BOILING LIQUID EXPANDING VAPOUR EXPLOSIONS: dynamic re-pressurization and two-phase discharge

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A detailed re-analysis of the catastrophic failures, or BLEVEs, of four 4.5-tonne water capacity LPG vessels subjected to jet fire attack has indicated that the severity of the event and the intensity of the fireballs formed was possibly a function of the initiating mode of vessel failure and the thermo-hydraulic state of the contents. The mechanism of vessel failure appeared to be a two-step process; first the formation of an initiating over-pressure crack in the high temperature vapor wetted walls of the vessel which arrests, followed later by a final catastrophic 'unzipping' of the containment and the nearly instantaneous release of its contents. This behavior is similar to that observed earlier with very small vessels. Possible reasons for the final rapid failure of the vessel are crack instability, local thermal stresses caused by quenching at the crack tip by the two-phase discharge, or over-stress due to re-pressurization.

In order to evaluate whether thermal stress and/or over-stress by re-pressurization could be responsible an experimental study of the venting process from a pressure liquified gas (PLG) vessel was undertaken. The release was suddenly initiated through a top slit orifice, simulating an accidentally formed crack. Measurements, over a range of fills, of the static and dynamic (top and bottom) pressure histories of refrigerant 22 (R22, chloro-difluoromethane) originally constrained at 20°C (0.91 MPa) demonstrated that significant dynamic over-pressures on the head-space of the vessel can occur with volumetric fills greater than 50% and openings of less than 4% of the vessel cross section. These results, in addition to time synchronized video records of the interior fluid behavior and the vessel's two-phase discharge process, allow a preliminary assessment of their roles in the catastrophic failure of a vessel and the ensuing **B**oiling **L**iquid **E**xpanding **V**apour **E**xplosions (**BLEVE**).

Keywords: BLEVE, LPG, two-phase flow, dynamic re-pressurization

BACKGROUND AND THE POSSIBLE BLEVE MECHANISM

A BLEVE has been defined as 'an explosion resulting from the failure of a vessel containing a liquid at a temperature significantly above its boiling point at normal atmospheric pressure', CCPS 1994.

Most work on this subject has, unfortunately, not been able to address the fundamental question as to **why** the BLEVE event exhibits such diverse fluid-vessel reactions; failures range from total catastrophic loss of containment (TLOC) to only the venting of the contents through an arrested crack; a partial loss of containment (PLOC). It is the intent of this contribution to help explain the very complex fluid structure interaction (FSI) observed in the BLEVE process and to support the hypothesis by referring to a detailed re-examination (Venart, 1998) of recent experimental data (Roberts and Beckett, 1996) and new experimental evidence of the initial processes taking place in the event (Ramier, 1996).

In the fire attack of a PLG vessel flames first heat up the vapor space walls and these increase in temperature more rapidly than the liquid wetted sides since heat transfer here is initially by free convection, and later by subcooled and then saturated pool boiling; only rarely is the critical heat flux exceeded for most fluids and fire exposures. As heating progresses both the liquid and vapor portions of the contents stratify with the temperature of the liquid surface setting the vapor pressure inside the tank. With continued thermal exposure the sub-cooled liquid core can become homogeneous as boiling proceeds from sub-cooled to saturated boiling; this usually occurs within the stratified liquid zone after the pressure relief valve (PRV) opens and later within the bulk liquid upon falling pressure (Venart et al., 1993).

With time, the pressure rises to the set pressure of the PRV which opens. Then, dependent upon fill and heating, this may cycle or remain open in its attempt to maintain the pressure of the contents at its design setting. If fill is low, the liquid wetted area is small, the evaporation rate may not exceed the capacity of the valve and the pressure can remain constant with only partial valve lift or the valve may cycle. As fill increases, wetted surface area increases, and the evaporation rate now can exceed the valve’s relief capacity, especially since the exiting vapor may be severely superheated due to vapor stratification; in this case there will be an increase in pressure with time until the level falls and along with it its evaporation rate. In all instances, aside from the vessel becoming liquid full, the opening of the valve will first depressurize the vapor which will then be followed by the formation of a two-phase swell within the now superheated liquid (Sumathipala et al., 1992). If fill is sufficient, the valve intake can continue to be vapor or, with greater swell, two-phase; conditions that will vary with valve size and fire exposure.

Two-phase valve flow can be caused either by entrainment or because the vessel becomes two-phase full. In the entrained case, mist/droplet flow usually results. If the vessel becomes two-phase full, churn-turbulent bubbly two-phase flow through the valve may occur. In any case the choke pressure for such flows is greater, and the choke velocity substantially less, than those for any prior superheated vapor flow. The pressure relieving capacity of the valve can now become compromised as the two-phase fluid exits with a much lower enthalpy, though greater density, compared to the earlier superheated vapor discharge (Sumathipala et al., 1988); the choke velocity of the mixture is also substantially smaller than that for the preceding vapour flow

With continuing fire attack the vapor metal walls weaken and commence plastic deformation at the hottest locations eventually leading to the formation of a crack which will cause further de-pressurization of the contents and an even greater two-phase swell of the contents. The size of initial fissure formed should be a function of the metal temperature, the fill level and the available energy in the vapor as only it is immediately available to perform the necessary plastic work. Crack development during this process should be relatively slow with choked, nearly isothermal vapor flow conditions being established as the crack lengthens. The crack should arrest locally in stronger, thicker and lower temperature but still very ductile metal (Venart, 1998).

Once formed the structural stability of such an opening now becomes a matter of vessel loading, the 'dynamics' of the subsequent flow and/or the local cooling of the metal surrounding the crack. If mist/droplet flow issues through the opening cooling times can be long since there will be little liquid contact with the wall. With impact of a low void fraction swell on the superheated head of the vessel, however, quenching by direct liquid contact and/or its water-hammer like pressure impulse (Ramier, 1996) may catastrophically restart the crack. These latter effects may be amplified by the interaction of both the thermal/hydraulic effects and the geometry of the head space (in both horizontal cylindrical and spherical vessels the vapor regions usually comprise convergent sections that lead to any crack).

Whether the cooled crack is now stable, in a fracture mechanics sense due to its size, or becomes unstable due to pressure or fluid impact loading, and/or its imposed thermal stress leads to differing fluid vessel interactions. On one hand we may have a long duration two-phase discharge with the vessel left intact. Alternatively, an apparent instantaneous catastrophic vessel failure can occur. A relatively long time two step failure is also possible. Both of these latter cases will yield a BLEVE. There have been many examples of all types of these adaptive fluid-structure behaviors in the process safety BLEVE literature (eg. (Pietersen, 1988)).

It is our view that such a two-step failure process may be the **cause** of **all** BLEVEs. That is a 'leak before break' (LBB) crack initiator followed by a total loss of containment of the PLG vessel is the normal sequence in the development of a BLEVE. The consequence of this is that the de-pressurization, re-pressurization magnitudes and their time responses involved influence both the pressure at failure and the boiling process within the remaining liquid; and thus any further fluid-structure interaction.

If the contents experience a continued increase in pressure, despite the additional relief provided by the crack, the contents will be subcooled and there will be few bubble nuclei within the bulk. If the pressure, however, is constant or falling it would have many uniformly distributed bubbles within the bulk fluid. Upon catastrophic LOC, and the liquid's abrupt de-pressurization and superheating, the immediate behavior of these can play a significant role in the consequent development of any fireball, since they are now unconstrained and at high pressure; they will thus expand and burst, shattering completely their surrounding superheated liquid host. A fine mechanically distributed aerosol will result. Any fireball formed from such a rapidly developing and evaporating aerosol cloud can involve the **total** contents of the vessel and not just the adiabatic flash fraction usually presumed (Roberts, 1982). The nearly instantaneous nature of its deflagration could also develop significant over-pressures such as noted in Pietersen (1988).

Whether the vessel fails completely, as a result of the severe 'quenching' of the superheated vapor-space metal, the imposed thermal stresses or the 'dynamics', ie. the water-hammer like impact of the swell upon the already damaged shell and its fracture mechanic 'criticality', the time scales for the two-step process envisaged could range from the near 'zero' to 10's of milliseconds (for an immediate quenching case) to the 10's of seconds (for the mist-flow cooling case). Analysis of several moderate scale BLEVE events indicated that crack formation and stabilization occurred with delays of up to about 50 seconds prior to TLOC (Venart, 1998).

In order to examine, in a preliminary manner, which of the vessel failure mechanisms may be appropriate to the BLEVE process this paper experimentally investigates the dynamic thermo-hydraulics which occur immediately following the partial loss of containment of a PLG through a simulated crack.

APPARATUS

The experimental facility (Figure 1) consists of a vertical cylindrical pressure vessel, a rupture unit, auxiliary equipment and instrumentation processing hardware.

Pressure Vessel and Pressure Transmitters

The pressure vessel was constructed from an aluminum tube (76..2 mm ID, 533 mm L) with tempered glass windows (4 - 140 x 64 mm) to allow for video and time-sequenced still photography (76..2 mm ID, 533 mm L) with tempered glass windows (4 - 140 x 64 mm) to allow for video and time-sequenced still photography (Figure 2). The ends of the vessel were sealed by aluminum head pieces or bosses 45 mm thick into which were fitted: two acceleration-compensated hermetically sealed dynamic pressure transducers (Kistler Type 603B1, 1 μs rise time, one each end); a static pressure transducer (Ashcroft K1, absolute pressure transmitter, 5 ms response time), a cartridge heater and type T interior fluid thermocouple, all of which were mounted in the bottom boss. The top boss contained the rupture slit, 51 mm long and 3.75 mm wide; this opening was sealed by a two ply aluminum foil diaphragm 50 μm thick. The diaphragm was capable of withstanding pressures of 1.6

MPa, when sealing a vent area of 171.4 mm^2. Cover plates were used to vary the vent area from 171.4 to 85.6 mm^2 and were mounted against elliptical O-rings (3 mm thick by 50 mm OD) fitted into the outside of the boss.

Slit Rupture Unit

The diaphragm rupture unit consisted of an aluminum head piece fitted with a hardened steel fine edged serrated knife blade running on two linear bearings supported by two vertical steel shafts; these allowed the unit to move vertically within a support frame surrounding the vessel. The knife assembly could be adjusted in all directions in order to cut the diaphragm uniformly and without binding. Two springs (100 mm, k = 2 kN/m) were utilized around the shafts and between the rupture unit and pressure vessel, in order to assist in knife retraction. Knife rupture to retraction took usually less than 50 ms.

Video and Auxiliary Equipment

The glass viewing windows in the pressure vessel allowed either video or still frame photography of the contents and/or discharge process. A Sony CCD_TR3000 Hi 8 Handycam was utilized for video. A 35 mm camera with a 1:1 macro lens, an electronic delay unit with an optical trigger, and remote flash was used to obtain still frame photography at precise instances after rupture of the diaphragm (Ramier, 1996).

Data Acquisition/Processing

A Nicolet Pro 90 digital oscilloscope was used to store the pressure transducer data. The scope had two 12 bit, 10 mega sample (MS)/s digitizers and two 8 bit 200 MS/s digitizers, with a capability to store up to 259 k data points per channel. The two 200 MS/s channels were used to record the dynamic pressure measurements at the top and bottom of the vessel. A 10 MS/s, 12 bit, channel was used for the static pressure and the other 10 MS/s channel was utilized for either temperature or accelerometer measurements.

Vu-Point3 (ver. 3.05) was used to process, analyze, and plot the oscilloscope data. Vu-Point was capable of filtering, frequency analysis, mathematical function analyses and all standard data set modification functions.

Video data, stored using the Hi 8 camera, was processed with a Sony EV_C200 video cassette recorder, custom frame grabbing facilities and a graphic editor.

EXPERIMENTS

A series of 55 experiments were performed with water and refrigerant-22 (R 22) as the test fluid. The results discussed here will concentrate on the R 22 data. R 22 was chosen as a test fluid due to its similarities to propane (approximately 2/3 of all PLG vessels contain propane or a mix of butane and propane) and the fact it was not flammable.

In the test series with R 22, the fluid was originally constrained at ambient temperature (20-24 °C, 0.9-1.2 MPa). Twenty experiments with volumetric fills ranging from 5 to 95 percent were conducted using a rupture area of 171 mm^2; four further experiments were conducted using the smaller slit orifice (86 mm^2). The larger area represents approximately 4% of the vessel reduced area, A°; the area of the vent divided by the vessel cross sectional area.

A video clip of the swell and flow development for a vessel approximately 50 percent full is shown in Figure 3 (a - e). In this sequence each frame is 33.3 ms apart; the figures are oriented such that the top of the vertical vessel is to the right hand side of the page. The original fill and the indications of vapour and two-phase discharge are as noted.

RESULTS

The static and dynamic transient pressure data, combined with frame by frame video analyses, were used to generate the following interpretation regarding the development of pressures in a partially filled PLG vessel upon sudden top venting. Figure 4(a) illustrates the top and bottom pressure records obtained from an R 22 experiment with the 171 mm^2 slit opening and a fill of H° = 0.7 (H° is the normalized fill height) and Figure 4(b) the corresponding static pressure.

Referring to the figures; upon vent initiation, the previously stagnant vapour is accelerated towards the opening and begins to exit at the vessel commences de-pressurization (A-B). The de-pressurization initiates boiling in the now superheated liquid beneath the vapour. First, heterogeneous nucleation along the walls of the vessel and within the liquid, where nucleation sites are available; and then, somewhat later, at the liquid-vapour interface. This void, combined with the boiling which is now growing within the liquid and at the two-phase interface, causes the interface to rise and develop into a rapidly rising two-phase swell, while the vapour continues its exit. As the pressure continues to fall, more rapid bubble nucleation and growth occurs within the increasingly superheated liquid which further accelerates the rising two-phase swell. The swell compresses the exiting vapour (B-C) causing an increase in its pressure and that recorded at the bottom of the vessel (B-D). Above the stratified two-phase swell exists a mist/droplet layer, created by the surface boiling and later liquid entrainment due to its acceleration. This is followed, when the vessel becomes two-phase full, by a churn-turbulent bubbly two-phase fluid. The two-phase fluid now begins to exit the vessel (C) but only after it has impacted the top of the vessel causing a water-hammer like impulse to the head (C-E). The vessel is now entirely filled with a quasi-homogeneous two-phase fluid, which exits under choked conditions (E-F) until the supply of fluid is exhausted or the two-phase level drops below a position sufficient for entrainment to ensure a continuing bubbly two-phase discharge; the flow now becomes a mist/droplet flow and later becomes unchoked.

The time and magnitude of the dynamic pressures experienced at the top and bottom of the vessel are dependent upon the liquid fill as well as orifice size; the times from initial vent to the commencement of re-pressurization (A-B, Figure 4.) for the top transducer is shown in Figure 5. The superheated liquid cannot boil, and thus cause vessel re-pressurization, until the vapour mass above it has sufficiently expanded. The amount of vapour initially present along with the area available for discharge, thus, directly influences the times for the bulk superheated liquid to commence boiling.

The rapid bubble nucleation, and therefor phase change of the bulk, point B, increases the volumetric vapour generation to a value greater than can exit from the vessel. The compressive force, exerted on the vapour, as the bulk two-phase fluid expands below produces an increase in the dynamic pressure at the top of the containment. This increase is gradual due to the relatively low density of the vapour flow. This may be seen as the inflection region (B-C) for the top transducer. The relationship between fill and duration of the inflection region is shown in Figure 6. It can be seen that the times decrease as the initial amount of vapour decreases due to the shorter distance for the two-phase swell to travel before its impact upon the vessel head. The size of the vent area influences the durations of the dynamic events. The top and bottom pressure traces for two different vent sizes are compared in Figure 7 for the same initial fill level (H°=0.36). The reduced flow area increases the time from initial venting to re-pressurization and the subsequent two-phase impact by nearly 2.6 times. The development and velocity of the advancing two-phase swell is also reduced; thus producing an impact pressure substantially less than that for the larger orifice area.

The two-phase swell impacts the top surface of the vessel with significant pressures if fill heights and vent areas are sufficient. The maximum impact pressures were observed at reduced heights of $0.5 < H° < 0.7$ for an A° of 0.04 (Table 1). Fill heights below H° = 0.5 produced lower impact pressures due to the greater distances for the swell to rise and the necessary heat transfer from the bulk lowering the saturation temperature and thus its pressure; the swell appeared to dissipate and also decelerate. For fills greater than H° = 0.7 the impact pressures were inconsistent, possibly due to the dependence of the acceleration of the swell on the vapour source strength and nucleation. Also, the velocity of the swell, at high fills, does not allow sufficient time for interface acceleration.

The two-phase impact at the top of the vessel produces significant over-pressures; such conditions were earlier speculated to occur by Grolmes (1984). The development of these over-pressures can perhaps play a significant role in vessel failure. The pressure may influence the local stress state of an already damaged vessel and/or the enhanced heat transfer, due to two-phase impact and possible direct liquid contact of the heated vapour wall metal, could result in significant thermal stresses due to quenching. Both these factors could result in crack growth and catastrophic vessel failure.

Table 1. Two-phase impact pressures (the pressure difference between top and bottom transducer at time of vessel filling) for a range of fills.

Test #	Fill Height (cm)	H*	Impact Pressure (kPa)
3.12	14	0.28	85
2.08	24.5	0.49	178
3.1	34.4	0.69	102
3.14	40	0.8	77

CONCLUSIONS

Measurements of the dynamic pressures experienced on the head-space of PLG vessels during top venting indicated that pressures, greater than original containment conditions, can be generated. These dynamic pressures, obtained discharging R 22 through slit orifices (simulating thermal or fatigue cracks), are as a result of the impact of the two-phase swell at the top of the vessel and the changes of momentum established between the preceding, and initial, vapour flow, and the subsequent, developing, two-phase flow. Maximum over-pressures are generated with normalized fills of $0.5 < H° < 0.7$ with a normalized orifice area, A° = 0.039; smaller areas delay and reduce the magnitude of the over-pressure. It is postulated that the impact of the swell on the head-space of a PLG container could cause catastrophic failure due to either thermal quenching or over-stress at the crack tip of a thermally or fatigue damaged vessel.

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NOMENCLATURE

$A°$	reduced area = A_v/A_x
A_v	vent area, mm^2
A_x	vessel cross sectional area, mm^2
$H°$	normalized fill height = H_L/H_T
H_L	liquid height, m
H_T	vessel height, m
P	pressures, kPa
P_c	interior choke pressure, kPa
t	time, seconds

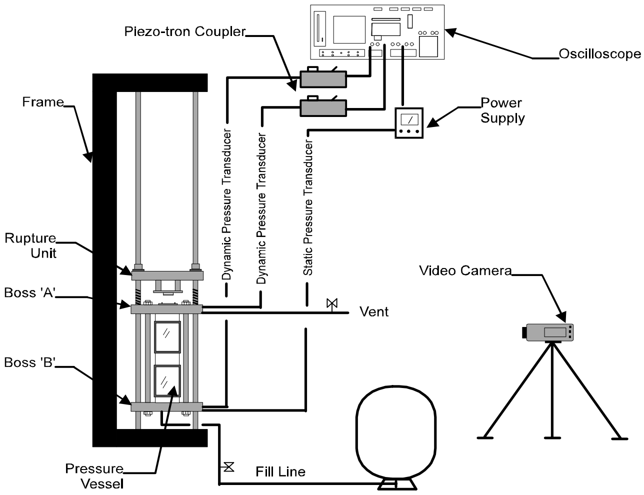


Figure 1. Experimental top venting facility.

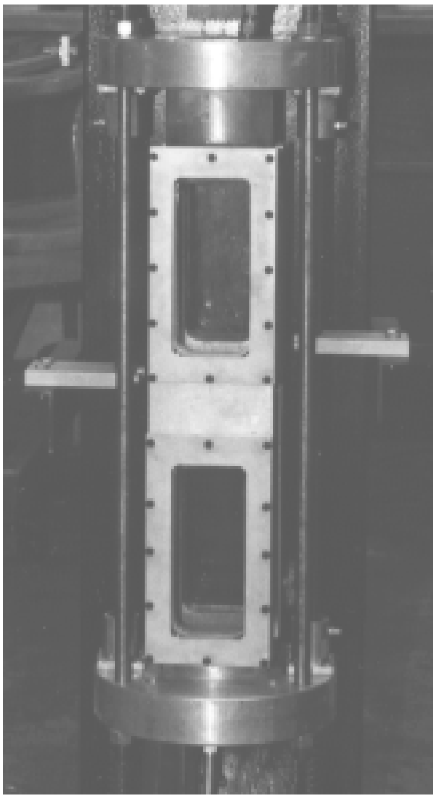
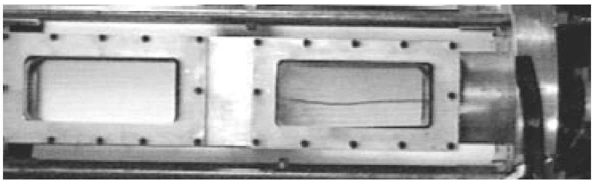
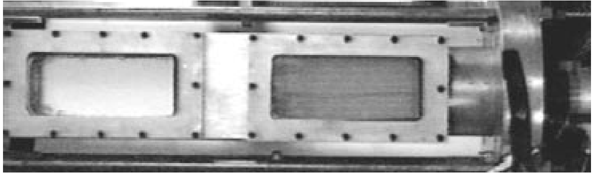


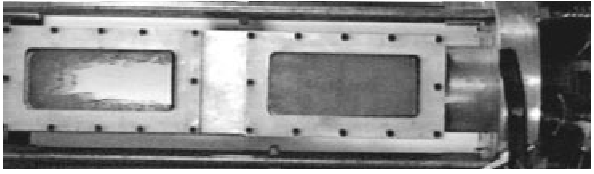
Figure 2. The pressure vessel.



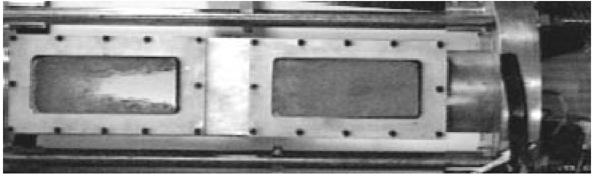
a) Liquid Vapour



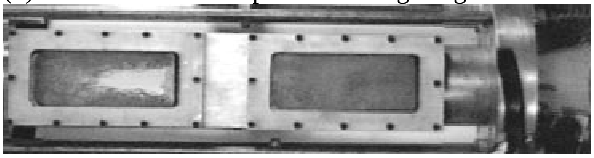
(b) Vapour discharge



(c)



(d) Two-phase discharge begins



(e) Two-phase discharge

Figure 3. Video data of swell development and discharges, Test (H° = 0.55)

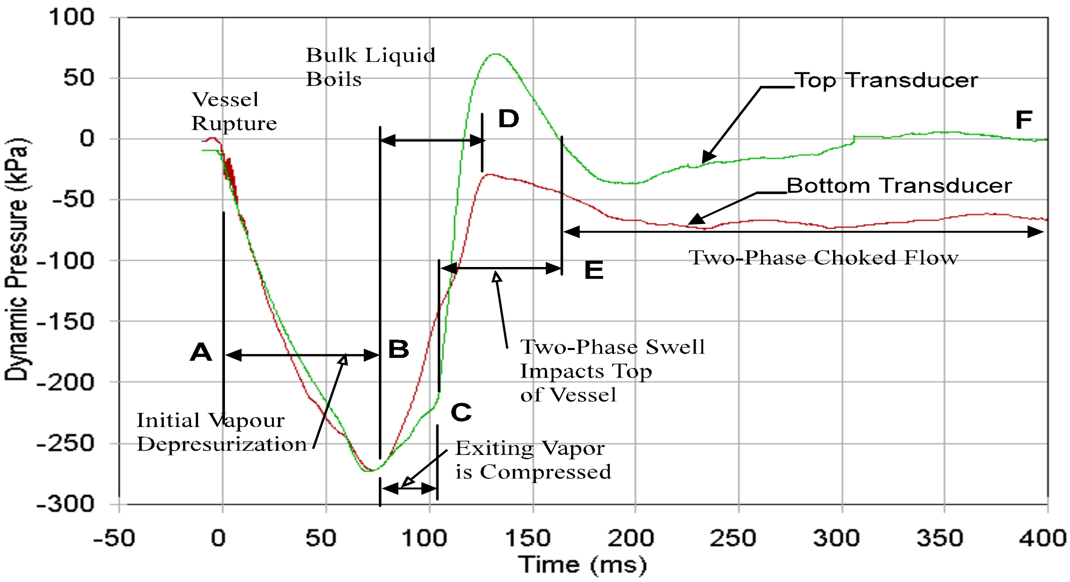


Figure 4(a). Top and bottom dynamic pressures: H° = 0.7, A° = 0.039.

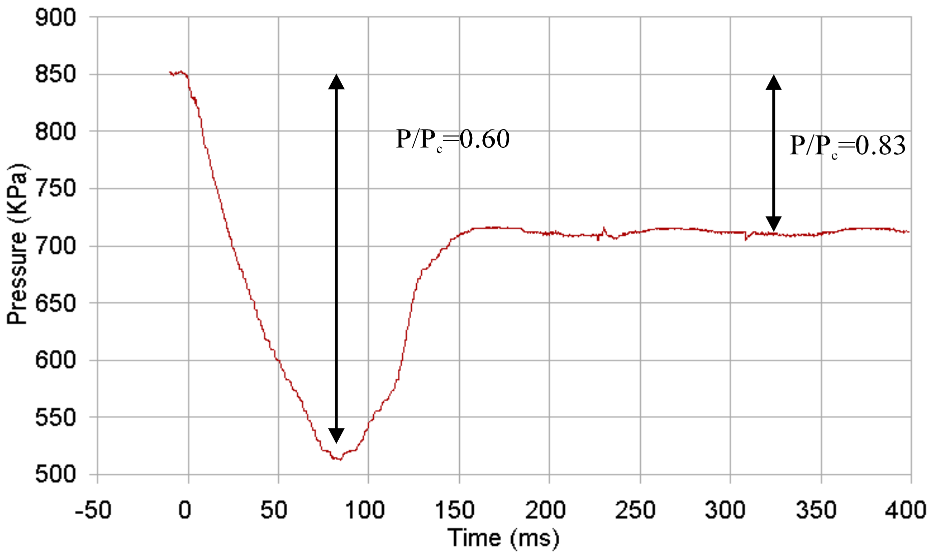


Figure 4(b). Static pressure; H° = 0.7, A° = 0.039

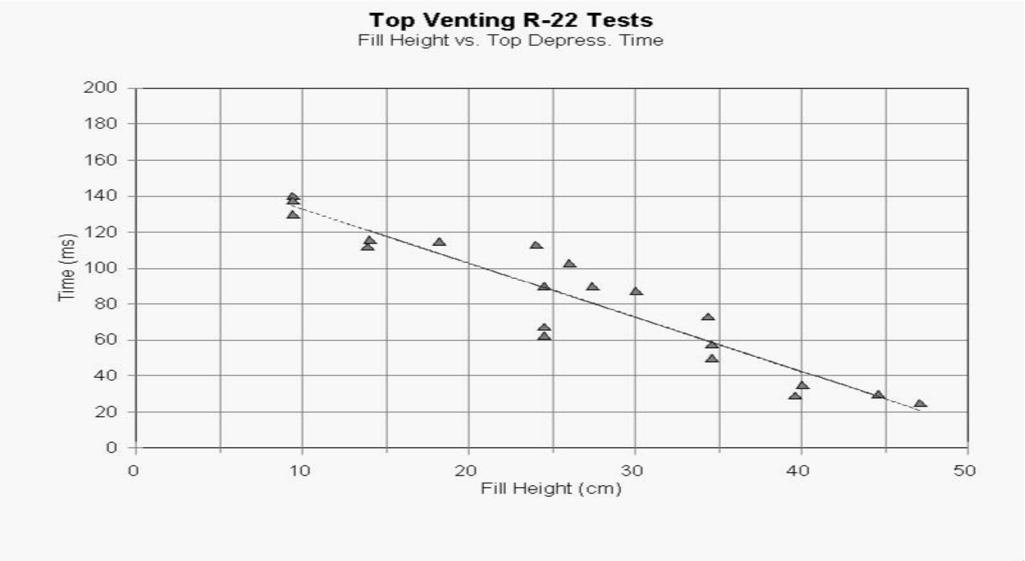


Figure 5. Top initial de-pressurization times versus vessel fill, large area crack.

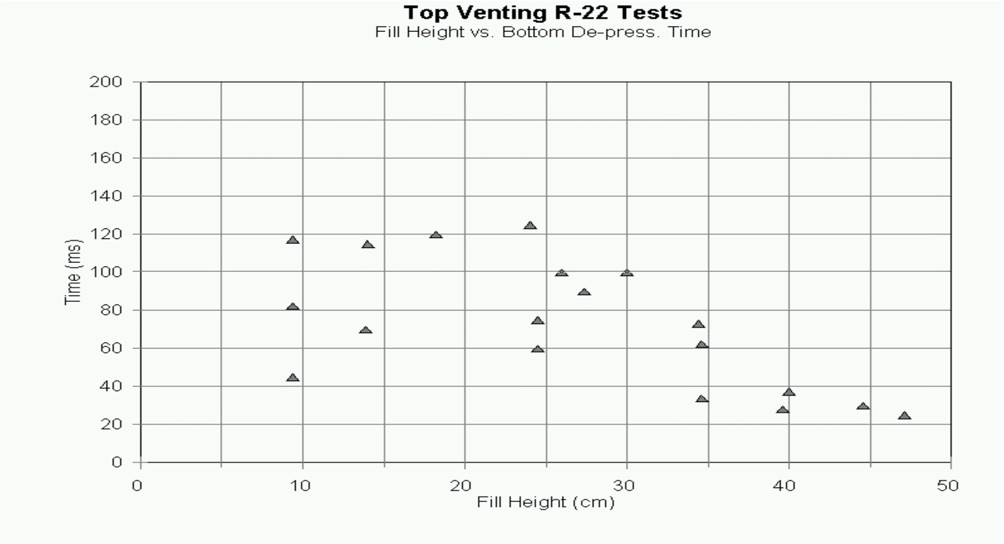


Figure 6. Inflexion times (time period between de-pressurization and swell impact), large crack.

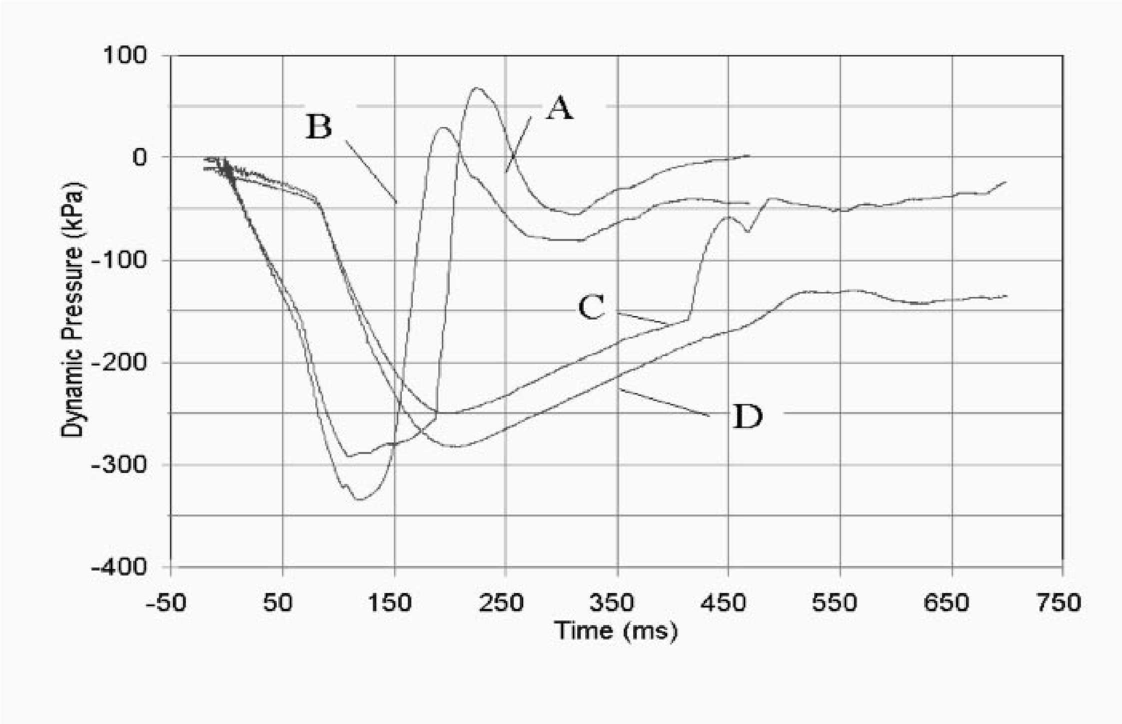


Figure 7. Dynamic pressure (H° = 0.36); A-B top and bottom transducers 171 mm^2, C-D top and bottom transducers 86 mm^2.