Is there a bomb in your basement? Boiler explosion hazards that are often forgotten in risk assessments

Gaynor Woodford-Phillips, Senior Consultant & Miriam Lander Safety Engineer, ABB Consulting, Belasis Business Park, Billingham, TS23 4EB

The key principle of the CIA guidance for the location and design of occupied buildings on chemical manufacturing sites is that people inside permanent and temporary buildings are not at a greater risk due to their location. The assessment needs to consider hazardous events resulting in fire, explosion or toxic gas effects and check that suitable and sufficient mitigation measures have been taken to reduce risks to a level as low as reasonably practicable (ALARP).

Companies operating high hazard chemical plants have a requirement to identify all foreseeable process safety hazards and document these in their COMAH Safety report. These hazards can be used as the starting point for an Occupied Buildings risk assessment (OBRA). However, boiler explosions are often overlooked as they fall outside of the scope of COMAH dangerous substances. There are also many non-COMAH regulated companies who operate boilers that could potentially explode, and are often unaware of the need to carry out an OBRA.

Boilers are often a forgotten hazard because they are closely governed by boiler code requirements. Boilers that are maintained and operated in line with best practice would not be expected to pose unacceptable risks to personnel. However, at the same time they are sometimes seen as “architectural” features and put on display in glass fronted boiler houses, can be hidden in basements adjacent to structural supporting members for large office blocks or located close to areas of high occupancy such as a workshop.

This paper will describe inherent measures that can be considered in building and plant layout design to minimise hazards from boiler explosions as well as providing suggested guidance for companies when including boiler explosions in an OBRA. It will also consider some of the critical assumptions when calculating the likely frequency of a boiler explosion which are directly linked to operating and maintenance practices.

Keywords: OBRA, Boiler explosions

Introduction

The hazards associated with boiler operation are nothing new, since the industrial revolution introduced steam locomotives and stationary steam engines in the early 1800s there have been many boiler explosions leading to fatalities. As a result modern day boilers are now closely governed by boiler codes which provide engineering standards for all aspects of design, fabrication, installation, inspection and maintenance. Compliance with boiler codes and adherence to best practice (Health & Safety Executive 10/11) should therefore minimise the frequency with which boiler explosions occur, however they still continue to occur. A look at more recent accident statistics such as OSHA accidents reports still indicate fatalities and injuries occurring annually due to boiler explosions.

In the high hazard industries in the UK the control and minimisation of risks to personnel is the norm and Occupied Buildings risk assessments (OBRA) (Chemical Industries Association, CIA 2010) are routinely carried out, however these may overlook boiler explosions as they are generally outside of the scope of COMAH dangerous substances and non-COMAH regulated companies may not appreciate the need to consider boiler hazards and the risks to personnel when locating boilers within occupied buildings.

This paper describes the types of hazards from boiler explosions and their consequences and how they could be quantified. With an understanding of the consequences then inherent measures can be considered in building and plant design. Inherent measures can be difficult and costly to retrospectively introduce, and therefore based on CIA, 2010 guidance a method is suggested for including boiler explosions into OBRAs.

Typical boiler explosion hazards

In simple terms there are two different types of boiler explosion hazards that can be considered.

1. Loss of containment from the fired (low pressure) side of the boiler envelope e.g. due to a flammable gas mix exploding, this could, for example occur due to inadequate air purging prior to restart. These types of explosions are protected by burner management and safety systems which are closely governed by fired equipment design codes.

2. Loss of containment from the high pressure boiler envelope e.g. due to the steam exit route being blocked in with continued boiler firing or in the case of a fired tube boiler rapid expansion of water to steam e.g. when there is a sudden introduction of water on to hot fired tubes usually combined with a weakening mechanism that causes failure of the pressure envelope leading to a release of high pressure steam and/or water. Depending on the industrial boiler type, each loss of containment has different safeguards, a “slow” accumulation of pressure uses relief valves and the burner management and safety system as safeguards whereas for the rapid expansion of steam, the relief valves will probably be unable to respond quickly enough.

Consequences

Each of these boiler explosion hazards result in very different consequences. To allow any quantitative risk assessment to be undertaken there needs to be an understanding of the nature and size of the hazard assuming no safeguards or active mitigation measures are in place.

The description of the consequences for these explosion events is described below with references to potential calculation methods. There are often challenges when assessing legacy equipment or package items where there may be an absence of equipment data and approximations need to be made. Generally the calculation of the hazard ranges is fraught with assumptions which can result in the hazard ranges predicted being overly conservative.

1. Overpressure of the low pressure, fired side of the boiler envelope due to a flammable gas mix exploding

This is a physical explosion. In the case of a fire tube boiler this is likely to blow the boiler firebox doors off or eject the burner assembly as a missile, but this is unlikely to lead to the catastrophic rupture of the fire tube. For a water tube boiler, which are not generally used in commercial building environments and therefore beyond the main scope of this paper, the pressures and volumes to be considered can be much higher.

For a fire tube boiler the associated overpressure is less and the effects are more localised than the overpressure of the high pressure steam side. There is a much lower potential to damage structures in the immediate area.

After the initial failure, if all the safeguards have failed, there is still the potential for a release of fuel which could lead to subsequent flash fire, pool fire or semi confined vapour cloud explosion (VCE) depending on the type of fuel in use. Unless there is a credible VCE event or significant missile formation then domino effects are less likely.

The initial overpressure can be modelled using a ‘pressure vessel burst’ model such as suggested in CCPS, 2010. For the fired side of the boiler the burst pressure will be considerably lower and probably harder to determine because the fired side may not be pressure rated and generally the system is not blocked in and can have a significant volume if the flue and chimney system is included.

2. Overpressure of the high pressure boiler envelope

Again this is a physical explosion but in the high pressure side of the boiler causing a burst of the boiler shell which will give rise to an overpressure and an impulse which, due to the likely failure pressure, has the potential to damage structures in the immediate area and have the potential for domino effects leading to collapse of walls and ceilings.

Depending on the credible failure location there could be a release of high pressure, possibly superheated steam which if within an enclosed area could cause an oxygen depleted atmosphere, this in turn could hamper escape and cause severe burns to anyone immediately adjacent to the point of failure. If the failure location is below the liquid level on the steam drum, depending on the design, then then there is the potential for release of flashing hot water which will cause severe burns. A failure at high pressure could also lead to missile generation which could cause further domino effects.

The primary consequence of concern with respect to fatalities is the overpressure and impulse as these can cause building total or partial collapse. The overpressure can be modelled using a ‘pressure vessel burst’ model such as suggested in CCPS, 2010. Care needs to be taken when selecting a credible burst pressure and volume to be considered.

- The burst pressure will depend on the design code for the boiler shell and therefore the multiplier that needs to be applied to the shell design pressure to estimate ultimate failure pressure e.g. ASME code compliant vessel 3 to 4 times design pressure.
- Volume of vapour/liquid considered is dependent on boiler design and internal layout.

Choosing a maximum burst pressure and the total shell volume is a conservative approach but this will give large hazard ranges which may need further refinement and/or a sensitivity analysis.

However if the loss of containment is due to a rapid expansion of water to steam this is analogous to a Boiling Liquid Expanding Vapour explosion (BLEVE) without the fireball effects. The overpressure and impulse profile for a BLEVE is very different to a pressure vessel burst. After the initial overpressure effects there are other consequences that have been seen to occur, there are numerous instances where the energy released has resulted in the boiler shell acting as a directional missile, along the longitudinal axis of the boiler, e.g. Dana Corporation, Paris, Tennessee 2007, where the boiler travelled over 30 metres. The failure mechanism can also give rise to a directional jet of superheated steam that lasts for a very limited duration but will cause a fatal injury to anyone in the line of fire.

The overpressure effects can be approximated by using BLEVE methods such as suggested in CCPS, 2010.

- The pressure at which the “BLEVE” occurs is a matter for debate, generally the steam relief valves cannot act quickly enough to prevent the over pressure resulting in failure. Some incident investigations have shown that localised overheating on low water level combined with the stresses associated with the rapid water expansion to steam leads to failure of the furnace tube and the expanding steam is released from the boiler on the low pressure side usually via the boiler firebox doors as these are effectively the weak point of the system i.e. the “burst” pressure is closer to the fired side than the steam side design pressure but as explained in (1) above this may not be easy to define.

- The volume of liquid available to expand needs to be approximated and relies on having information about the boiler including the internal layout, so that the minimum liquid level that exposes the furnace tube can be calculated.

It should be noted that the using the high pressure shell design conditions as the BLEVE pressure results in overpressures that are extremely conservative especially when compared with historical incident reports for fire tube boiler explosions.

Fire tube boilers are widely used for providing steam for process and commercial heating and can be located in buildings with large numbers of occupants. This can lead to them being located in basements (out of sight) which could be near critical supporting structural members or, if located at ground level the directional effects need to be considered. In the UK Architects and Building Service Engineers would generally not favour locating them in buildings and basements, however there is no specific building regulation that prohibits industrial boilers from being located in high occupancy buildings.

Given the directional effects of this mechanism when considering the consequences it is vital that the "line of fire" along the longitudinal axis of the boiler is considered, and therefore it should be assumed that up to 100m along the longitudinal axis is impacted by a missile or directional jet which should be assumed to demolish non strengthened walls.

In summary of these two events (2) overpressure of the high pressure boiler envelope will dominate the hazard ranges with rapid expansion of water to steam and failure of the high pressure envelope giving the largest hazard ranges.

Risk reduction Measures

Inherent

Having indicated some of the challenges associated with determining the extent of the hazard ranges associated with boiler explosions it is often simpler to consider inherent measures if possible.

The simplest way to employ an inherent measure to reduce the risk is to separate people from the hazard. Boiler rooms are generally not occupied areas except during maintenance and potentially at start-up. Given that start-up can often present a greater risk consideration should be given to the feasibility of a remote start-up facility.

If a boiler is located within an occupied building the number of occupants should be minimised and ideally there should be no individuals exposed to the hazards. In commercial premises (non-process plant applications) this is often a non-credible option, as the boiler may provide the building heating source.

During the design phase of a fire tube boiler installation thought should be given to the layout and the longitudinal orientation of the boiler to ensure that the "line of fire" is not directed at vulnerable areas. If there is a release of a directional steam jet, although it may be a short duration event and the length of the steam jet is difficult to predict, the orientation should avoid being longitudinally directed at pedestrian thorough fares or any areas with a low frequency but high population density.

Prevention and Control

If a fire tube boiler is already operational within a building there are specific vulnerabilities to bear in mind when assessing the likely consequences and possible control measures.

If the boiler acts as a missile, what would be impacted within 100 m of the line of fire?

- Is there a control room or control station? Can it be relocated?
- If the boiler exits the building are there any occupied areas including pedestrian thorough fares or areas where there is a low frequency but high population density? Is it credible to divert pedestrian thorough fares?
- If located at ground floor level are there any car parking or loading areas which if impacted could lead to vehicles becoming additional projectiles? Can parking/waiting in the exposed areas be banned?
- If located on process plant are then any vulnerable inventories or process equipment which if damaged could lead to a major accident hazard? Relocating equipment is unlikely to be a credible measure.
- If located in a basement the construction of the floor can it be redesigned to prevent collapse? Again this is likely to be a costly option.
- Are there any critical structural supporting members that could be impacted? It is unlikely that these can be retrospectively strengthened without significant expense, it may be possible to consider whether safe explosion venting from a building is credible

Domino effects

If the boiler is an existing installation and the orientation and location are fixed there needs to be some consideration of the domino effects resulting from a boiler explosion.

When considering the domino effects both over pressure and where relevant "line of fire" impacts need to be considered. As with most occupied building risk assessments the dominant consequences, that will cause the largest number of fatalities, are events which can cause supporting structures to fail resulting in floor and ceiling collapse trapping and killing occupants.

Traditionally OBRAs look at process hazards where the explosion overpressure acts on the external walls of a building not acting outwards on the internal walls, intuitively this would appear to be a worse scenario. A boiler located in a basement could "retain" the over pressure i.e. if no venting route. Boilers located above ground and within a building as a worst case would retain the overpressure but doors or windows are likely to be blown outwards reducing the consequences of an overpressure by effectively "venting" the overpressure. The effects of the overpressure on the building structure would need further assessment depending on the construction methods used.

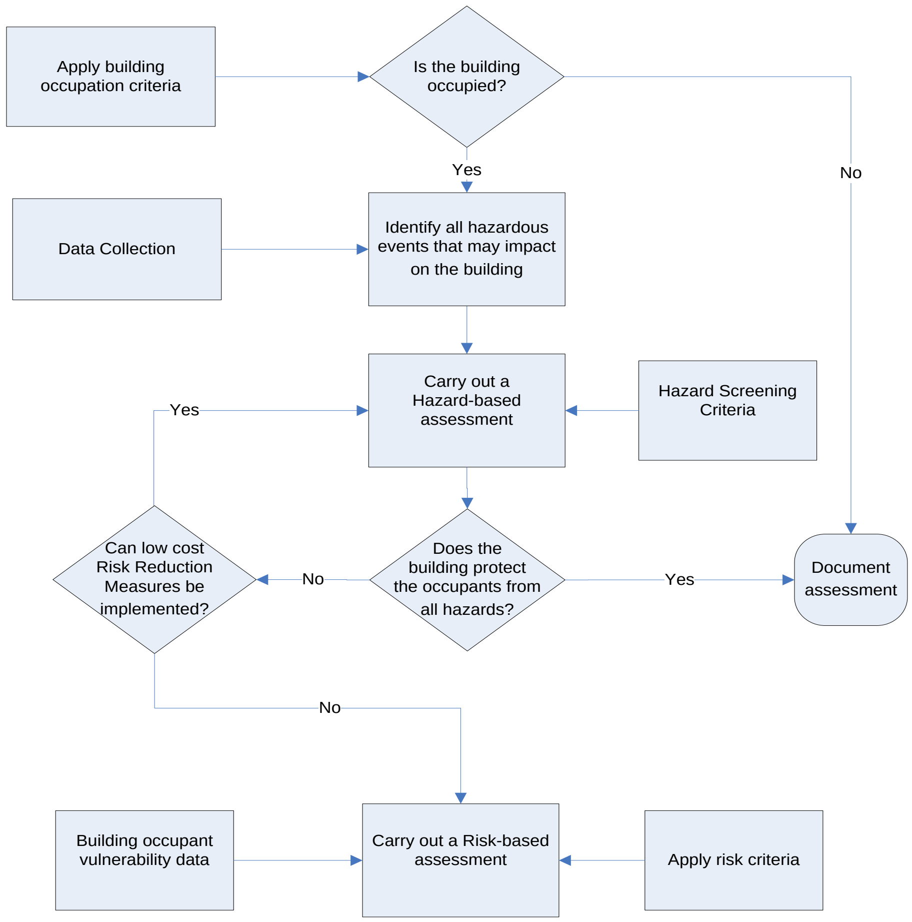
- Overpressure can lift concrete floor sections which are then dislodged.
- Overpressures that are 'retained' can amplify the overpressure by reflection off walls
- If a fire tube boiler: will any "missiles" impact on critical support mechanisms

Structural assessment methods are beyond the scope of this paper, particularly when considering overpressures "retained" within buildings. The conservative assumption is that the building collapses and all occupants are injured. However there are methods available which look at the vulnerability of occupants within buildings from the effects of external blast effects CIA 2010 and Mays and Smith 1995 but these methods need to be treated with some caution.

OBRA

If it is necessary to include boiler explosions in an OBRA the Occupied Building Risk Assessment method in CIA, 2010 can be applied but given some of the uncertainties identified in the consequence prediction a pragmatic approach is required. The CIA, 2010 method was developed for applying to process hazards and occupied buildings on chemical manufacturing sites and the steps are shown in Figure 1. For each building in turn it is necessary to identify all the hazardous events that may impact on the building and then carry out a Hazard Based Screening exercise for which screening criteria are required. Any buildings that cannot protect the occupants from the hazard are then carried forward to a Risk based assessment for which event frequency, vulnerabilities and numbers of occupants are required.

Figure 1 Overview of occupied building assessment methodology



Hazard Based Screening

CIA 2010 provides some often applied benchmarks as suggested screening criteria for the hazard based approach but as discussed above boiler explosions can give their own particular hazards that need screening criteria. Table 1 below suggests hazard screening criteria for use with boiler explosions when carrying out the Hazard based OBRA screening.

Table 1 Hazard screening criteria for use with boiler explosions

Hazard	Criteria	Comment
Explosion	0.725 psi (50 mbar)	Derived from Appendix 2 – Figure A2.1 of the CIA 2010. This figure shows that a 5 kPa (0.725 psi) explosion overpressure represents a vulnerability to an occupant of all typical building constructions of less than 0.01.
	0.4 psi (30 mbar)	All buildings within the 30mbar (0.4 psi) overpressure range should be reviewed in terms of vulnerable windows. Table 4.1 of the CIA 2010
Fire tube boiler directional failure	100m	The damage due to a directional release from the boilers can be determined by the line of fire from the longitudinal axis of the boiler, specifically from the boiler doors, which are a known weak point on the boiler. When identifying the vulnerable occupied buildings for a directional release, it is assumed that if the boiler is in the basement, the pressure is “retained” and the building is affected by overpressures. If the boiler is on the ground floor level and there are external building doors or non-strengthened windows in the line of fire from the boiler it is considered that the directional release could ‘escape’ the building and no overpressure effects are experienced. The building that contained the boiler is considered to be reasonably unaffected, but there is the potential to impact on other buildings in the line of fire.

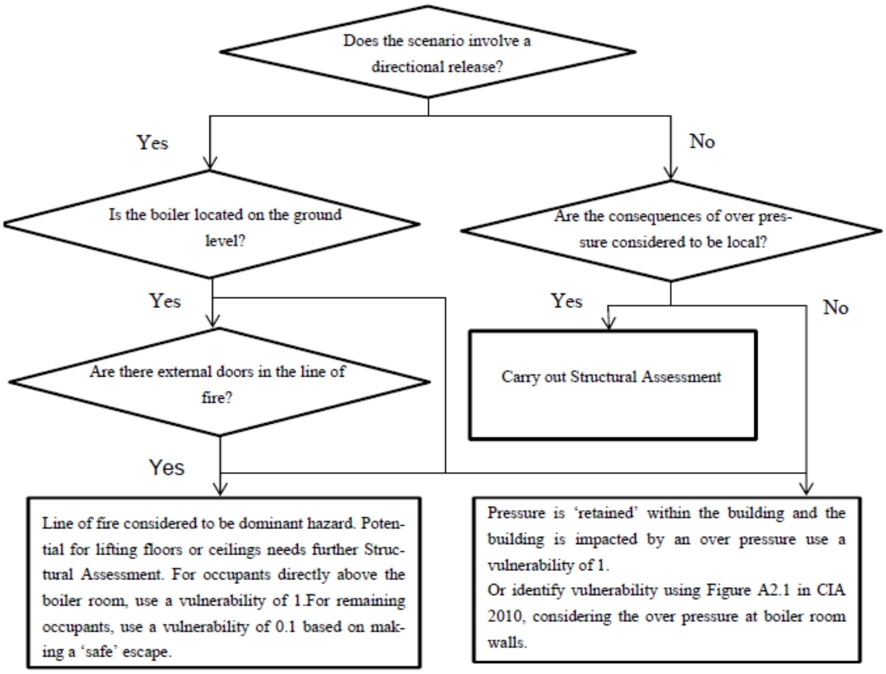
Risk based assessment

The risk based stage of an OBRA requires the frequency with which the hazards arise and an estimate of the building occupant vulnerability.

The frequency with which the hazards arise should be relatively easy to obtain given that the two types of explosion have a safety instrument function as safeguards. If IEC 61508 (2010) or relevant sector standard has been applied then there should be safety integrity level (SIL) requirement definition or achieved SIL, and depending on the method used to calculate the SIL requirement it should be possible to deconstruct the assessment to calculate an event frequency. In the absence of any SIL calculations then further root cause analysis may be required to determine the event frequency. If there is compliance with best practice then the event frequency for a boiler explosion will be in the region of 10^{-4} to 10^{-6} per year i.e. the risk is tolerable and could be considered ALARP if supported by an ALARP demonstration. However event frequencies will need to be increased if there is known degradation of safeguards. Carrying out an audit against good practice HSE10/11 can be useful to inform the variables to be considered in a sensitivity assessment on the risk calculation.

The occupant vulnerability can always be conservatively assumed to be unity for a building which contains a boiler however if there is a large number of occupants affected the aggregated risk of fatality can be significant, which is always likely to drive the need for a more detailed structural assessment. Figure 2 below suggests a decision making guide for occupant vulnerabilities that can be applied to boiler bursts.

Figure 2 Flow sheet outlining approach to identify vulnerability within occupied buildings for boiler burst scenarios



Conclusion

There are two types of boiler explosion and the hazard ranges are dominated by (2) overpressure of the high pressure boiler envelope. Modelling the consequences of boiler explosions is not an exact science and relies on detailed information on the boiler design and construction.

It is possible to incorporate boiler explosions into Occupied Buildings risk assessments but the assessment is likely to demonstrate that the risk is "Tolerable if ALARP" unless there are known failings against boiler codes or best practice. Therefore ensuring that operating boilers continue to comply with boiler codes and best practice throughout their operating life are the essential and most cost effective methods of risk control.

Building designers should be encouraged to consider the application of inherent safety and then the prevention and control measures described in this paper where boilers are to be located within high occupancy buildings. The real question remaining that remains unanswered is should boilers be located within high occupancy buildings at all? Particularly when in some countries such as France locating industrial boilers in occupied buildings is prohibited by regulation.

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