In this case there is generally a single fragment that is the end cap, fitting or plug.
   b. All the stored energy is turned into kinetic energy through the opening caused by the failed end cap, fitting or plug.
   c. This type failure resembles a rocket or gun barrel projectile.
   d. The fluid jet created by this opening continues to try to accelerate the fragment until the internal pressure is at ambient.
   e. The fluid jet dynamics as it moves from the opening is complex but generally decays rapidly with distance.
   f. This case is most likely to produce the highest velocity fragments

4. Water jet failure mode.
   a. This mode of failure can occur in all of the above modes, but can occur with out any fragmentation when a small hole is formed in the system.
   b. Initial jet velocities can be found using the Bernoulli’s equation.
   c. Fluid jets have complex dynamics and loose kinetic energy as they move from the opening.
   d. The jet speed leaving the opening will decrease as the internal pressure drops, but will continue to be a danger until the internal pressure reaches near ambient.

Analysis Implementation:

Brittle Failure

Glass Light Bulb - Example of Brittle Failure

In the case of brittle failure a sphere holding the 84 gallons of fluid is the smallest surface area and thus the smallest mass of all the possible containers. The smallest mass will give us the highest fragment velocity. In this analysis each fluid will be used to calculate the potential energy stored using the above analysis. This potential energy will then be converted completely to kinetic energy and the velocity of the fragment found by solving the kinetic energy equation.

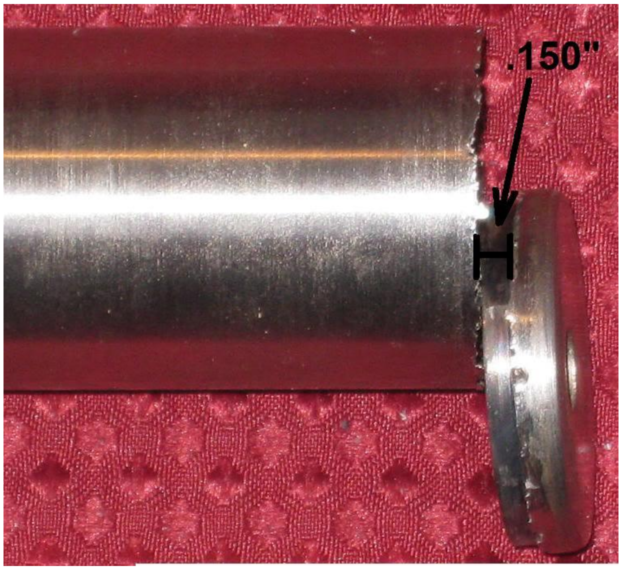
$$E = ½*m*V^2$$

Where:

E is the Kinetic Energy
m is the mass of the container
V is the velocity of the fragments

This will be a conservative solution, because the fluid that expands between fragments is ignored and the smallest mass holding vessel was chosen. For this analysis it is assumed that the vessel is made of 0.5 inch thick steel at 20.42 lb/ ft^2. A sphere that can hold 84 Gallons has a radius of 1.389 feet and thus has a surface area of 24.25 ft^2. This results in a mass of 495.2 lbs or 15.38 slugs. From these numbers the fragment velocities can be calculated for each fluid.

End cap, Fitting or plug failure



Example of an End Cap Failure

The end cap, fitting failure, or plug failure is where an end cap, fitting or, plug mechanically fails and is ejected from the system. In this case the piston model from above potential energy model is reversed. The piston is replaced with the fragment and allowed to decompress. In this case, we can assume that the area of the cylinder is now the area of the fitting or fragment. We then can look at the working pressure forcing the fragment up the cylinder causing acceleration. This acceleration can be integrated to determine velocity and position. The position of the fragment can then be used to determine the when the fluid has fully expanded. Once the fluid has fully expanded the final velocity of the fragment can be determined. This is the Gun Barrel or rocket analysis approach, because we allow the water to push on the object until there is no more pressure and the fluid has fully expanded.

In this analysis method we must also account for the large amount of fluid that must be accelerated up the gun barrel or tube. The acceleration of the fluid uses a lot of the stored energy and thus reduces the amount of stored energy that can become kinetic energy of the fragment.

Further, in this analysis approach the fragment is not really held in a tube or gun barrel. It is really in free space with a water jet pushing it away from the main container. If we look at this water jet, we can see a very complex fluids problem. The effects of not being contained in a tube of barrel cause this water jet to loose its force the further it gets from the original container. Experimental results have shown that this complex fluids problem results in a linear reduction in jet pressure in relation to distance from the jet origin divided by the jets original diameter. This works well in our gun barrel model as we know both the distance from the jet and the diameter of the jet opening as it is the diameter of the fragment. Applying this we get a pressure that is reduced by:

$$P_{jet} = P_{tank} * (-0.0127*jet/D+1)$$

Where;

P_{jet} is the pressure at the current fragment location

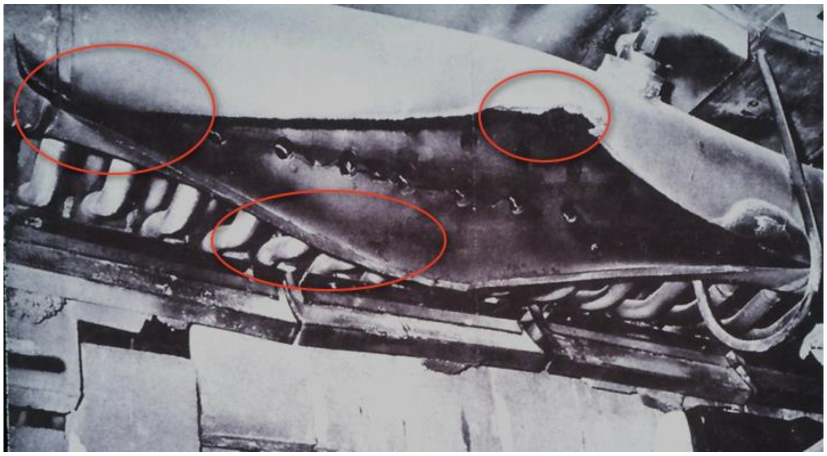
P_{tank} is the pressure in the tank that the fragment was ejected from

Jet is the distance the fragment has traveled

D is the equivalent diameter of the fragment and thus the jet diameter a the tank

With this pressure loss function applied, this analysis approach now accounts for most of the effect that influence the fragment velocity. It is still a very conservative approach thus it is expected that the velocities predicted are higher than will be seen in actual tests. It is expected that this failure mode will produce the highest velocity fragment both in this analysis as well as in the real world.

Ductile Failure



Example of a Ductile Failure with Fragments

Looking at the fragmentation process in hydraulic failures where a ductile failure occurs we generally get a large area where the fluid expands quickly with a small number of very large fragments in a complete system failure or a small number of fragments of smaller size in a partial failure. In both cases a large majority of the fluid expansion is into free space between fragments. Because of this the amount of force applied to the fragments is significantly reduced. For this case, the gun barrel or rocket model from above can be modified to account for the extra water expansion. To adapt the gun barrel approach to this, we allow the total energy of the system to be drained through the expansion of water over the full area of the rupture including the area of the fragment. For this analysis we decided to take a rupture that was 10 times the area of the projectile. This means that the pressure in the tank reduces 10 times faster than in the end cap, fitting or plug failure mode and thus causes large reductions in fragment velocities.

Fluid Jet Failure

Example of a Fluid Jet Failure

Fluid jets appear in many of the hydraulic failure modes. For this analysis we will look at the fluid jet failure as just a Fluid jet caused by a small hole in the system. The velocity of the jet can be determined using Bernoulli equation which in this case reduces to:

$$v = \sqrt{\frac{2p}{\rho}}$$

Where:
v is velocity of the jet at the opening
p is the pressure of the fluid in the system
ρ is the density of the fluid in the system

The size if the jet opening effects only the time the jet will be present as it controls the volume of fluid and thus the expansion of the fluid in the system. For this analysis a velocity will be determined for each fluid type.

Initial Conditions:

Fluid volume of 84 gallons
Operating pressure of 15000 1/psi.
Seawater compressibility 3.39x10-6 1/psi.
Crude Oil compressibility 5.0x10-6 to 8.0x10-6 1/psi
(8.0x10-6 chosen as worst case)
Drilling Mud compressibility 4.16x10-6 1/psi
The 5 lb Fragment or fitting is assumed to have an area of 0.25 sq ft
The 0.5 lb fragment or fitting is assumed to have an area of 0.025 sq ft
All storage vessel configurations are assumed to be made of ½ inch steal plate

Analysis Results:

Brittle Failure Analysis with Sea Water

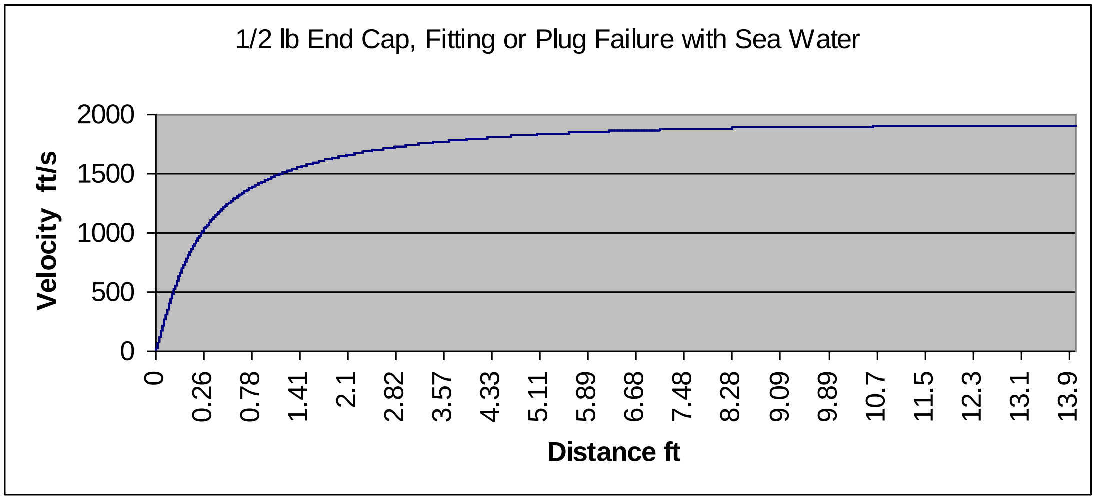
In this analysis all the fragment will have an initial velocity after the brittle failure of

$$V = (E*2/m)^{1/2}$$

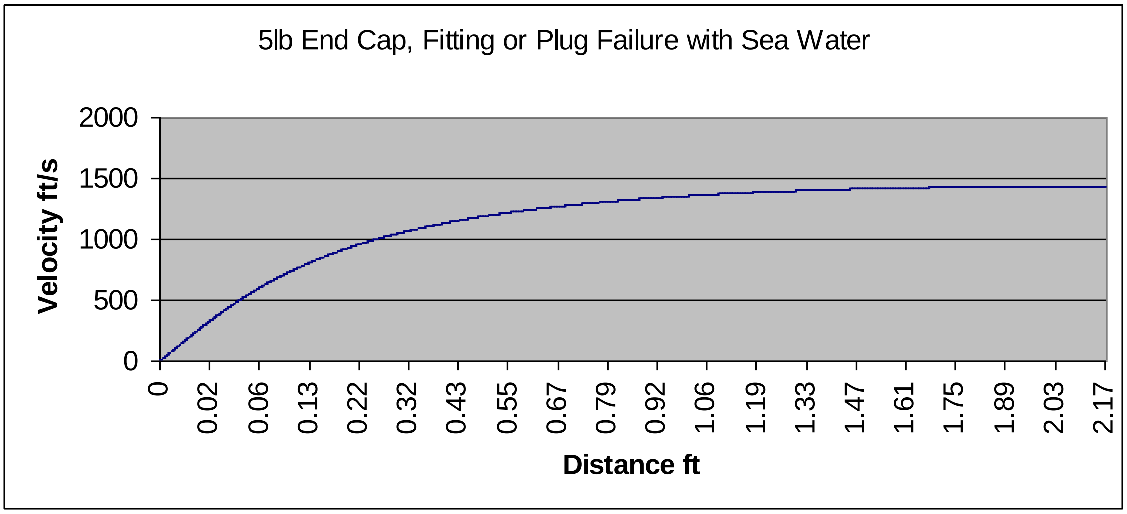
Given the constraints from the above of a spherical container with a mass of 15.38 slugs and the available potential energy of 616674 ft-lb from water being compressed to 15000 psi. The initial velocity of all the fragments is 283.2 ft/s

End cap, Fitting or plug failure with Sea Water

In this analysis the ½ lb and 5 lb fragment are simulated using the gun barrel method as presented above. The simulation was stopped when the internal pressure reached zero or when the effective jet pressure reached zero.



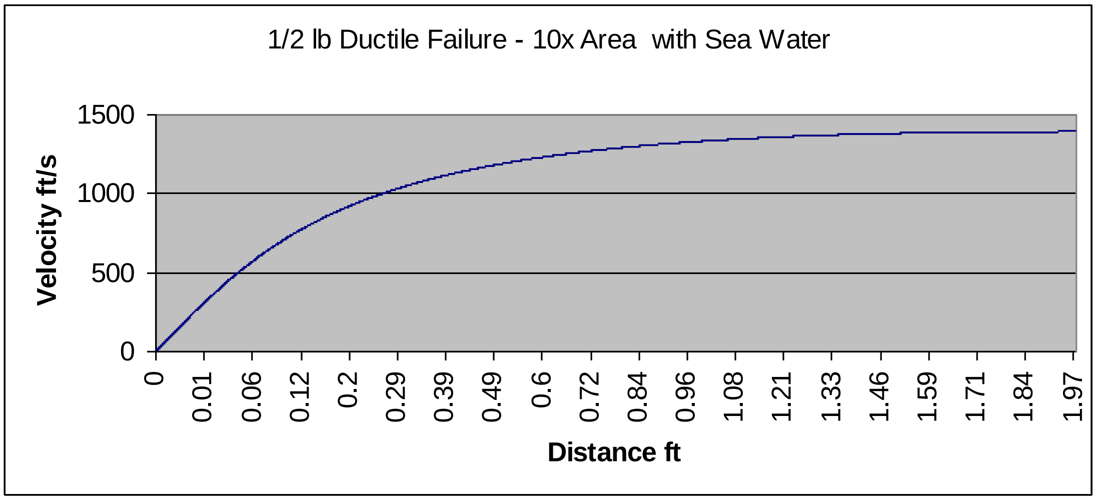
For the 1/2 lbs object the maximum velocity is 1903.3 ft/s at 14.1 ft.



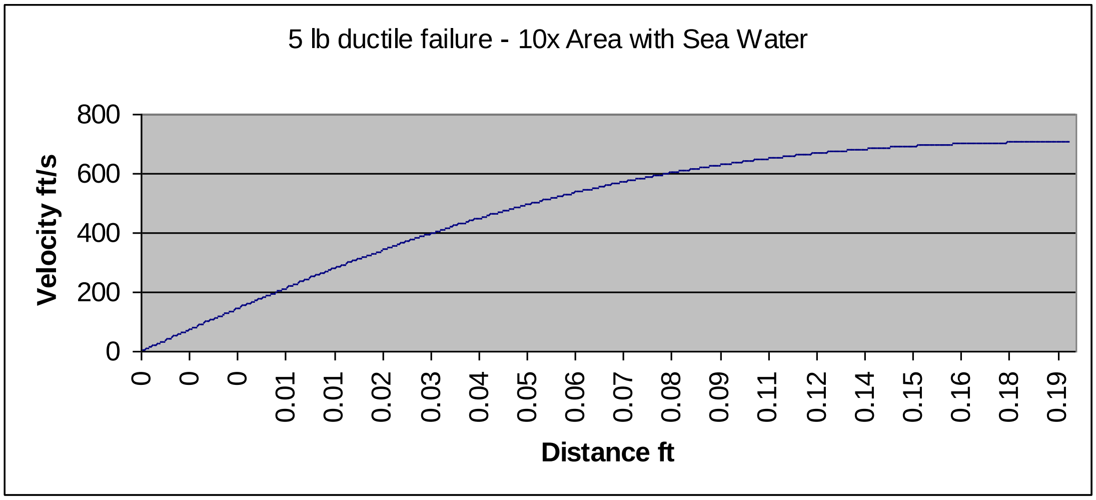
For the 5 lbs object the maximum velocity is 1436.3 ft/s at 2.1 ft.

Ductile Failure with Sea Water

In this Sea Water case, the Gun Barrel analysis now has a ductile rupture that is 10 times the area of the fragment. This allows water to expand over the entire rupture area and reduces the amount of force applied to the fragment. We can see both a reduction in velocity, but also a large reduction in the distance that the force acts over. Velocities present in this analysis are closer to fragment failure where the pressure vessel ruptures and fragments are thrown. Many ruptures have no fragments thrown during the failure event.



For the 1/2 lbs object the maximum velocity is 1393 ft/s at 1.9 ft.



For the 5 lbs object the maximum velocity is 707.6 ft/s at 0.2 ft.

Fluid Jet Failure with Sea Water

Using the Bernoulli equation with 15000psi pressure and a sea water density of 1.936 slugs/ft^3 at 15000psi, the maximum jet velocity 1493.8 ft/s

Brittle Failure Analysis with Crude Oil

For the crude oil analysis the crude with the largest compressibility was used. This means that it is the lightest crude oil and was selected because it presents the worst case. Most oil has less compressibility and might be as low as 5.0e-6 1/psi. Those heavier crude oils would present lower velocities.

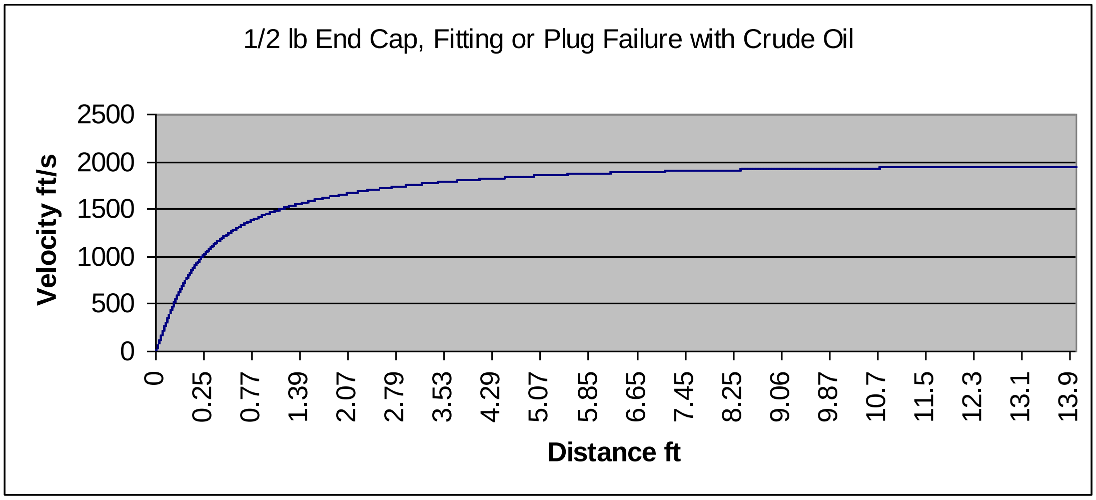
In this analysis all the fragment will have an initial velocity after the brittle failure of

$$V = (E*2/m)^{1/2}$$

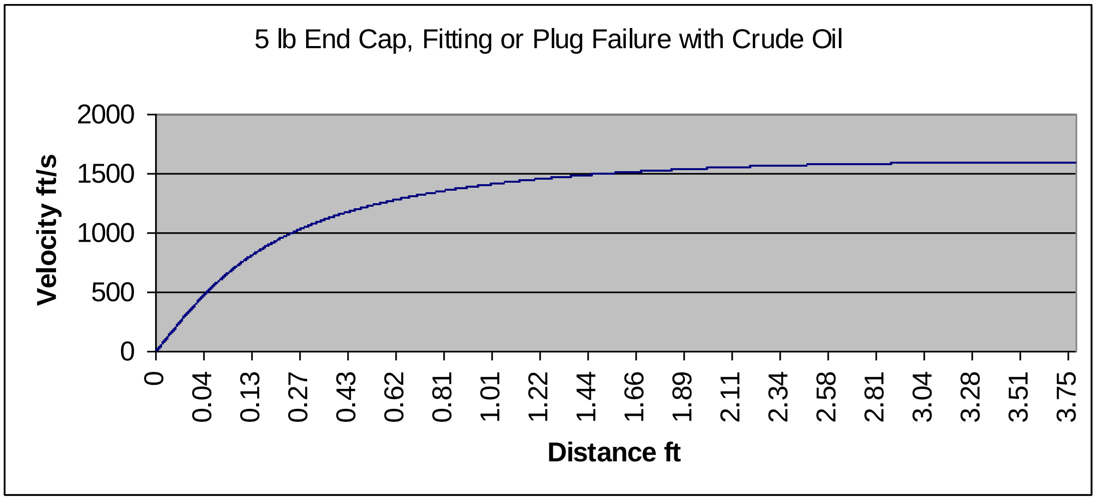
Given the constraints from the above of a spherical container with a mass of 15.38 slugs and the available potential energy of 909549 ft-lb from Crude Oil being compressed to 15000 psi. The initial velocity of all the fragments is 343.9 ft/s

End cap, Fitting or plug failure with Crude Oil

In this analysis the ½ lb and 5 lb fragment are simulated using the gun barrel method as presented above. The simulation was stopped when the internal pressure reached zero or when the effective jet pressure reached zero.



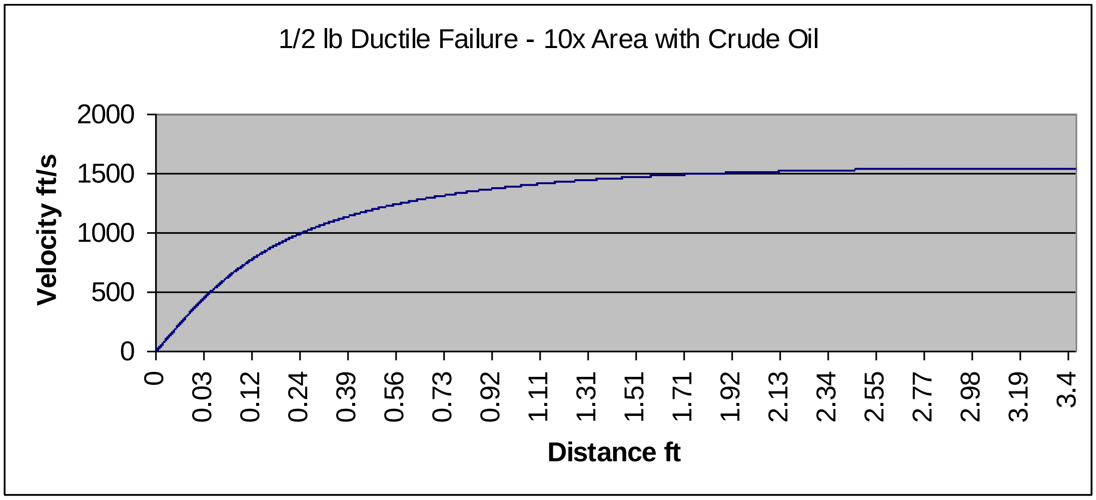
For the 1/2 lbs object the maximum velocity is 1940 ft/s at 14.0 ft.



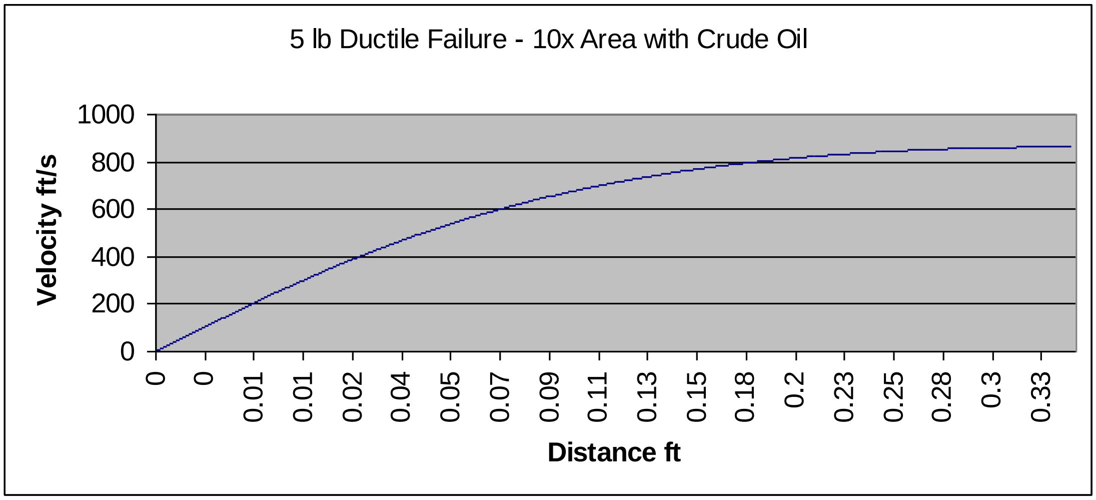
For the 5 lbs object the maximum velocity is 1597.8 ft/s at 3.8 ft.

Ductile Failure with Crude Oil

In this Crude Oil case, the Gun Barrel analysis now has a ductile rupture that is 10 times the area of the fragment. This allows fluid to expand over the entire rupture area and reduces the amount of force applied to the fragment. We can see both a reduction in velocity, but also a large reduction in the distance that the force acts over. Velocities present in this analysis are closer to fragment failure where the pressure vessel ruptures and fragments are thrown. Many ruptures have no fragments thrown during the failure event.



For the 1/2 lbs object the maximum velocity is 1546.9 ft/s at 3.4 ft.



For the 5 lbs object the maximum velocity is 863.1 ft/s at 0.34 ft.

Fluid Jet Failure with Crude Oil

Using the Bernoulli equation with 15000psi pressure and a crude oil density of 1.605 slugs/ft^3 at 15000psi, the maximum jet velocity 1640.7ft/s

Brittle Failure Analysis with Drilling Mud

In the Drilling Mud analysis, the mud chosen was a simple 80% oil, 20% water mixture, with 10% volume fraction of solids. Increasing the oil percentage would increase the velocities. Increasing the water percentage would decrease the velocities.

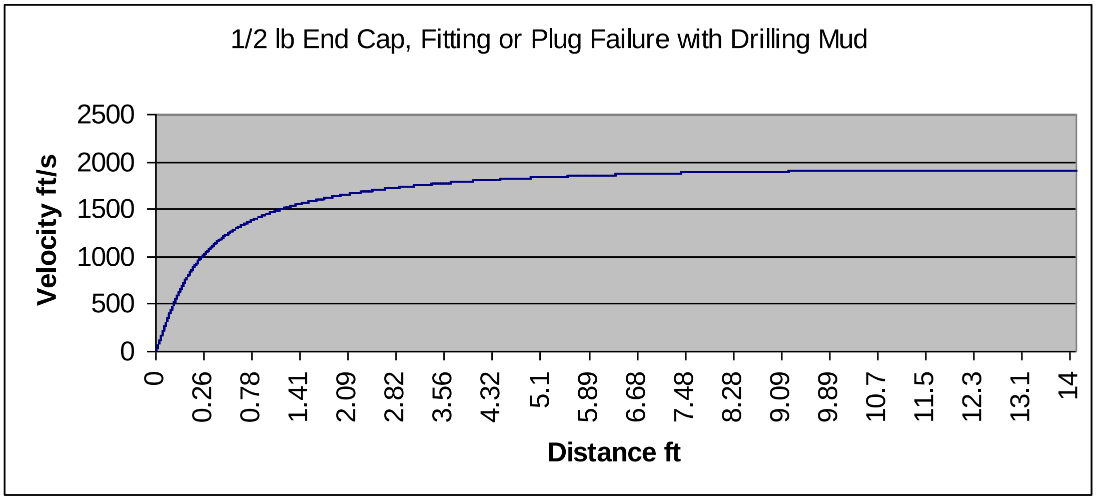
In this analysis all the fragment will have an initial velocity after the brittle failure of

$$V = (E*2/m)^{1/2}$$

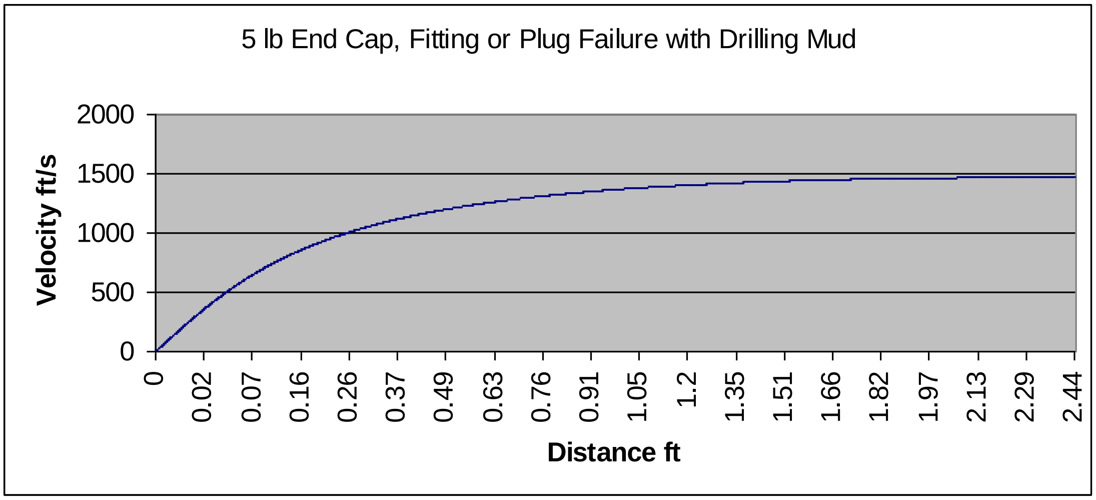
Given the constraints from the above of a spherical container with a mass of 15.38 slugs and the available potential energy of 754830 ft-lb from Crude Oil being compressed to 15000 psi. The initial velocity of all the fragments is 311.4 ft/s

End cap, Fitting or plug failure with Drilling Mud

In this analysis the ½ lb and 5 lb fragment are simulated using the gun barrel method as presented above. The simulation was stopped when the internal pressure reached zero or when the effective jet pressure reached zero.



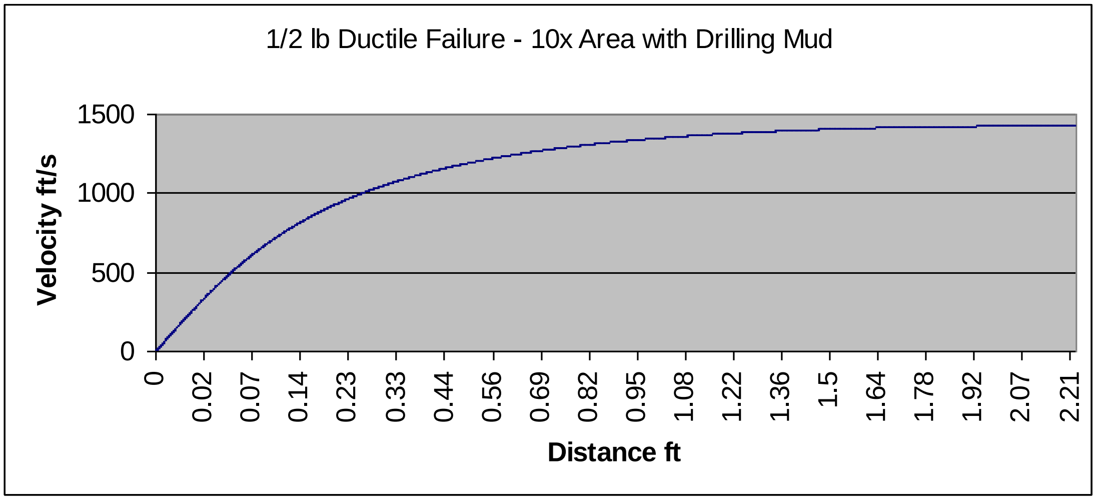
For the 1/2 lbs object the maximum velocity is 1912.1 ft/s at 14.1 ft.



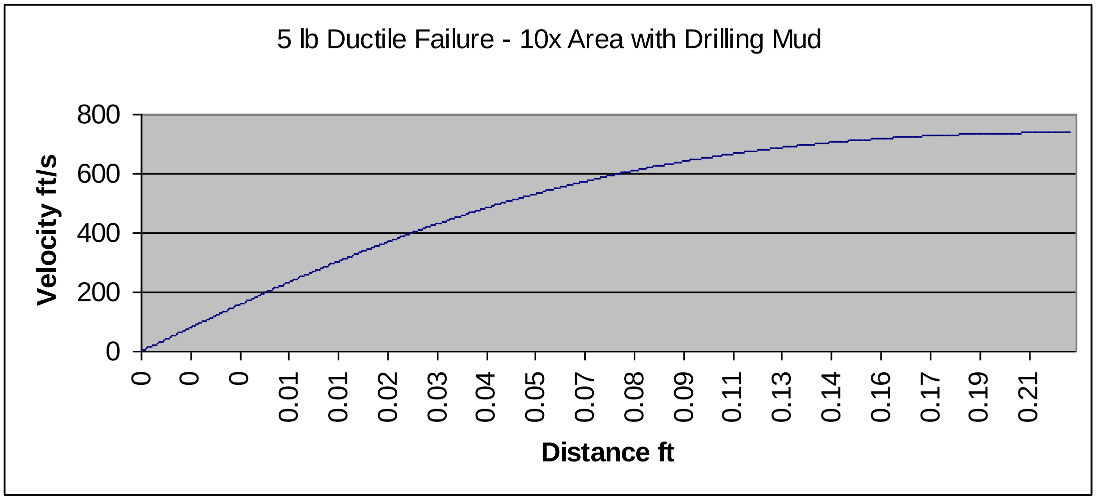
For the 5 lbs object the maximum velocity is 1470.6 ft/s at 2.4 ft.

Ductile Failure with Drilling Mud

In this Crude Oil case, the Gun Barrel analysis now has a ductile rupture that is 10 times the area of the fragment. This allows fluid to expand over the entire rupture area and reduces the amount of force applied to the fragment. We can see both a reduction in velocity, but also a large reduction in the distance that the force acts over. Velocities present in this analysis are closer to fragment failure where the pressure vessel ruptures and fragments are thrown. Many ruptures have no fragments thrown during the failure event.



For the 5 lbs object the maximum velocity is 1426.8 ft/s at 2.2 ft.



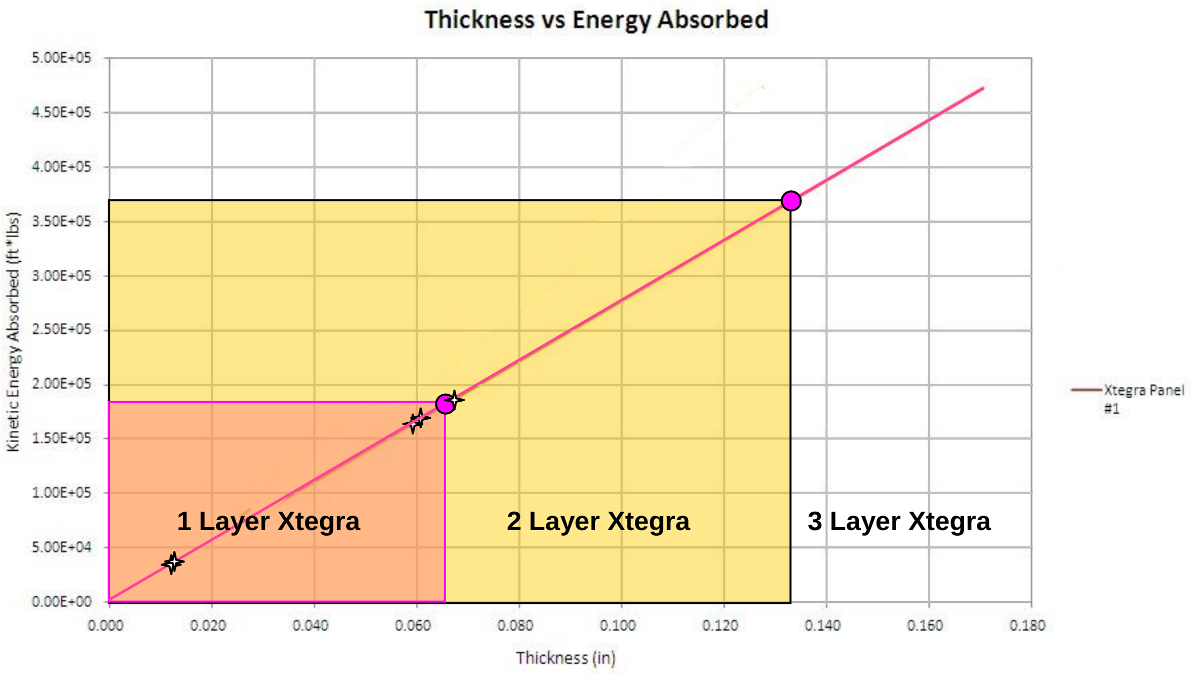
For the 5 lbs object the maximum velocity is 739.2 ft/s at 0.22 ft.

Fluid Jet Failure with Drilling Mud

Using the Bernoulli equation with 15000psi pressure and a crude oil density of 2.09 slugs/ft^3 at 15000psi, the maximum jet velocity 1437.7 ft/s

Xtegra material thickness Selection:

With the above analysis we now have velocities and masses for all the objects under each fluid condition. That data can be used to calculate the total Kinetic Energy for each size projectile. To size the Xtegra thickness, the chart below can be use that give thickness as a function of kinetic energy.



For sea water, the maximum velocity of the ½ lb object was found to be 1903.3 ft/s, resulting in a kinetic energy of 28125 ft*lbs. From the chart above, that could be stopped by a single layer of Xtegra 0.01537 inches thick.

Again, looking at the sea water results for the 5 lb object, we see a maximum velocity of 1436.3 ft/s, resulting in a kinetic energy of 160167.5 ft*lbs. From the same chart, this requires Xtegra thickness of 0.060 inches or 2 layers of fabric. We use two layers of fabric here because we are right at the failure point for one layer of fabric.

The worst case velocities occurred with the Crude Oil analysis. Very light crude was selected because it had the largest compressibility factor. This was chosen to make sure this analysis is conservative, but caution should be used as this appears to be lighter than the average oil. Using the number from the crude oil analysis we see that for the ½ lb object at 1940 ft/s results in a kinetic energy of 29220.4 ft*lbs, requiring on layer of Xtegra fabric.

Switching to the 5lb mass with crude oil, we had a maximum velocity of 1597.8 ft/s and a kinetic energy of 198211.5 ft*lbs. An Xtegra thickness of 0.075 inches or 2 layers of fabric would be required.

Looking at the Drilling Mud results for the ½ lb object the maximum velocity was found to be 1912.1 ft/s resulting in a kinetic energy of 28386.1 ft*lbs. At this velocity and mass 1 layer of Xtegra fabric is needed.

The 5 lb object in the drilling mud analysis had a maximum speed of 1470.6 ft/s resulting in a kinetic energy of 167908.7 ft*lbs which would require .06 inches of Xtegra or 2 layers of fabric.

Conclusions:

As can be seen from the above analysis, most of the small objects can be stopped with a single layer of Xtegra fabric. As the mass of the projectile moves up to 5 lbs, the number of layers of Xtegra also goes up. In the worst case, light Crude Oil, 2 layers of Xtegra is needed to absorb the impact kinetic energy of the 5 lb mass.

All the velocities used in the thickness calculations would represent a fitting failure in perfect conditions and, thus, are conservative numbers.

One of the concerns in hydraulic failures is high speed fluid jets. A single layer of Xtegra would handle most of the fluid jets. Two layers would provide absolute protection against the high speed fluid jet problem.

Recommendation:

Using 1 to 2 Layers of Generation 3 Xtegra™ in Ballistic Nylon Sheath is an effective compliant minimum thickness barrier system

- Gen3 Xtegra™ = 0.0669 inch per layer
- 2 Gen3 Xtegra™ layers = 0.1338 inch total ~0.13 inch total
- Ballistic Nylon total thickness = 0.21 inch