BLAST DAMAGE TO STORAGE TANKS AND STEEL CLAD BUILDINGS†

Graham Atkinson, Health and Safety Laboratory, Buxton, Derbyshire, UK

INTRODUCTION

The Buncefield vapour cloud explosion showed the huge cost associated with blast damage to commercial property surrounding a major explosion incident [Ref 1]. Both steel frame and masonry structures were damaged over a wide area – with large steel warehouse type structures being affected at particularly long range. In most cases there was serious disruption to business activity and in many cases the buildings had to be demolished or abandoned for long periods until extensive repairs were carried out.

Another key feature of Buncefield (and other recent vapour cloud explosions) has been the damage done to large bulk storage tanks. The blasts almost invariably causes a rapidly escalating fire in any tanks surrounded by the vapour cloud – even if they contain relatively high flash-point materials such as diesel [Ref 2 and 3]. The simultaneous lighting of so many tanks makes an effective emergency response to the incidents difficult to plan and implement and adds greatly to the final level of damage and environmental pollution.

In the context of response to explosions there are some strong parallels between steel frame warehouse buildings and storage tanks: in both cases the high surface area and relatively lightweight construction makes pressure forces applied by the wind a key structural consideration. Both tanks and warehouses are designed to withstand wind forces up to a specified wind speed threshold. Beyond these pressures increasing amounts of damage are to be expected in unwetted parts of the tank. Design wind speeds and pressures vary depending on the local climate/exposure but the figures below are typical for warehouses.

WAREHOUSE WALLS

Pressure (general zones) = 0.72 kN/m^2	720 Pa
Suction (general zones) = 0.51 kN/m^2	510 Pa
Suction (corners) = 0.72 kN/m^2	720 Pa

WAREHOUSE ROOF

Imposed (including snow) = 0.60 kN/m^2	600 Pa
Wind suction (general zones) = 1.00 kN/m^2	1000 Pa
Wind suction (eaves & gable) = 1.20 kN/m^2	1200 Pa

These figures are low compared with the typical levels for other types of building. For example the threshold for serious damage to a conventional brick built control room is 50 millibars (5000 Pa) [Ref 4]. This is the fundamental reason why serious damage to large warehouses was observed over such a wide area at Buncefield. Furthermore, because almost all of the surface structural steel and cladding is potentially at risk (rather than just windows) the level of damage to warehouses may be particularly extensive and time-consuming to repair, increasing the level of disruption to business.

BUNCEFIELD WAREHOUSES

The location of all the buildings and tanks examined in this study are shown in Figure 1. Two warehouses in the Buncefield area have been chosen. They illustrate the general character of damage to similar properties around the site whilst exhibiting significant differences that are linked to the type of construction – especially the cladding. The character of the damage to both of these buildings can be seen in Figures 2 to 7. In both cases the blast opened extensive vents in the front face of the building (that closest to the Buncefield site) – See Figures 3 and 7. These large vents in the front face allowed the formation of a strong internal pressure surge which passed the length of the (substantially unobstructed) interior before impacting on the back wall (furthest from the Buncefield site). In both cases reflection of this internal surge and the associated rise in internal pressure pushed the building cladding outwards over the full extent of the back wall and the parts of the sidewall closest to the back (corresponding to areas where the reflected surge was not weakened by venting) – see Figures 4 and 6. The rarefaction phase of the explosion did not cause widespread outward failure of the rest of the walls or roof. By this stage the warehouses were very well vented the rarefaction would pass along the inside and outside of the warehouses with almost equal intensity. The process of blast wave transmission through partially obstructed barriers is discussed further below and in Appendix 1.

Cladding on the majority of the sidewalls and roof of Warehouse 1 (WH1) – apart from near the ends – was undamaged and did not have to be replaced when the warehouse was repaired. By contrast cladding on the roof and sidewalls of WH2 was all significantly damaged and had to be replaced (Figure 7). The reason for this difference is traceable to the type of cladding and the venting mechanism during the blast. WH1 was a "built-up" cladding system that remained intact to higher pressures. The building vented when wind posts along most of the front face failed, tearing purlins from intact frames and allowing large sections of (substantially intact) cladding to swing inwards.

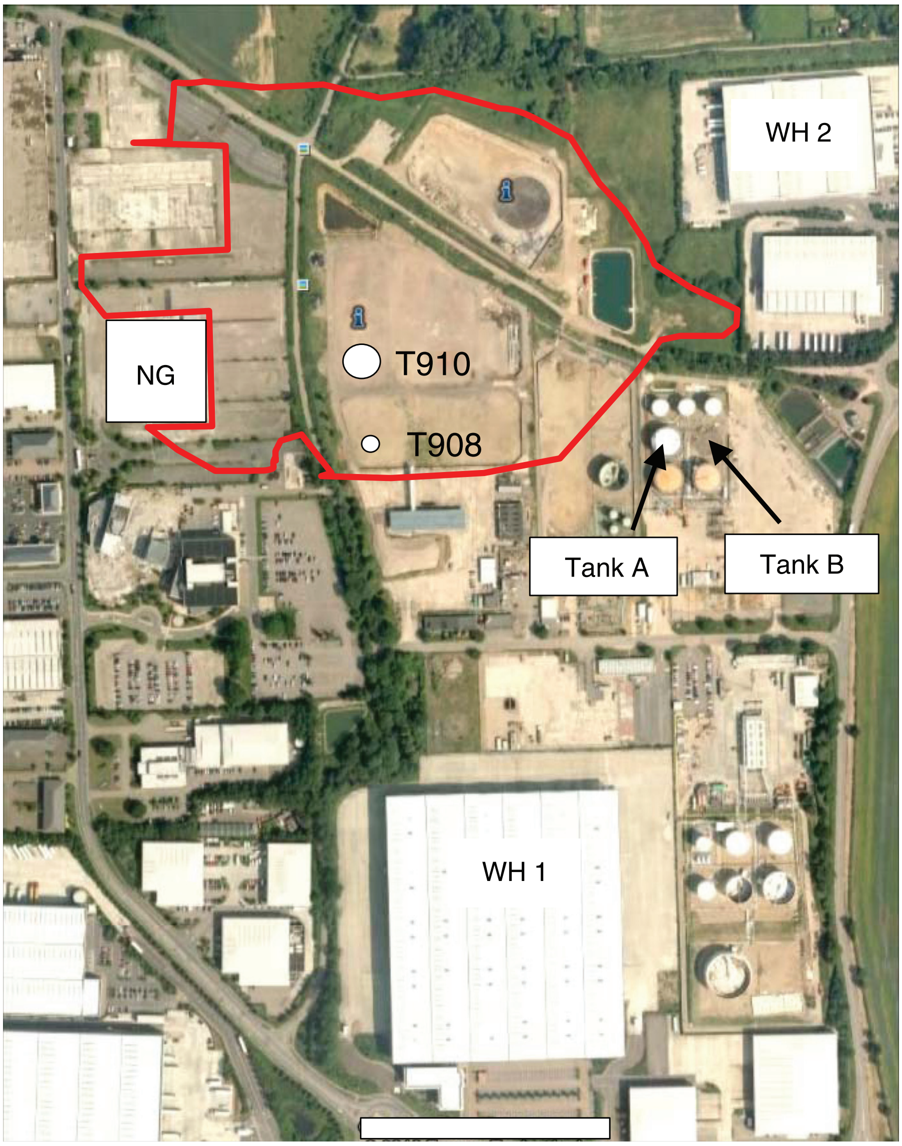


Figure 1. Locations of buildings and tanks described. Red line shows extent of the vapour cloud. NG indicates the Northgate building

This mechanism is illustrated schematically in Figure 5. Where the underlying structural steel framework did not fail the strong built-up cladding suffered no permanent deformation and remained serviceable.

By contrast in Warehouse 2 (WH2) the cladding panels and support frames were weaker than the structural steels (which remained substantially intact). As the blast pressure rose large parts of the cladding and support frame suffered inward deformation without opening up substantial vents that could allow pressurisation of the interior. When the connections between the cladding frames and the main structural steel failed (finally venting the structure) cladding on almost all of the roof and sidewalls had already been damaged and had to be replaced. Examination of shows the outward deformation of cladding supports on and near the rear wall of WH2 showed that approximately 50% of the support frames yielded (in an outward direction in this case) before failure of the cladding fixings – in the other cases the fixings failed first. This suggests the cladding system was rather carefully designed to withstand suction forces with support frames and cladding fixings well-matched in strength.

When a warehouse is vented, by rapid failure of a significant proportion of the front face, an internal pressure surge is formed. The pressure behind this front is a function of both the fractional open area of the face and the external pressure. Appendix 1 derives a formula for the strength of the internal pressure surge for weak blast waves ($P_{ext} \ll 1$ bar).

In the case of WH1 the fractional open area of the vented face at the end of the positive phase was around 30%. Table 1 in Appendix 1 shows how the transmitted

Figure 2. Warehouse 1after remains of cladding removed

pressure varies with the external pressure for a vent this size. If the external pressure is in the range around 1000–4000 Pa the net inward pressure on the roof and sidewalls is less than the threshold likely to cause damage whilst the reflected pressure at the back wall exceeds the external pressure by enough to cause cladding loss. These results explain the general form of the damage observed to different parts of the structure.

BUILDING DEFORMATION AND BLAST PROFILE

A previous study by Weidlinger of the deformations of various reinforced concrete panels from the upper parts of a building adjacent to the Buncefield cloud showed that the damage could only be explained if the pressure rose progressively to 15–30 kPa over a period of several hundreds of milliseconds [Ref 5]. This implies that the average progress of the flame front was sub-sonic. The associated blast wave ran ahead of the flame and the strength of the blast increased as the flame expanded and approached the target. A wealth of other evidence (especially numerous CCTV records) support this conclusion. This evidence and the relationship between flame average speed and blast profiles inside and outside the cloud are discussed in detail in Ref 6.

The damage to warehouse buildings around the Buncefield site lends further support to the idea that pressure increased gradually over a period of many hundreds of milliseconds. In all cases the buildings suffered a single mode of failure that opened large vents in the structure; further increases in pressure did not cause additional failures because, after venting, the internal and external pressures were efficiently equalised. WH1 provides an illustration of the selectivity with which only the lowest pressure mode of venting failure operates, if the pressure rises slowly. Figure 8 shows the roofline of the north wall of the building (facing the blast). The corners of the building are provided with additional purlins to resist elevated suction forces near the corners (Figure 9). Also a part of the wall is somewhat shielded by a group of trees in the fetch. These factors make relatively small differences to the local vulnerability

Figure 3. Warehouse 1 before cladding was removed

Figure 4. Warehouse 1 showing outward displacement of cladding on or near the back wall by an internal pressure surge

of the structure but they are sufficient to curtail or even prevent local failure. By the time the pressure rises to the point where the (minor) stiffening of the wind-posts provided by the additional purlins would be overcome, there has been large scale venting of the rest of the wall and differential pressures between inside and outside have collapsed.

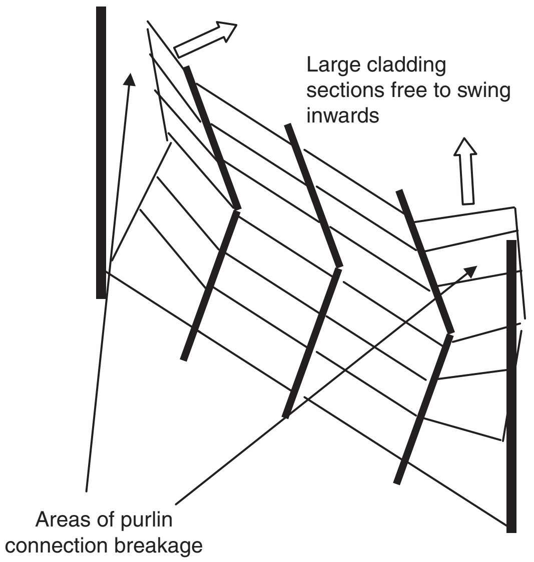


Figure 5. Schematc showing mechanism of venting of WH1

Another striking example of this effect is provided by damage to a steel clad warehouse roof at a minimum distance of 130 m from the edge of the Jaipur VCE. In this case the warehouse walls were constructed of reinforced concrete and did not fail. Venting occurred through large open area failure of the section of roof closest to the explosion. As the explosion pressure increased the vented area stretched further from the explosion into the building. When the open vent was large enough to allow rapid pressurisation of the interior, the progressive roof failure stopped. The differences in applied external pressure at the front and back of the roof were very slight (~20%) but at the front there was complete structural and cladding displacement (to floor level) whilst at the back the damage was negligible. At the time of writing photographs of this building cannot be published for legal reasons.

ASSESSMENT OF DAMAGE TO WAREHOUSE BUILDINGS BASED ON EXPERIENCE AT BUNCEFIELD AND JAIPUR

1. At very long distances from a vapour cloud explosion (where side-on overpressures are <500 Pa) there is likely to be relatively minor damage to parts of the cladding and or vulnerable parts of the structure such as roller shutters. Such damage may be on any side of the building.
2. Much closer to the site where maximum side-on overpressures are in excess of 2000 Pa the first (lowest pressure) venting mode is likely to operate as the pressure rises. If the cladding is strong relative to the

Figure 6. Warehouse 2 showing inward venting of front face and outward cladding loss on the back face caused by an internal pressure surge

Figure 7. Warehosue 2 showing pressure damage to the (unvented) sidewall

structural steel (as in WH1) there will be serious structural damage to the vented face but the majority of the cladding may remain intact. If the cladding system is relatively weak (as in WH2) there may be little or no effect on structural steel, but widespread cladding damage.

3. In all cases where substantial venting occurred at Buncefield there is evidence that this occurred rapidly with the formation of a relatively strong internal pressure surge. Any internal partitions and compartments are clearly likely to be disrupted by such internal pressure surges. People and equipment deep within

Table 1. Transmission of blast waves of different intensities – Open Area Ratio 0.30

Incident (external) pressure (kPa)	Internal (transmitted) pressure (kPa)	Net inward pressure on roof/sidewalls (kPa)	Reflected pressure at back wall (kPa)	Net outward pressure at back wall (kPa)
1	0.92	0.08	1.84	0.84
2	1.7	0.3	3.4	1.6
3	2.4	0.6	4.8	1.8
4	3	1	6	2
5	3.6	1.4	7.2	2.2

Figure 8. Variation in deformation of roof line on North face of WH1. Image digitally stretched (vertically)

Figure 9. Doubling of purlin density near corners of WH1

warehouse structures may still be at risk from large vapour cloud explosions.

4. If the wall facing the explosion is reinforced, another building face (typically the roof) will suffer a large open area failure.

FORMATION OF INTERNAL SHOCKS

The formation of an internal shock in a weak light structure does not require perforation of the wall and inflow of gas. Movement of the wall increases the internal pressure and generates a downstream shock. For a wall speeds v ($v \ll c$, c is the speed of sound) the internal pressure generated by the moving wall is simply $P = \rho cv$ [Ref 7]. This internal pressure provides a damping force and rapidly limits the rate of movement. This form of fluid-structure interaction is discussed in Appendix 2.

BLAST DAMAGE TO BULK TANKS

Empty bulk tanks have broadly similar problems with resisting wind forces to large warehouse buildings and are built to withstand roughly similar conditions. For example the tanks used to contain gasoline at Buncefield were designed to withstand an inward directed net pressure of 6 millibar (600 Pa). On the roof of the tank this figure would correspond to a combined wind and snow load. Experience at Buncefield and other sites suggests that the roof is normally the weakest part of a fixed roof tank.

The strength of the roof is typically very low compared to the imposed forces on tank surrounded by or close to a substantial vapour cloud. The structure is also rather light responding fully to an imposed load within a few tens of milliseconds (Appendix 2). Since pressure rises over a period of several hundreds of milliseconds the tank structural response can be understood with a quasi-static analysis.

DAMAGE TO PARTIALLY FILLED AND EMPTY TANKS OUTSIDE THE CLOUD

At significant distances outside the flammable cloud maximum overpressures are relatively low but still well above the strength of the roof. The roof rapidly moves downward to equalise the internal and external pressure. An illustration of this from Buncefield is shown in Figure 10; the two tanks A and B in the centre are of similar design and both contained low volatility liquids. They have both only suffered significant plastic deformation of the roof . Tank B was empty at the time of the explosion and high levels of plastic deformation occurred before internal and external

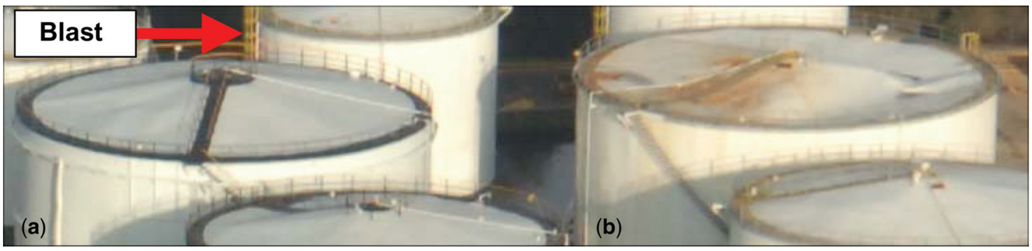


Figure 10. Deformation of tank tops outside the Buncefield cloud – Tanks A and B

pressures were balanced. On the other hand Tank B was 60% filled at the time of the blast and, despite being closer to the edge of the cloud, it shows significantly less plastic deformation because pressure balancing would have occurred at much lower levels of compression of the ullage.

PARTIALLY FILLED TANKS WITHIN A SHALLOW VAPOUR CLOUD

Within the cloud the degree of plastic deformation of tanks depends on the fill level and the cloud depth. Figures 11 and 12 show Tank 908 at Buncefield: this tank was completely immersed in a cloud of depth approximately 1.25 m deep. The tank experienced a prolonged ramping up of pressure as the sub-sonic explosion approached. Given the flame speed observed in CCTV records at Buncefield it is possible to show that the pressure would have risen to around 20 kPa over a period of around 600 ms. The tank had a relatively low fill level and, after a certain stage, such a high pressure could not be balanced simply by downward deformation of the roof. At this point the net pressure on the upstream face would exceed the yield pressure of the wall and it would start to fail. Once plastic failure commenced the wall would move quickly and the internal pressure would rise – tending to delay and (in the event) prevent failure of other faces of the tank.

Badly crushed objects at ground level all around the tank show that very high (but short lived) pressures were developed all around the tank at low level. These high pressures that were developed within in the cloud clearly weakened very markedly with height and this diffraction process, combined with the short duration of the high pressure shocks, meant that vulnerable parts of the tank above the fill level suffered only small permanent deflections.

These findings mirror those from the Weidlinger study of failure of wall cladding panels at the top of the Northgate building [Ref 5] which was also exposed to the Buncefield vapour cloud at its base. Again very high pressures (several hundreds of kPa) were observed at ground level but Weidlinger were able only able to explain the observed failures of cladding panels at an elevation of around 12 m by assuming that pressure at this elevation increased relatively slowly to a few tens of kPa over several hundred milliseconds. Both the timing and magnitude of the pressure ramp match those derived from observations of tank deformation.

Figure 11. Front (North) face of Tank 908 showing extensive plastic deformation

Figure 12. Side (West) face and roof of Tank 908. The weak, lightweight roof has bowed upwards at the end of the positive phase. E, W and S faces undeformed

FAILURE OF AN EMPTY TANK IN A DEEP PART OF THE VAPOUR CLOUD

Close to the overfilled tank the average depth of the Buncefield cloud was probably well in excess of 5 m [Ref 8]. The dramatic effects of explosion in such a deep layer on an adjacent empty tank (Tank 910) are shown in Figure 13. The external overpressure exerted by the approaching explosion would have rapidly exceeded the level that could be accommodated by downward deflection of the roof. Very rapid inward deflection of the upstream wall then occurred with peeling back of the base a corresponding increase in internal pressure. As the explosion reached the front of the tank very high pressures (several hundreds of kPa) would have been applied to much of the upstream wall (none of which was supported by any liquid fill). The inward wall movement and corresponding internal shock was so pronounced that the opposite wall was blown outwards, tearing vertically through the wall. This pattern of deformation is analogous to the outward deflection of the end wall in portal frame buildings but the extent of the internal compression is of course massively greater. It is worth noting that at the end of the positive phase internal pressurisation of this tank led to the roof being throw off – coming to rest around 70 m from the tank.

Figure 13. Tank 910 – the red arrow indicates the direction of explosion propagation

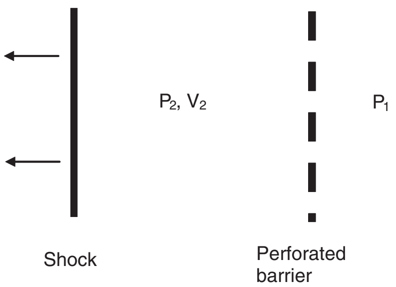
CONCLUSION

Warehouses and tanks seriously affected by the Buncefield blast show single-mode venting or ullage compression failures characteristic of blast profiles in which pressures ramp up relatively slowly. The first large-area failure mode leads to rapid internal pressurisation that prevents failure of other walls and the roof, even if the pressure continues to rise. Large area vents that are opened up in warehouse walls also allow efficient transmission of the rarefaction phase and this limits or prevents outward cladding loss and other rarefaction damage.

APPENDIX 1: Transmission of a (weak) shock through a perforated wall into an enclosure

A weak shock passes a building, establishing a pressure P_1 outside the structure. After the shock has passed and stable flow around the building has been established any dynamic pressures are small compared with P_1. The blast last a long time relative to the time for relaxation of any reflected wave.

The building has a perforated upstream wall and the external pressure drives a flow through the wall (barrier). Within the building the pressure and velocity are P_2 and V_2.



If the shock is weak

$$V_2 = \frac{P_2}{\rho V_s}$$

where ρ is the density and V_s is the speed of sound.

If the fractional open area ratio of the barrier is F and the discharge coefficient for flow through the barrier is C_d then the speed (volume flux) downstream of the barrier is given by

$$V_2 = \frac{C_d F}{\sqrt{1 - F^2}} \sqrt{\frac{2(P_1 - P_2)}{\rho}}$$

which gives P_2 as a function of P_1 and F

$$P_2 = \frac{\rho V_s C_d F}{\sqrt{1 - F^2}} \sqrt{\frac{2(P_1 - P_2)}{\rho}}$$

$$P_2 = \frac{C}{2}\left[\sqrt{1 + \frac{4P_1}{C}} - 1\right] \quad \text{where } C \text{ is a constant}$$

$$C = 2\frac{F^2}{(1 - F^2)} C_d^2 \cdot \rho V_s^2$$

For example if F = 0.3 (30% open) $C_d = 0.6$ so that $C = 10.1$ kPa and the pressures for various intensities of incident blast are given in Table 1.

APPENDIX 2: Internal shock formation behind a freely yielding wall (piston).

The case of a shock front incident on building with an unrestrained wall (piston) is illustrated in Figure 14. The pressure behind the shock is P_1. As the piston begins to move a shock is generated that propagates into the building (piston tube) [Ref 7]. As the piston accelerates the shock strengthens. The pressure immediately behind the piston is

$$P_2 \text{ (behind piston)} = P_0 + \rho; \quad C_{\text{sound}} \cdot V_{\text{piston}}$$

The additional pressure $\rho C_{\text{sound}} \cdot V_{\text{piston}}$ resists the piston acceleration and is referred to below as “shock damping”. In this case it is constant (with time) after the piston has reached its final velocity.

The net pressure on the piston is $P_1 - (P_0 + \rho C \cdot V_{\text{piston}})$

The piston acceleration is given by the first order linear differential equation

$$\mathrm{d}V_{\text{piston}}/\mathrm{d}t = P_1 - \rho C_{\text{sound}} \cdot V_{\text{piston}}$$

In the wake of a long duration shock this has the solution

$$V_{\text{piston}} = \frac{P_1 - P_0}{\rho C_{\text{sound}}}\left[1 - e^{\frac{\rho C_{\text{sound}}}{m}t}\right] = V_1\left[1 - e^{-\frac{\rho C_{\text{sound}}}{m}t}\right]$$

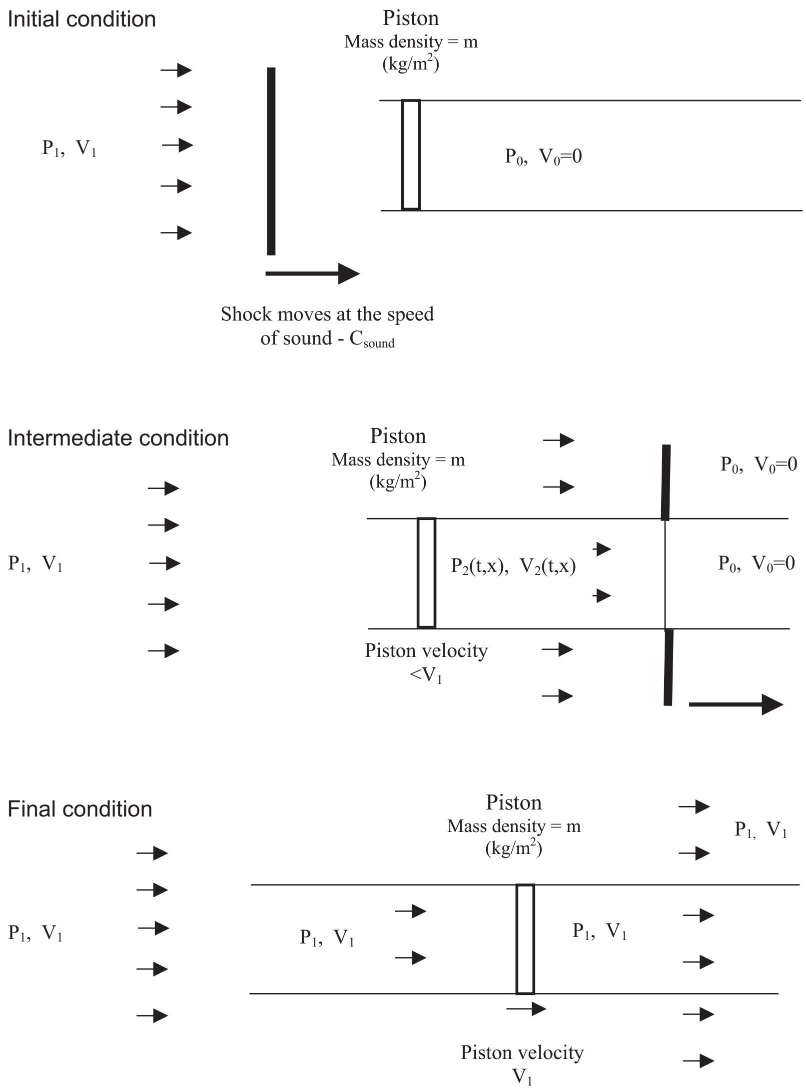


Figure 14. Schematic showing the dynamics of an unrestrained piston impacted by a weak shock

The acceleration takes a time $\rho C_{\text{sound}}/m$ (the inertial time scale) and the final piston speed is

$$V_{\text{piston}}(\text{final}) = V_1 = (P_1 - P_0)/\rho C_{\text{sound}}$$

If the duration of the incident shock T is much greater than $\rho C_{\text{sound}}/m$ then the displacement of the piston is again approximately TV_1.

It is perhaps worth noting that shock damping also rapidly reduces the speed of the piston if the pressure pulse is terminated by a rarefaction shock. The timescale is again $\rho C_{\text{sound}}/m$. The solution of the equation of motion in this case is

$$V_{\text{piston}} = V_1 e^{-\frac{\rho C_{\text{sound}}}{m}t}$$

where t runs from the time the applied pressure falls to zero.

WALLS WITH A WEAK PANEL

If the only part of a wall of a building can move (yielding area = a; total wall area A)

$$P_{\text{final}} = P_0 + a/A \cdot \rho C_{\text{sound}} \cdot V_{\text{piston}}$$

The strength of shock damping therefore depends on the proportion of the exposed face that is free to move. The final velocity of the yielding panel may exceed the fluid velocity in the incident shock.

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