AN ACCIDENT WITH BRITTLE FRACTURE DURING HYDROTEST

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A Case was referred to us, regarding a LPG storage vessel burst in a plant during hydrotest. The photographs of the failed vessel and the observations by the investigating team were sent to us for an opinion on the cause of failure. Very we get a chance for real life examples to understand the material science. This is a case which will help us to understand the brittle failures in service.

Vessel history

The burst of a LPG storage tank on hydrotest

The pressure vessel was fabricated in the year 1994. The vessel was in service from 1996. Annual inspections were being done as per government regulations. A competent certified agency is authorized to perform the hydrotest. The vessel had burst out at the time of hydrotest. The energy stored was so high that there was a loss of life, while inspection of flange leaks. Normally the pressure gets released instantly on beginning of crack. Here the stored energy was sufficient to cause a fracture to a high magnitude.

Findings

1. The cracked edge of the shell indicated brittle failure.
2. The stub in the failed area was seen to have swollen. This is an indication that the vessel was over- pressurized. See photo 2 & 4.
3. Pressure gauges are to be mounted only after seeing the free issue of water. At times dirt can enter in to the pressure gauge and indicated pressure can go wrong. This is a possibility for over-pressurization. We had come across a package boiler yielding under over pressurization during a shop hydrotest about 20 years back, on this cause.
4. The hydrotest procedure adopted was wrong. The vessel volume is 100000 liters. There were no vents envisaged during hydrotest. It could be possible that blanking of flanges was done first. The air must have been released via the pressure gauge stub at dished end only. This vent would not have been sufficient. When water was filled and overflowed through the pressure gauge stub, the pressure gauge would have been fitted. The remaining air that got trapped above must have undergone compression during hydrotest. The energy absorbed for compressing air is much more than water, since water is not compressible (as compared to air). The energy would go for temperature rise at the top of the vessel, where the air was trapped. Even water temperature rises considerably during hydro when the air is trapped. The energy transferred must have led to weakening of the vessel at the top by heating & by molecular activity. Possibly, this led to the vessel burst at the top section. Moreover lifting lug location could be the place of crack initiation.
5. Hydrotest procedure should have been done as per the written procedure. The procedure outlined in drawing no BCL/DPE/01 is right.

6. There is no thinning of the metal anywhere along the failed edge. It is not a ductile failure. This means the vessel had turned brittle already. This would happen at LPG tanks area subject to low temperature (particularly during winter) as the vessel would turn cold during the gas withdrawal process.
7. It is possible that the vessel was cold at the time of test / water filled was cold.
8. Checking thickness cannot identify whether the shell plate has turned brittle or not. Ultrasonic flaw detection was required. The crack seemed to have been present near the lifting lug area. The lifting lug seemed so small, that even while handling at shop, crack would have developed at HAZ of the weld.
9. SA 516 Gr 70 in normalized condition has better strength on low temperature. It was possible that the material was not normalized. Its impact strength might not have been proven at the lowest possible service temperature. The IS 2825 code may not address special requirement for low temperature service. It is possible that the shell plate is not normalized.
10. There are specific code requirements for low temperature service. ASME section VIII calls for impact test requirements. These might not have been demanded as per IS 2825 code. At the time of fabrication, the code regulations might not have been sufficient to address low temperature service requirements.

What we need to learn from this incident?

1. Cold water cannot be used for hydrotest. In winter times, the hydrotest must be done in day time itself. Water temperature must be above 30 deg C.
2. Air venting arrangement is a must.
3. Pressure gauges must be calibrated before use. Standard test gauges are to be used. At least two pressure gauges are required.
4. Hydrotest should be done under supervision. The personnel are not to be allowed during hydrotest. At many construction sites, we see this is not followed.
5. Relief valve is required at the discharge of the pump itself, so the pressure can be reduced immediately.

Brittle failure theory & auto refrigeration phenomenon

Out of this incident, I had to review the brittle behavior of the steel and the disasters that had occurred. I remembered the cooling of LPG cylinders, when used for gas cutting at construction sites. I found good literatures / write ups are available in the internet. I have included them in this article for reader’s benefit.

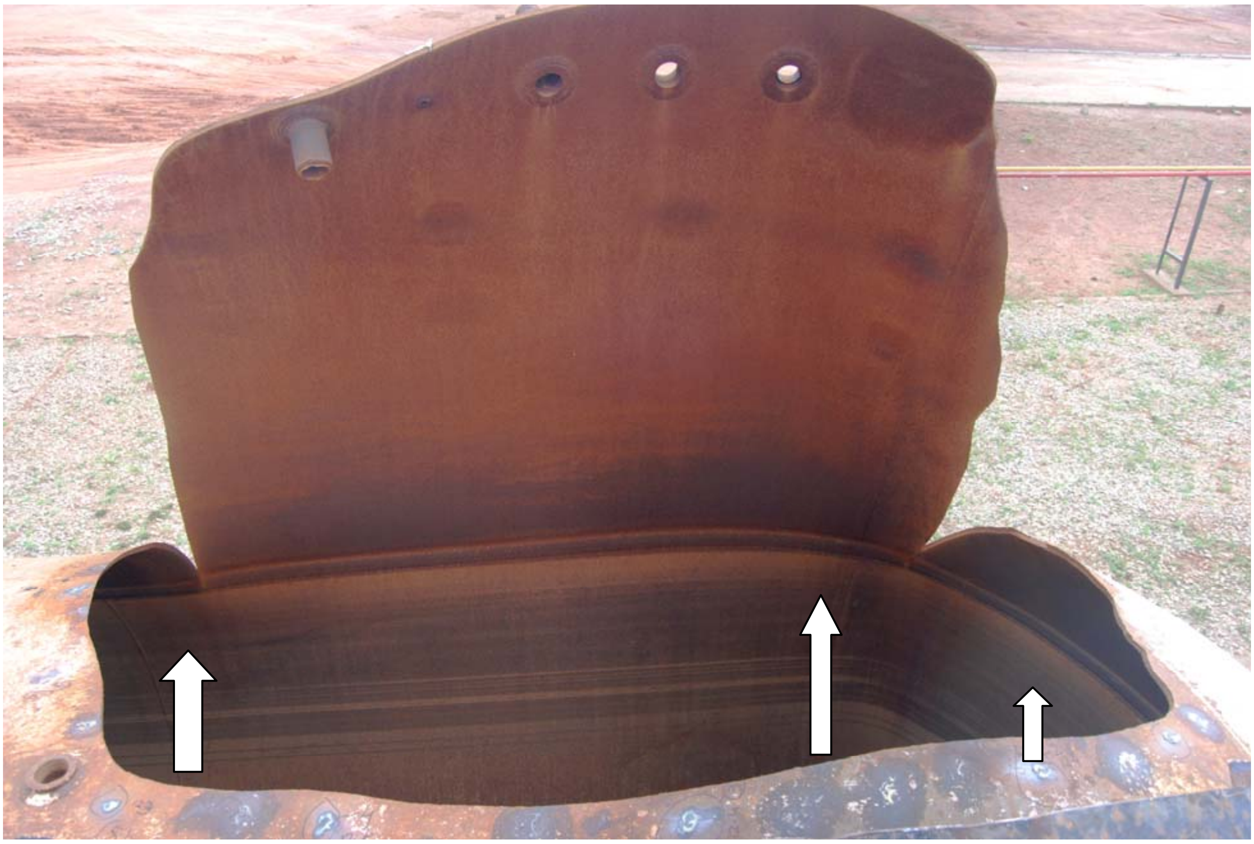


Photo 1: It appears that the air was trapped here. There is a water mark at the level shown. There is a step by step water marks seen below.

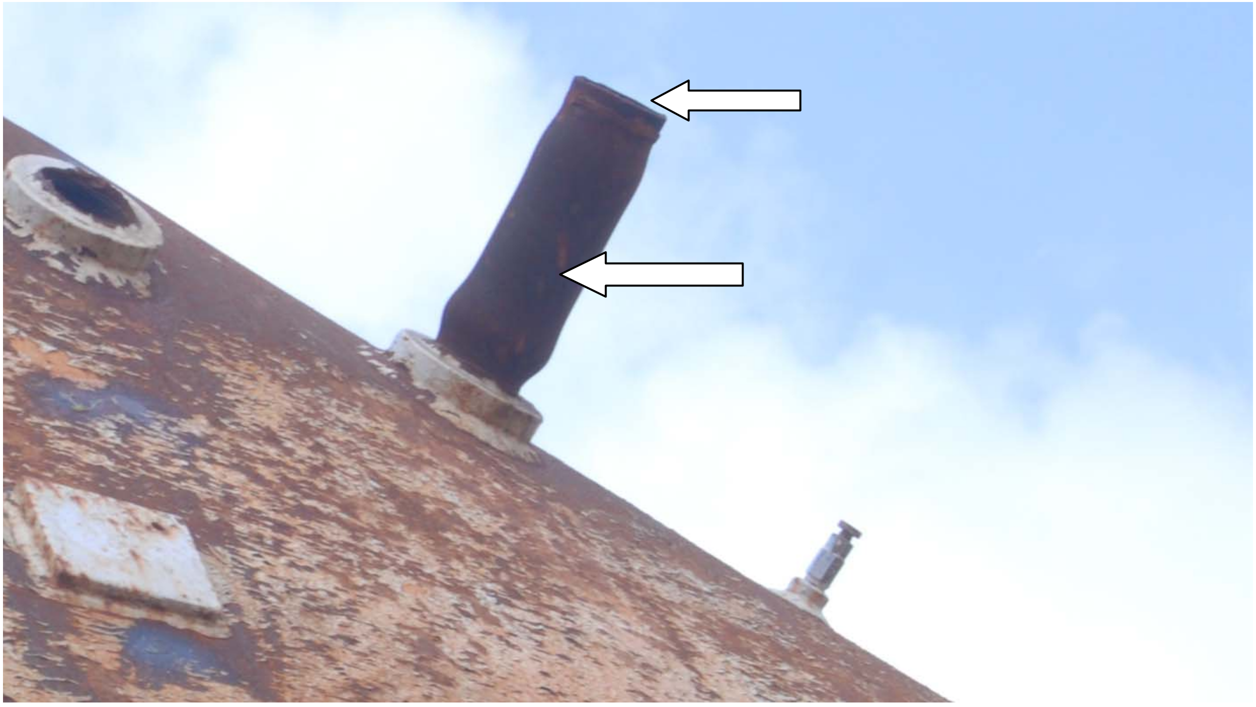


Photo 2: The stub in the failed area is seen swollen. There is over pressurization coupled with heat, perhaps.

Photo 3: Along the failed edge no lamellar kind of defect is seen. No thinning is seen. This is a brittle failure. A section of plate from other place should be tested for impact test.

Photo 4: Swelling of stubs seen. The edge shows the thick brittle fracture.

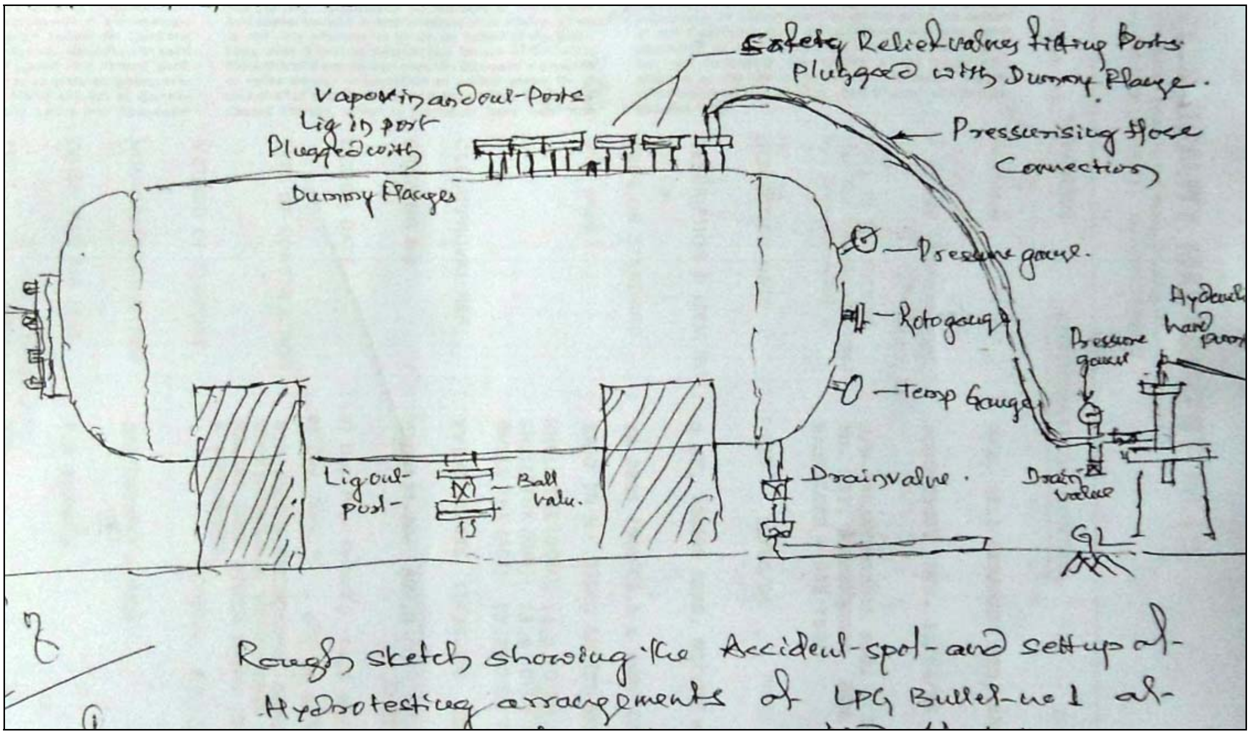


Photo 5: This arrangement did not envisage proper air release during hydrotest. The pressure relief valve was not seen in the rig.

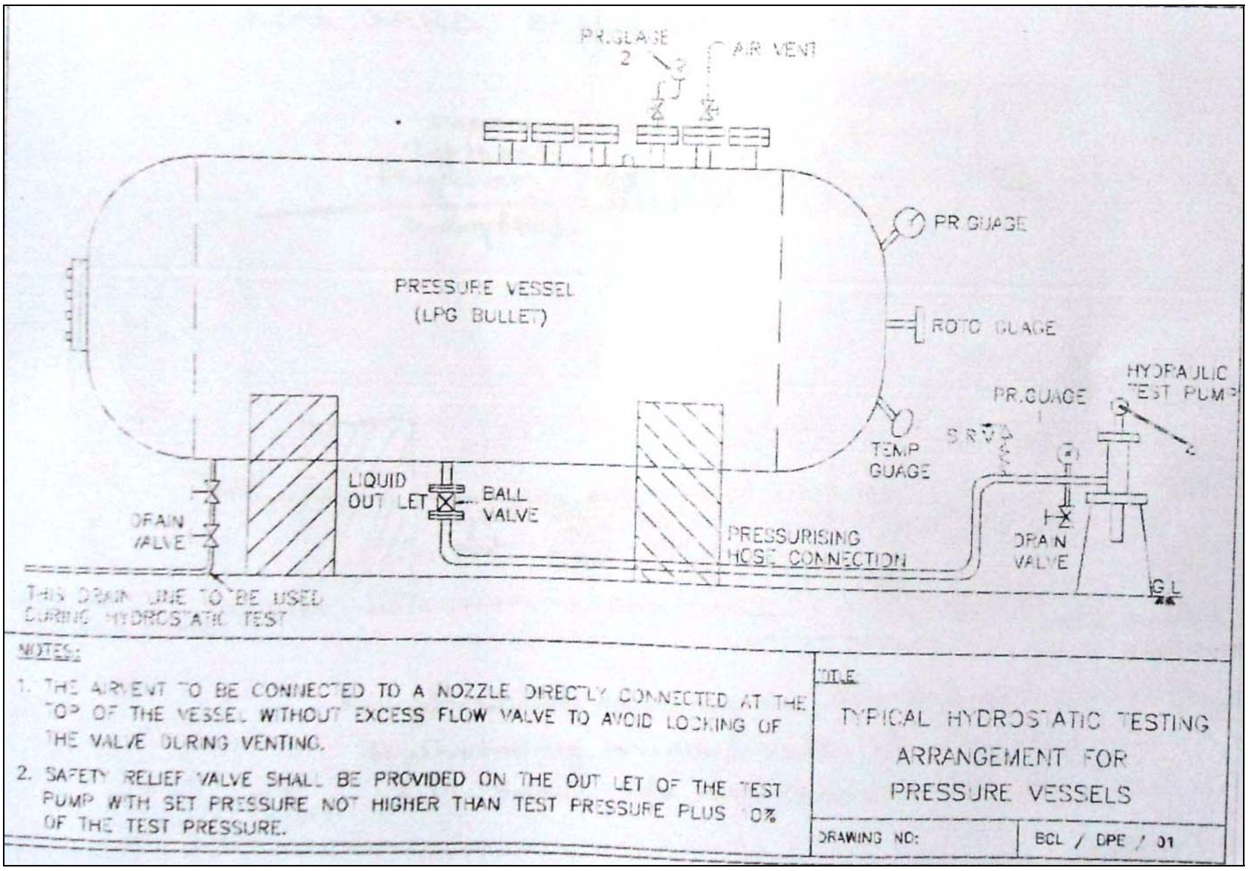


Photo 6: This is the right procedure for safety as well. The SRV, top most vent are essentials.


Photo 7: The hydrotest set up does not have relief valve.

Photo 8: Failure seemed to have started at lifting lug zone and travelled on either side. The edge of failed section is thick. Hence this is a brittle fracture. The vessel must have turned brittle in service.

An article from website of The National Board of Boiler and Pressure Vessel Inspectors http://www.nationalboard.org

Auto refrigeration
By Francis Brown, P.E.

Auto-refrigeration is a phenomenon common to liquefied compressed gases. Liquefied compressed gases exist in both the liquid and gaseous phases at ambient temperatures with pressures ranging from 2 psig up to 2,500 psig. That is, there is a gaseous layer over the liquefied gas within the pressure vessel. Some common liquefied gases are shown in the following table:

Ammonia	Carbon dioxide	Chlorine
Hydrogen chloride	Hydrogen sulfide	Liquefied petroleum gases
Methyl chloride	Monomethylamine	Nitrous oxide
Sulfur dioxide	Sulfur hexafluoride	Tungsten hexafluoride

An example of auto-refrigeration can often be seen when using an LPG (Liquid Propane Gas) grill. On a warm, humid day, moisture in the air condenses on the lower part of the propane tank when the burners are in operation. The withdrawal of propane gas from the tank reduces the temperature of the liquid propane and the tank itself below the dew point temperature, causing the moisture in the air to condense on the surface of the tank. Cooling occurs at very modest rates of gas withdrawal, with the temperature decreasing more as the gas withdrawal rate increases. Withdrawing gas from the pressure vessel reduces the pressure as well as the temperature within the vessel. The gas that is withdrawn is replaced as the liquid vaporizes by absorbing heat from the remaining liquid and the vessel itself. Auto-refrigeration occurs when the gas is withdrawn at a rate so that cooling exceeds the heat available from ambient sources.

The cooling, if excessive, may lower the vessel metal temperature to the point where failure from brittle fracture is possible. Flaws (cracks) in the welds or the pressure boundary materials, that are located in areas of high stress are subject to rapid crack growth when vessel temperatures reach the Nil Ductility Temperature (NDT). The NDT is that temperature at which the behaviour of the vessel material (steel) changes from ductile to brittle. Fortunately, pressure decreases as temperature decreases. For example, for a vessel containing liquefied carbon dioxide, a decrease in vessel temperature from 20°F to -20°F (-7°C to -29°C) decreases the pressure from 400 psig to 200 psig. The decrease in pressure associated with the decrease in vessel temperature reduces the stresses from pressure in the vessel material, thus reducing the energy available to produce crack growth. Cracks will not propagate if the total stresses are sufficiently small, even though the vessel material is at or below the NDT.

Total stresses include residual stresses, pressure stresses, and thermal stresses. **Residual stresses** are the stresses remaining in the vessel from the manufacturing process, and are constant. **Pressure stresses** decrease with decreasing temperatures, but the **thermal stresses** induced by the rapid cooling may be increasing. Rapid cooling causes the thermal stresses. It is very difficult to determine the total stress in a vessel during auto-refrigeration.

With the possibility of vessel failure by brittle fracture, appropriate measures should be taken to prevent auto-refrigeration of vessels that were not designed for low operating temperatures. However, vessels that were not designed for low operating temperatures may be cooled to a temperature below the NDT with no apparent damage. Damage will not occur until the total stresses increase to a critical value. To minimize the possibility of damage, the vessel should be very slowly warmed to ambient temperatures in the non-pressurized condition. This will keep the thermal and pressure stresses low, thus minimizing the total stresses in the vessel. Vessels not designed for low operating temperatures, but which have been subjected to auto refrigeration should be thoroughly inspected for cracks before the vessel is returned to service.

This inspection should include a thorough examination of all nozzles (especially the outlet nozzle) and the major weld joints, including the heat-affected zone, of the vessel. A visual inspection of the vessel is inadequate because small cracks may not be detected. The vessel should be inspected by the magnetic particle, liquid penetrant, or ultrasonic method, whichever is most appropriate and compatible with vessel contents and materials.

Compliance with all OSHA requirements for safety of personnel, including entry into a confined space, is essential. Also, knowledge of the vessel contents is required because many of the gases are combustible and may explode when exposed to an ignition source. The vessel interior must be well ventilated and caution exercised when using sources of electrical energy where these gases may be found.

In summary, auto-refrigeration of a pressure vessel not designed for low-temperature operation places the safety of the vessel in question. During auto-refrigeration, a pressure vessel may be cooled to temperatures at which vessel failure by brittle fracture may occur. The thorough inspection required to ensure the vessel can be safely returned to service is both time consuming and costly. Therefore, auto-refrigeration of pressure vessels not designed for low temperature operation should be avoided.

Editor's note: Some *ASME Boiler and Pressure Vessel Code* requirements may have changed because of advances in material technology and/or actual experience. The reader is cautioned to refer to the latest edition and addenda of the *ASME Boiler and Pressure Vessel Code* for current requirements.

BRITTLE FRACTURE MECHANISM - An extract from DOE handbook on material science

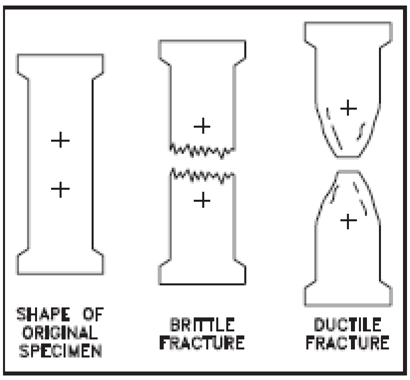
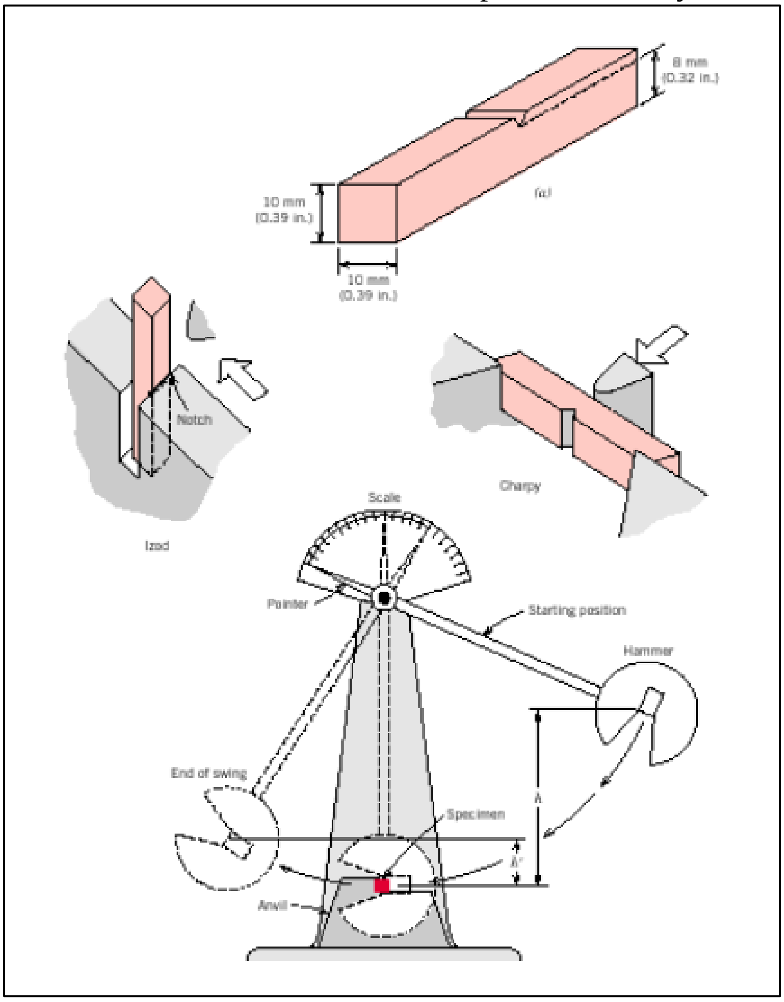


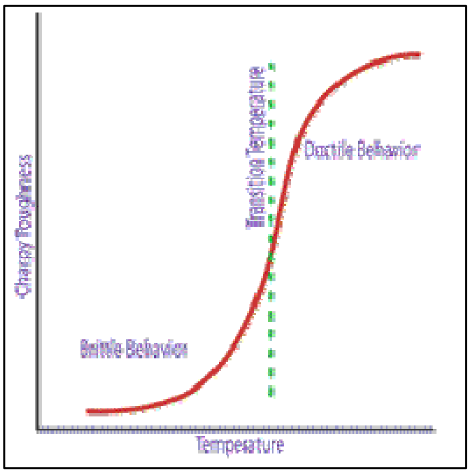
Figure 1 Basic Fracture Types

Metals can fail by ductile or brittle fracture. Metals that can sustain substantial plastic strain or deformation before fracturing exhibit *ductile fracture*. Usually a large part of the plastic flow is concentrated near the fracture faces.

Metals that fracture with a relatively small or negligible amount of plastic strain exhibit *brittle fracture*. Cracks propagate rapidly. Brittle failure results from *cleavage* (splitting along definite planes). Ductile fracture is better than brittle fracture, because ductile fracture occurs over a period of time, whereas brittle fracture is fast, and can occur (with flaws) at lower stress levels than a ductile fracture. Figure 1 shows the basic types of fracture.

Brittle cleavage fracture occurs in materials with a high strain-hardening rate and relatively low cleavage strength or great sensitivity to multi-axial stress. Many metals that are ductile under some conditions become brittle if the conditions are altered. The effect of temperature on the nature of the fracture is of considerable importance. Many steels exhibit ductile fracture at elevated temperatures and brittle fracture at low temperatures. The temperature above which a material is ductile and below which it is brittle is known as the *Nil-Ductility Transition (NDT) temperature*. This temperature is not precise, but varies according to prior mechanical and heat treatment and the nature and amounts of impurity elements. It is determined by some form of drop-weight test (for example, the Izod or Charpy tests). Ductility is an essential requirement for steels used in the construction of reactor vessels; therefore, the NDT temperature is of significance in the operation of these vessels. Small grain size tends to increase ductility and results in a decrease in NDT temperature. Grain size is controlled by heat treatment in the specifications and manufacturing of reactor vessels. The NDT temperature can also be lowered by small additions of selected alloying elements such as nickel and manganese to low-carbon steels.





Pressure vessels are also subject to cyclic stress. *Cyclic stress* arises from pressure and / or temperature cycles on the metal. Cyclic stress can lead to fatigue failure. Fatigue failure can be initiated by microscopic cracks and notches and even by grinding and machining marks on the surface. The same (or similar) defects also favour brittle fracture.

Stress-Temperature Curves

One of the biggest concerns with brittle fracture is that it can occur at stresses well below the yield strength (stress corresponding to the transition from elastic to plastic behaviour) of the material, provided certain conditions are present. These conditions are: a flaw such as a crack; a stress of sufficient intensity to develop a small deformation at the crack tip; and a temperature low enough to promote brittle fracture. The relationship between these conditions is best described using a generalized stress-temperature diagram for crack initiation and arrest as shown in Figure 2.

Figure 2 illustrates that as the temperature goes down, the tensile strength (Curve A) and the yield strength (Curve B) increase. The increase in tensile strength, sometimes known as the ultimate strength (a maximum of increasing strain on the stress-strain curve), is less than the increase in the yield point. At some low temperature, on the order of 10°F for carbon steel, the yield strength and tensile strength coincide. At this temperature and below, there is no yielding when a failure occurs.

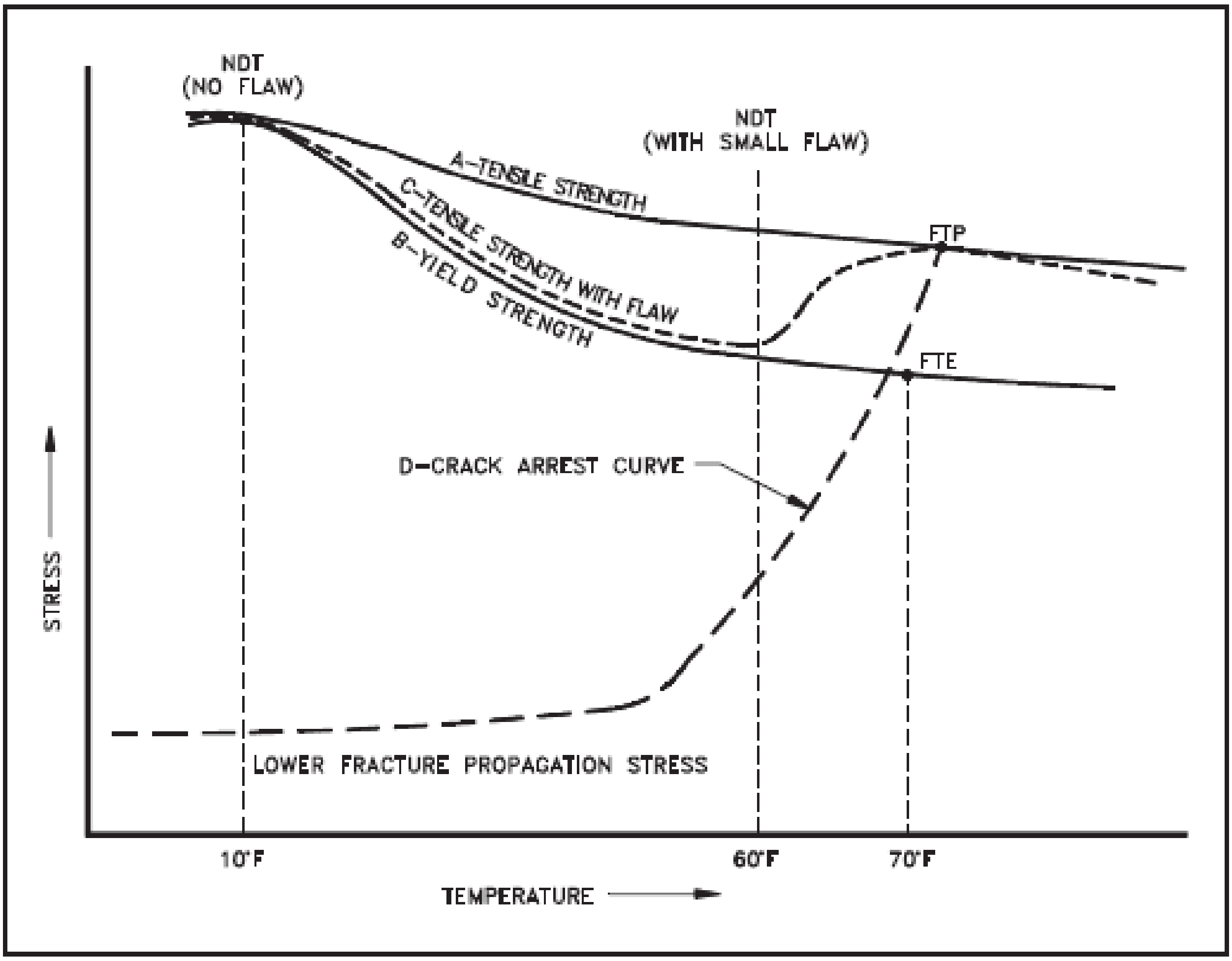


Figure 2 Stress-Temperature Diagram for Crack Initiation and Arrest

Hence, the failure is brittle. The temperature at which the yield and tensile strength coincide is the NDT temperature. When a small flaw is present, the tensile strength follows the dashed Curve C. At elevated temperatures, Curves A and C are identical. At lower temperatures, approximately 50°F above the NDT temperature for material with no flaws, the tensile strength curve drops to the yield curve and then follows the yield curve to lower temperatures. At the point where Curves C and B meet, there is a new NDT temperature. Therefore, if a flaw exists, any failure at a temperature equal or below the NDT temperature for flawed material will be brittle.

Crack Initiation and Propagation

As discussed earlier, brittle failure generally occurs because a flaw or crack propagates throughout the material. The start of a fracture at low stresses is determined by the cracking tendencies at the tip of the crack. If a plastic flaw exists at the tip, the structure is not endangered because the metal mass surrounding the crack will support the stress. When brittle fracture occurs (under the conditions for brittle fracture stated above), the crack will initiate and propagate through the material at great speeds (speed of sound). It should be noted that smaller grain size, higher temperature, and lower stress tend to mitigate crack initiation. Larger grain size, lower temperatures, and higher stress tend to favour crack propagation. There is a stress level below which a crack will not propagate at any temperature. This is called the lower fracture propagation stress. As the temperature increases, a higher stress is required for a crack to propagate. The relationship between the temperature and the stress required for a crack to propagate is called the crack arrest curve, which is shown on Figure 2 as Curve D. At temperatures above that indicated on this curve, crack propagation will not occur.

Fracture Toughness

Fracture toughness is an indication of the amount of stress required to propagate a pre-existing flaw. The fracture toughness of a metal depends on the following factors.

a. Metal composition
b. Metal temperature
c. Extent of deformations to the crystal structure
d. Metal grain size
e. Metal crystalline form

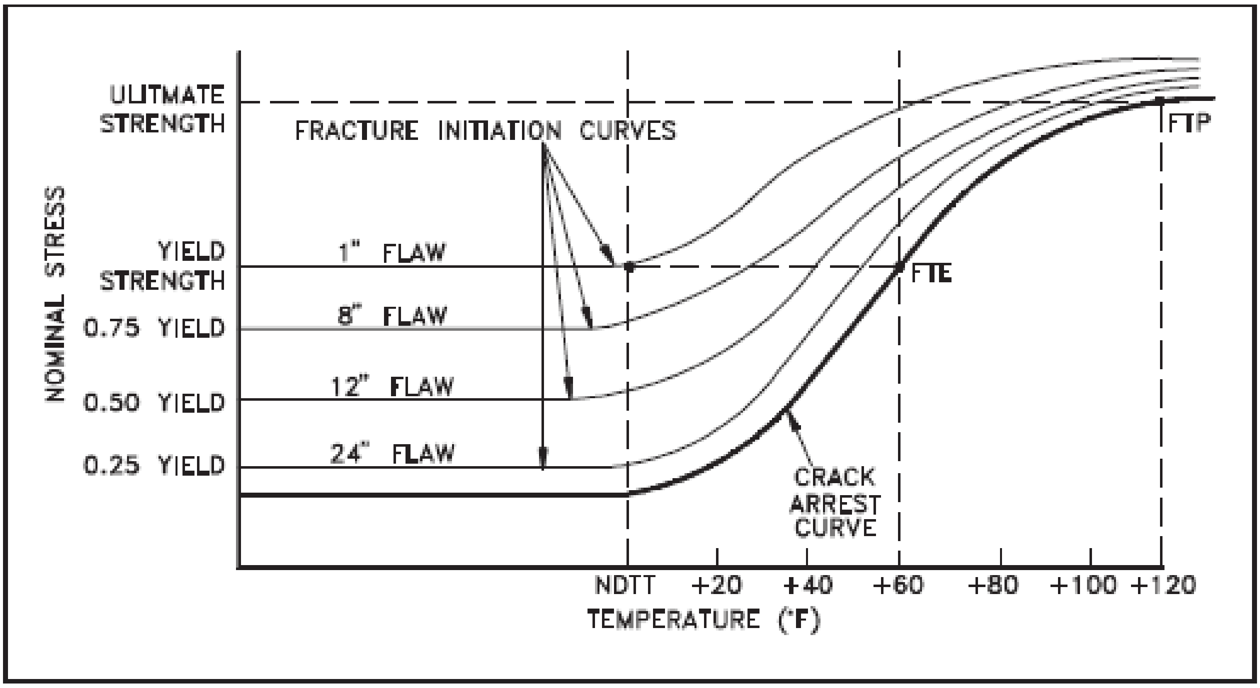


Figure 3 Fracture Diagram

The intersection of the crack arrest curve with the yield curve (Curve B) is called the *fracture transition elastic* (FTE) *point*. The temperature corresponding to this point is normally about 60°F above the NDT temperature. This temperature is also known as the Reference Temperature - Nil-ductility Transition (RTNDT) and is determined in accordance with ASME Section III (1974 edition), NB 2300. The FTE is the temperature above which plastic deformation accompanies all fractures or the highest temperature at which fracture propagation can occur under purely elastic loads. The intersection of the crack arrest curve (Curve D) and the tensile strength or ultimate strength, curve (Curve A) is called the *fracture transition plastic* (FTP) *point*. The temperature corresponding with this point is normally about 120°F above the NDT temperature. Above this temperature, only ductile fractures occur.

Figure 3 is a graph of stress versus temperature, showing fracture initiation curves for various flaw sizes. It is clear from the above discussion that we must operate above the NDT temperature to be certain that no brittle fracture can occur. For greater safety, it is desirable that operation be limited above the FTE temperature, or NDT + 60°F. Under such conditions, no brittle fracture can occur for purely elastic loads.

The low temperature operation of a pressure vessel can raise the NDT temperature over the lifetime of the reactor pressure vessel, restricting the operating temperatures and stress on the vessel. It should be clear that this increase in NDT can lead to significant operating restrictions, especially after 25 years to 30 years of operation where the NDT can raise 200°F to 300°F. Thus, if the FTE was 60°F at the beginning of vessel life and a change in the NDT of 300°F occurred over a period of time, the medium used in the pressure vessel would have to be raised to more than 360°F before full system pressure could be applied.

If we just review now the cause of failure, it would have been clear that the vessel had a flaw initiated at lifting lug. The low temperature operation of the pressure vessel must have shifted the NDT upwards. At the time of hydrotest, the vessel was overstressed and the crack propagated and led to catastrophe. Periodical ultrasonic flaw detection is a requirement as per code. It is perhaps time to scrap the storage tank after use for particular life cycle as the ultrasonic detection of flaw depends on the skill of the inspector to detect the crack. The inspector has to be an expert to assess the size of the crack and to revise the permissible load. The fool proof method could be a sample plate removal and testing for impact properties.
