MAJOR HAZARDS OF NATURAL GAS STORAGE

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INTRODUCTION

Ever since coal gas was developed as a source of heat and light in Victorian times, we have needed to store flammable gas, to balance out the pattern of supply and demand, which varies sharply over the course of a single day, as well as from summer to winter. When the UK moved away from coal gas during the 1960s to using natural gas, a different range of issues arose in connection with gas storage. Towns gas used a large number of local production sites, each with their own small scale low pressure storage, while natural gas was imported from a relatively tiny number of sources and a national grid of pipelines had to be constructed, operating at much higher pressures and with it, a small number of much larger storage units, largely for peak shaving of the demand.

For the last 20 years we have mainly used gas from the North Sea, and smaller reserves from UK gas fields elsewhere, but as these supplies become exhausted, the gas industry is having to look to gas from much further afield to keep our homes warm, industry operating and to generate electricity. Some of the new supplies are coming by sea from the middle east as liquefied natural gas (LNG), while other supplies are coming from Norway and Central Asia in high pressure pipelines. The form in which the gas is transported influences the method of storage. Whether the gas comes by sea or pipeline, there is a need for additional storage in the UK, and from a low base, a substantial expansion in the storage capacity is now being planned or constructed.

This paper looks at the range of storage technologies now in use, and in particular the expansion of salt cavern storage, from a safety perspective.

LOW PRESSURE STORAGE

The oldest technology used for gas storage, was in low pressure gas holders that were developed for storing towns gas, from Victorian times. There are a number of different designs, but from the safety perspective, I think they split tidily into the types that rise and fall, as the volume of gas inside changes, and the waterless, MAN or Wiggins type that were always less common, but which are very prominent, because of the fixed shell that encloses the internal piston.

The Wiggins type, based on a design from 1951 are still being built at steelworks and elsewhere, for holding gas at low pressures. They clearly have the potential for gas to escape around the piston, and fill the casing above with a gas air mixture, with the risk of a confined explosion but lack of data and interest in these means they are not considered further in this paper.

The hazards of watersealed gas holders have been back in the news in recent years, as a consequence of two planning appeals in London, where HSE advised against development and gave evidence about the hazards, and how they derived the consultation zones.

The gasholders next to the Kennington Oval cricket ground are a familiar landmark, with the largest dating from 1878. The owners of the cricket ground proposed reconstructing three stands with 1830 additional seats, and a new 168 bed hotel within the consultation zones for the gas holders. The proposal was rejected, but at a subsequent appeal, planning permission was allowed in June 2009 and development will go ahead.

HSE had originally set consultation zones around low pressure gas holders of 60 m. This figure came from an analysis of seal fires and the calculated consequences an internal explosion, but following the introduction of COMAH in 1999, and a review by Transco of incidents and failure mechanisms, the advice changed. New potential failure modes were analysed, including decoupling of the sections, crown failure and escalation from a seal fire to a large fireball. One of the more uncertain factors in any analysis is the probability that a major release will ignite. This was disputed at the planning enquiries, but HSE's best estimate of a 0.5 chance of ignition drawn from 6 major gas release incidents was accepted. The planning advice is now based on the consequences of a decoupled seal causing a large sudden release which ignites after a delay followed by a fireball which ignites 50% of the maximum capacity of the gas holder, and total collapse leading to loss of 100% of the gas contents .

The incident history of such units is actually good, with major fires in 1912 (Ilkeston, seal decoupled), 1927 (Manchester, two holders collapsed following seal fire) and Mytholmroyd (1929, roof buckled and failed), and unignited releases in 1919 (Port Glasgow, major roof failure), 1922 (Ashton u Lyne, decoupling of sections) and a further poorly documented incident mentioned in the 1912 report. There appear to have been no serious fire incidents since 1929, apart from a terrorist attack on a gas holder in Warrington in 1993, despite a population of 5000 or more such holders which were dotted for decades all across the country.

There are interesting issues relating to the public perception of risk here. Low pressure gas holders have been familiar in the urban scene for over 100 years, and they never seem to have caused public concern. Smaller gas releases that do not ignite are scarcely news, and such big incidents as there have been are long forgotten. There is in consequence a credibility gap, when analysis shows the hazard radius from some of the largest gasholders can now extend to over 600 m, and hence cover 113 Ha from a single gas holder (see Table 1). That is a lot of land in an urban area.

Table 1. Hazard ranges low pressure storage

Consultation zones for planning purposes	Gas holder 1	Gas holder 2
Inner zone fireball radius	120 m radius for largest holder 113 t	233 m
Middle zone 1000 tdu	270	510
Outer zone 500 tdu	360	693

In the event, HSE's recommendation to turn down new development at the Oval cricket ground was not accepted at the called-in planning inquiry, mainly because the gas holder is likely to be at less than full capacity during the times when the Oval had a cricket match that attracted a sellout crowd. The development of a new hotel within the hazard zone was accepted by the minister.

The opposite view prevailed more recently, when proposals came in for extensive new development and two tower blocks, close to the gas holder in Wandsworth High St, London. The planning inspector's report was published in March 2010. HSE quite understandably observed that the developers proposals took no account at all of the risks from the gas holder, and that evacuating tower blocks which perhaps had multiple fires started by a single incident at the gas holder was an unreasonable risk.

Thermal dose units (tdu) combine radiation intensity with time for short duration incidents. At 1000 tdu there is a 1% fatality risk to the general population, at 500 tdu there is some small risk to vulnerable groups.

SALT CAVERN STORAGE

The use of specially constructed salt caverns for gas storage is not a new technology, with the earliest examples found in America from the 1950s.

In the UK however the only existing salt cavern sites for natural gas are at Hornsea, and a small but slowly expanding site near Middlewich are in current operation. However, there are two big new projects under construction near Northwich,

The application of health and safety legislation to these sites is intricate. Because the salt caverns are created from a borehole, the Boreholes Directive applies, and this has requirements relating to abandonment. So a borehole remains subject to the directive until it is finally sealed. To avoid overlapping legislation, the Seveso Directive implemented as (COMAH) contains an exemption for any site subject to the Boreholes Directive. So the natural reading of the regulations is that salt cavern storage falls outside COMAH. HSE has decided, seemingly without serious challenge from any source, that this is illogical and decided to treat the depleted field storage/caverns, pipelines and processing plant as a single COMAH site. This brings in the gas processing plants which have an inventory of only a few tonnes and elsewhere would be outside the scope of COMAH, but on the other hand excludes the pipelines between the wellheads and the gas processing area from the requirements of the Pipelines Safety Regulations (PSR). Consequently HSE loses the right to insist on six months prior notification before construction, and a few other detailed requirements from PSR. This interpretation of the legislation encompassing wellheads and a processing plant scattered across a few kilometers of farm land perhaps ought to have some limit if the pipelines become extended across land where the operator does not have full control, as is the case with normal pipelines.

The technology is essentially simple to understand, but slightly daunting in scale. A well is sunk into a strata of rock salt, and a concentric pipe inserted into the main bore. Water is pumped down the hole, and dissolves the rock away, so brine is extracted from the annulus of the well. Over a period of months a cavern forms, and the shape can be controlled to some extent by suitable adjustment of the solution mining process. A variant uses separate wells for water injection and brine extraction. The size of the developing cavern can be calculated by measuring how much salt has been extracted, and the 3D shape can be determined by echo sounding techniques from a probe inserted into the cavern. The typical cavern size at completion is 300,000 m^3, but some caverns up to twice this size are being brought into service. A single cavern of 300,000 m^3 size holds around 15 kt of gas at 70 bar. In comparison to steel pressure vessels, these really are huge volumes and quantities of gas. Geomechanical analysis of the stability of the completed cavern is used to demonstrate that the shape is stable, and assign a minimum operating pressure, that will prevent or minimise incremental spalling of the walls.

In safety terms, underground storage has some important benefits; the containment system is immune from external fire attack, and is there is comparatively little to show at the surface.

No secondary containment system is possible, however, which means that the rock salt deposits have to be very carefully evaluated before use. Rock salt is chosen as a strata for gas storage for three reasons; the ease with which storage caverns can be created from the surface by solution mining; the very low permeability of the rock to gas or liquid migration, and the property of halite rock to flow under pressure, which means that minor cracks seal, and wells drilled into the rock do not depend on the cement around the well string alone to make a gas tight seal.

Proving the suitability of the rock salt strata for gas storage is done by seismic studies, trial bore holes, and laboratory testing of rock samples extracted from within the rocksalt layer. Geological data always has residual uncertainty, and it is inherently difficult to prove the negative, that there can be no flaw in the rock where caverns are to be constructed. Drilling multiple bore holes is liable to create more potential routes for gas to escape. To some extent, the proposals for salt caverns at Preesall, Lancashire fell into this trap; enough doubts were raised by the local protest group and the geologists' evidence was conflicting. Planning permission has been turned down twice.

Operating pressures of salt cavern storage depend on depth, and may be above or below the pressure in the National Gas Transmission system (NTS), at different times in the operating cycle. Minimum operating pressures tend to be relatively high, to ensure the stability of the cavern. One parameter that has been used to set the maximum cavern pressure is the overburden weight, the pressure from the gas on the roof must not exceed a set fraction of the downward force from the overburden.

The tendency of rock salt to creep means that if the pressure is marginally too low, the cavern will tend to contract, but this is not an immediate hazard. However, if the pressure is seriously too low, the roof is liable to spall, because the rock is not strong under tension. Some spalling over time must be anticipated, but this can be checked by periodic repeats of the echo sounding analysis of the shape. Complete loss of gas pressure would, over a period of days or weeks or perhaps months, in most cases lead to collapse of the cavern, and eventually a crater at the surface. Some examples of this exist within the Preesall salt field, from very old workings developed for salt extraction alone. Minimum safe operating pressures can be established using geomechanical analysis of the shape of each individual cavern.

Analysis of the worst case scenarios associated with salt cavern storage need to consider release from the surface, or from a fracture of the riser pipe between the top of the cavern and the ground level. Provided the geologists and geomechanical specialists have done their analysis correctly, and the cavern remains stable, and leak tight, the only source of gross release of gas is through the riser pipe itself. The consequence of a serious failure at the wellhead is a high velocity gas jet, which if ignited would produce a large jet flame. This could be vertically orientated, or if a side arm of the Christmas tree fractured, a horizontal release at or just above ground level is possible. The flow rate of such releases is however limited by the vertical well riser or connecting pipework at an individual well head. These have a diameter of 250 mm or less.

Table 2. Hazard ranges from release from a salt cavern production well

Scenario modelled	Conditions	Distance to metres		
Release		12.5 kW/m^2	6.3 kW/m^2	LFL
Vertical	45 bar 225 mm pipe D5 weather	52	86	Not reached
Horizontal	45 bar 225 mm pipe D5 weather	145	164	142
Vertical	95 bar 220 mm pipe D5 weather	65	95	2
Horizontal	95 bar 300 mm pipe D5 weather	335	375	200

Modern plant design includes a subsurface valve, which should prevent complete loss of pressure in a cavern from any event at the surface, and in addition multiple valves at the wellhead Christmas tree. Instead of 3 zone maps as produced by HSE, the hazard ranges in Table 2 have been derived by Haztech colleagues who modelling ignited and unignited releases using PHAST software.

The 12.5 kW/m^2 contour represents the range at which external wooden parts of buildings can ignite after prolonged exposure. A radiation intensity of 6.3 kW/m^2 is considered the limit for escape from buildings, exposed skin will rapidly cause pain.

The duration of these scenarios depends on the time taken for automatic closure of the valves in the system. Compared with cross country pipelines, the isolatable inventories tend to be small, and if the valves operate correctly, any jet flame or gas release should last only a few minutes.

Although the typical cavern size is large, in the range 300,000 to 600,000 m^3, the economics of the development mean that these are never developed singly, instead the smallest site has 4 such caverns with 10 more planned. The largest of the facilities under development has a planned capacity of 700 kt but this will take 5 more years to complete. The consequence of this, is that sections of the pipelines connecting the different caverns to the processing plant often have larger diameters than the riser pipe of an individual well, up to 750 mm. Analysis of major accident scenarios show that those with the greatest hazard range result from complete rupture of a large diameter pipe, rather than failure of the pipework at the wellhead. In this event, gas would be released from both ends of the pipe. In normal operation the valves to a multiple of caverns could be open at the same time, so the flow from the well direction is not then limited by the diameter of a single well riser. In addition the large diameter main will be connected to the gas processing plant and no throttling effect is likely.

All salt cavern storage facilities need a high pressure compressor and in addition dehydration units, as gas will pick up water from residual brine at the bottom of a cavity. Large jet flames from gross failure of above ground pipework need to be analysed for the major accident potential. Further hazard ranges may also arise if the gas processing plant has sufficient congestion to allow explosion overpressures to develop following a gas release.

LIQUEFIED NATURAL GAS

LNG is characterised by a developing technology, and a diversity of tanks designs, which influence the major accident potential. Back in 1978, at the time of the Canvey Island report, British Gas operated 6 above ground tanks, each of capacity 4 kt, and 4 underground tanks each of capacity 20 kt. A ship load then was 12 kt. The gas at that time came from North Africa; new long term supplies to the UK are now secured from the Persian Gulf.

The new wave of construction in the UK is all of above ground tanks, and the tanks at two sites in Pembrokeshire are all around 70–75 kt capacity. By comparison a shipload of gas is now 67 kt. Japan is the leading user of LNG, and they have adopted other designs of storage facility, with an in-ground design, showing only the roof dome above ground level. This is seemingly the preferred option and the largest tank now has a capacity of approximately 92 kt.

The oldest designs of above ground tanks used earth bunds as secondary containment, but this was superseded by concrete outer tanks as high as the inner tank. Modern standards are now described in BS EN 1473 and 14620 which distinguish between double containment, full containment and membrane designs.

Double containment types retain liquid lost if the inner tank fails, but do not contain vapour which is subsequently released. Full containment tanks have a roof covering the secondary tank which is vapour tight and which is designed to release vapour in a controlled way, through a pressure relief system. Membrane tanks have a comparatively thin inner tank, with its own vapour sealed roof. The load from the inner tank is carried via loadbearing insulation to the outer tank which has its own closed roof, with pressure relief. What is clear is that major hazard considerations have not yet forced the adoption of one design over the alternatives and available data suggests the same catastrophic failure rate for double containment, full containment and membrane designs of tanks.

The oldest LNG tanks in current use in the UK were provided for peak shaving; all the recently constructed tanks are associated with import jetties. Tank construction details were not readily available.

The hazards may come from a variety of scenarios, and are much more complex than a high pressure gas jet to model, but much work was done in the 1980s. In the event of a major spillage, the evaporation and dispersion of LNG is a multistage process, with a liquid pool evaporating quickly at first where the ground is warm, then more slowly as the ground cools. Gas dispersion alters as it warms up. The cold gas can generate clouds capable of exploding where there are confined areas, as well as flash fires.

Gas within a storage tank can from discrete layers where the product from different batches has a different composition and density. This creates a roll over risk, which can cause the boil off of large amounts of gas over an extended period, and elaborate controls are needed to prevent this. Despite the complexity of the technology of controlling storage at −160 °C, major incidents in the UK are relatively few.

These hazard ranges are composites based on both thermal radiation and blast overpressure, as analysed for specific sites by HSE (see Table 3). It is assumed that the analysis used the computer model GASP for the source term, but a recent research report published by HSL reviews 18 different models that have been developed to calculate the source term for gas formation following an LNG spill. Full details of the methodology used by HSE to generate their advice to planning authorities around these LNG sites have not been made available.

Table 3. Hazard ranges from LNG storage

	Old peak shaving plant tank at 28.5 kt	Modern import terminal tank size 71 kt
Inner zone radius 1800 tdu/600 mbar	137 m	134
Middle zone 1 cpm (1000 tdu/1140 mbar)	300	190
Outer zone 0.3 cpm (500 tdu/70 mbar)	575	270

GAS PIPELINES

The grid of natural gas pipelines which operate in the main at a maximum pressure of 75 bar act as a form of storage, as the pressure can be allowed to fall during periods of high demand. The pressure can be allowed to drop in many cases to 45 bar, without causing downstream problems. From a safety point of view, buried pipelines are safer than pressure vessels on the surface, which are used in a few places for gas storage, but there remains a risk that must be managed of damage by third parties. The potential for disaster was shown by the pipeline explosion at Ghislenghien, Belgium in 2004. A nominal 80 bar pipeline was apparently damaged by excavation work, and started to leak somewhile later, when the pipeline pressure was being raised. Evacuation was delayed and had not been completed when the pipeline ruptured. The eventual death toll was 24. Media reports suggest a major section of pipe was ejected 150 m from the point of failure. More recently in September 2010, failure of a 750 mm gas main at St Bruno California resulted in 8 deaths and 53 homes destroyed. The pipeline was 60 years old, and it appears that buildings had been constructed very close to the route in the intervening years. No official reports were available as at October 2010.

In the UK Hazard ranges for pipelines are expressed as a building proximity distance (see Table 4). These are set out in IGEM code TD1 and BS PD 8010. PD 8010-1 contains a formula which allows the hazard range for a pipeline to be calculated as a function of the fluid type, diameter and pressure. The basis for this is elaborated in PD 8010-3, and is essentially risk based. Key inputs are the failure frequency of the pipeline, the probability of ignition and the consequences following immediate or delayed ignition. PD

Table 4. Hazard range from high pressure pipelines

750 mm pipeline/100 km length	
Inventory at 75 bar	2460 t
Inventory at 45 bar	1410 t
Building proximity distance for 75 bar	65 m
Land area affected	650 Ha

8010-1 recommends that the distance between a pipeline and an occupied buildings should not be less than the individual risk contour for a risk of 10^{-5} pa.

DEPLETED FIELDS

This superficially is the most attractive technology for gas storage. The structures necessary for storing gas already exist, and its integrity has been proved over geological time, not a few hours or days as you might test a tank or salt cavern. That does not reassure local residents when planning proposals are put forward, and permission to develop a site near Bridlington only went through on appeal. There are however, comparatively few suitable sites in the UK. Less attractive commercially are the limitations on the rate at which gas can be injected or withdrawn.

From a major hazards perspective, a depleted field gas store seems to have some very significant positive features; invulnerable to external fire attack, little on the surface vulnerable to damage, no risk of ground collapse in the event of complete loss of pressure. As with salt caverns, comparatively small diameter boreholes are used, which limits the maximum gas flow rate in the event of complete rupture at the surface.

A particular feature of these depleted fields is the high pressures used, which relate directly to the depth of the porous strata. Moveover, forcing gas into porous rock is slower and requires higher pressure differentials than injecting gas into a simple salt cavern. That implies for some of the deeper strata used a surface pipeline between the compressor and wellheads running at double the pressure of the NTS, and of larger diameter than any of the bore holes. The occupied building separation table in IGEM TD1 for natural gas pipelines extends only to 100 bar.

These hazard ranges (see Table 5) are taken from the map provided by HSE to the local planning authority for a specific site currently in operation, other information is taken from documents submitted to the planning authority by the developer. The model and input data used to calculate the thermal contours has not been made available.

In fact the major accident hazard scenario with the greatest hazard range is likely to be a jet flame from failure of the link line or an explosion at the compressor station and not from the wellhead itself, despite the fact that this probably contains less than 2 t of gas.

Table 5. Hazard range depleted field gas storage

200 kt stored gas/ 168 mm riser pipes	Hazard range m	Operating pressures
200 kt stored gas		Upper storage strata injection pressure 128 bar Lower strata injection pressure 160 bar
Inner zone (1800 tdu)	700	
Middle zone (1000 tdu)	750	
Outerzone (500 tdu)	1000	
Building proximity distance 220 mm pipeline/160 bar	45	

CONCLUSIONS

This short review of the technologies used for natural gas storage started with an observation that the range of technologies used for natural gas storage was much more diverse than for other hazardous products. Major Accident Hazard ranges for even the old, low inventory forms of storage, with less than 150 t of gas extend to more than 600 m. More modern forms of gas storage can hold over 1000 times as much gas, but produce hazard ranges not much greater.

1. People feel comfortable with a technology which has been visibly prominent for over one 100 years, like LP gas holders. With no headline hitting examples of casualties from a fire involving these units in the UK in the last 80 years it is inevitably difficult to convince people of the potential for a major accident.
2. It is never easy for HSE to find the right time say that a facility that has been in use for decades is no longer acceptable, when nothing very obvious has changed, except that available technology has moved on.
3. With salt cavern and depleted field storage, the hazards do not scale with quantity, the worst case scenarios depend more on releases from surface equipment.
4. Diverse LNG storage designs remain popular, and are seen as acceptably safe, but perhaps we should establish what, in safety terms is the best available technology, and press for this to be used.
5. COMAH criteria based on weight alone are a very crude basis for assessing which sites pose the most serious MAH potential.
6. Gas storage in densely populated urban sites makes little sense.

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Hazard ranges quoted are taken from 3 zones maps produced by HSE for land use planning purposes. The author was asked not to identify the specific sites to which the ranges quoted apply.

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