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Hazards to water resources and life safety from exploitation of onshore wells by hydraulic fracturing

Abstract

This article addresses risks of damage to surface and ground water, and safety of operating personnel and the general public. It includes the experience from the exploitation of shale hydrocarbons in USA, Canada and China, as applicable to the conditions in the United Kingdom and elsewhere. The accident and pollution rates in drilling, fugitive methane and water pollution in these countries are significant and widely reported and need consideration in relation to proposed activities in UK and other countries. The article gives detailed explanation of the failure mechanisms that have led to accidents and pollution incidents overseas and may apply to UK and other countries. Much reference is to authors in USA and China and it is shown that the hydraulic fracturing operation itself is a major cause of well integrity failures that are not normally present in conventional onshore oil and gas exploitation sites. Methods used for the conventional sites can be applied selectively, but differences are not well covered in existing UK guidance or elsewhere. Significant amendments are proposed in the article. Hydraulic fracturing inter-acts with geology faults, which cannot be predicted, prevented, detected nor mitigated, and must be prohibited as such. The US experience cannot be applied in this aspect as the density of faults in UK is four-times higher than in US, and also the density of population, infrastructure and facilities are much higher in UK than in US. The hydraulic fracturing activity also increases the risk of loss of life of operation personnel and general public, whereas the three highest risk types are associated with transportation, contacts with equipment and fire and explosions. The objective of the article is to take a whole picture view as it is the interaction of factors that is key to the overall hazard. It explains the problem, describes the method of solution of the problem, the verification of the solution method, the solution itself with results, conclusions, recommendations and references. It presents the simulations of multi-physics, non-linear thermodynamics and strength behaviour of key process equipment. The article also briefly outlines the methods of holistic semi-quantitative risk assessment and the design of Safety and Environment Critical Elements and Barriers. It is pointed out that the findings in relation to risk of well leakage can apply also for carbon dioxide sequestration. This is due to the currently favoured practice of injecting cold liquid carbon dioxide into reservoirs that may have high temperature rocks. On the subject of computational intelligence, it is recommended that the thread of computational intelligence be interrupted by audit points, at each of which, the parallel safety management system (SMS) can control and amend the parameters of the thread. This is to cover for inherent risk uncertainties identified in the SMS process.

Keywords: hydraulic fracturing (fracking), hazards during drilling, fracturing, production and decommissioning, failure mechanisms, faulting, seismic risks and fracking, environmental risks and risks associated with transportation, contact with equipment and explosion and fire risks, response to accidents**,** computational time simulations of accidents and mitigations

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Introduction

This article addresses risks associated with the exploitation of shale hydrocarbons. The risk of damage to surface and ground water is the primary objective but the article also considers safety of operating personnel and the general public. It follows the publication of a web learning programme by the authors, which is available online to members of the Institution of Civil Engineers,[1] but looks further into the hazards aspect.

This article includes the experience from the exploitation of shale hydrocarbons in USA, Canada and China, as applicable to the conditions in the United Kingdom. The accident and pollution rates (drilling, fugitive methane and water pollution) in these countries are significant and widely reported by Environmental Protection Agency.[2] and need consideration in relation to proposed activities in UK and other countries. The fatal accident rate within the industry in USA is 7 times the USA industrial average.

The risk is considered at the exploration (or production) well, sub-surface environment, transport to disposal site, disposal site and cleaning (e.g. of fracturing water and produced water). This article focusses on the following:

Hazards to water resources and life safety at onshore shale oil and gas production sites and associated downstream activities. Hydraulic fracturing takes place at such sites and 62% of the wells drilled each year in USA are hydraulically fractured "fracked".

As there is a lack of published information on the overall activities undertaken at hydraulic fracturing sites in UK, the article includes the background to the industry and a summary description of drilling and hydraulic fracturing as applied onshore leading on to pilot and full production phases and decommissioning, and discusses briefly the problems of potential subsequent use of fracked wells for carbon sequestration. The application of computational methods is in simulation of the behaviour of equipment and personnel. The bulk of this article is devoted to a review of hazards associated with onshore oil and gas wells where hydraulic fracturing takes place.

Much of the information on production methods and accident rates is obtained from USA sources as this is where the majority of the experience lays. The practice is largely new to the UK, which has hitherto seen conventional oil and gas production from porous reservoirs at Wytch Farm in Dorset where the largest onshore oil and gas field in Western Europe has been exploited. 200 wells were used (including injection wells), but with only a few undersea legs fracked to enhance recovery.

It will be shown in this article that the risk to environment and persons is much higher at sites where fracturing takes place than with conventional oil and gas exploitation. The hazards to water resources are illustrated in Figure 1. A major report was prepared by the US Environment Protection Agency.[2] (EPA) for US Congress. It is a comprehensive assessment of the impact of onshore oil and gas activities on water resources and provides much descriptive information on techniques applied by the industry as well as failure rates and reports. The risk of environmental damage is significant with up to 40% of wells in some areas showing signs of integrity failures leading to fugitive methane emissions or groundwater pollution.[2,3]

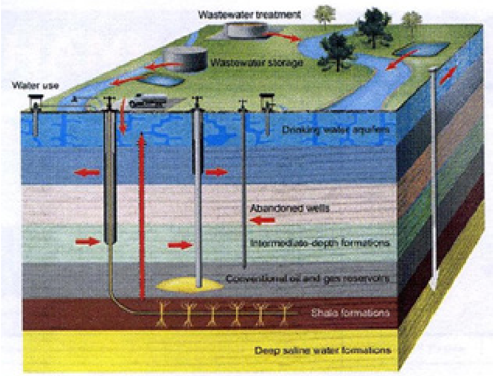

Figure 1 Illustration of hazards to water resources.

Information on fatality rates comes from OSHA (Occupational Safety and Health Administration) and National Institute for Occupational Safety and Health.[4] in USA: The overall fatality rate for US onshore oil and gas industry for all causes apart from chemical health problems and silicosis is 119 fatalities per year which is 7 times the US average industrial rate. Fatalities show no strong signs of falling year on year.

In 2012 the Royal Academy of Engineering produced a comprehensive review of the activity for the UK but was published prior to.[4] and does not refer to material contained in it, nor does it contain much material on the production phase of onshore oil and gas operations.

Hydraulic fracturing has taken place in 2019 near Blackpool in Lancashire as part of an appraisal / pilot production activity. Problems with earthquakes were encountered at that site. The government has decided that rather than making an update to the 2012 report, the Royal Society/Royal Academy of Engineering have been undertaking a major review of all the relevant literature since that date. In August this year the USA.[2] report is included in the review. The current UK policy originated from the Oil and Gas Authority (OGA) in November 2019 is that it "will not support fracking until the science shows categorically that it can be done safely". This moratorium puts back exploitation in the UK but exploitation of fracking overseas may continue, especially in China, which has major water stress problems and where the pressure to reduce their 70% reliance on coal for energy is very strong.

The dash for gas

The largest producer of shale oil and gas (and tight oil) fields is USA where 15000 wells are drilled each year. Canada produces and exports large quantities of unconventional oil and gas to USA and the USA has become a net exporter of oil and gas. In 2009 Barrack Obama signed a technology exchange deal between USA and China for shale oil and gas exploitation so China is now a major producer using USA technology, to assist them in the process of reducing reliance on coal. It is understood that China has commenced developing its indigenous technology.

For the UK currently has a diverse energy supply base and the energy debate centres the replacement of fossils based oil and gas by alternative means of energy security.

The fundamental difference between shale oil and gas and exploitation of conventional porous reservoirs is that well yields with shale gas / tight oil wells are much lower than with conventional wells so that, for a given production level, many more wells are required for the former and this affects the economics.

The sales price of gas in USA.[5] has been falling for the last 10 years. Also affecting the economics of fracked wells is that the wells have to be designed for high injection pressures and they are more complicated than conventional wells. In the USA the onshore oil industry has for some time been subsidised by the tax payer.[6] China also subsidises its onshore oil and gas industry.

Hydraulic fracturing, what is it?

Hydraulic fracturing is a process applied to oil and gas wells in an underground reservoir of hydrocarbons whereby water is pumped down the well into the oil/gas bearing zone at very high pressure (approximately 700bar / 10000psi) to expand micro-fissures in the rock.

The water is laced with significant quantities of "proppant" (also known as proppant sand) which comprises large quartz or bauxite granules, so that when the pressure is released the micro cracks are held open by the proppant granules, most of which remain trapped in the fissures.

A development that has fundamentally facilitated hydraulic fracturing is the ability to drill a well vertically down to the oil/gas bearing zone and then deviate it horizontally for some kilometres, as shown in Figure 2.

The well has to be cased in the upper zones and through important geological boundaries to prevent migration of produced fluids out of the reservoir other than via the well bore and to contain the pressures that can occur within the well. The seals between the casings or annuli must be adequate to prevent failure under pressure and transmission of fluids through the annuli or from the external formation. This is illustrated in Figure 2.

Drilling phase

At the surface there is a wellhead and "Blow-Out Preventer" (BOP). During the drilling phase, that precedes the fracturing phase, the BOP is big enough to accept the entry of the drill string, casings and drill bit during lowering and drilling the hole.

The drill string consists of a number of drill pipe sections 9 to 15m long screwed together and has an outside diameter of from 2.375" to 8.5" (60mm to 216mm), depending on the well design adopted at the outset. The drilled hole is full of bentonite mud during drilling and the up-flow of drill cuttings, up the annulus outside the drill pipe, conducts the drill cuttings up to the surface where they are separated from the mud in tanks or pits with the mud being re-used Figure 3.

As with conventional wells, the annulus between the outer casing and the rock is cemented by ejecting cement into it from the bottom of the casing (Figure 5). In practice it is not possible to cement more than 300m above the injection point.

Once this is done for the upper casing string, drilling of a smaller diameter hole commences and the hole extended downwards with a smaller diameter casing which is hung off the bottom of the larger casing above. At the bottom of this smaller casing a further cement injection is undertaken into the annulus bounded by the rock. Casings are typically in the diameter range 100mm to 200mm. Figure 4

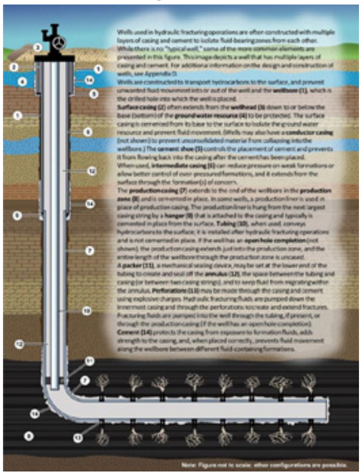

Figure 2 Overview of well construction (Al Granberg/ProPublica).

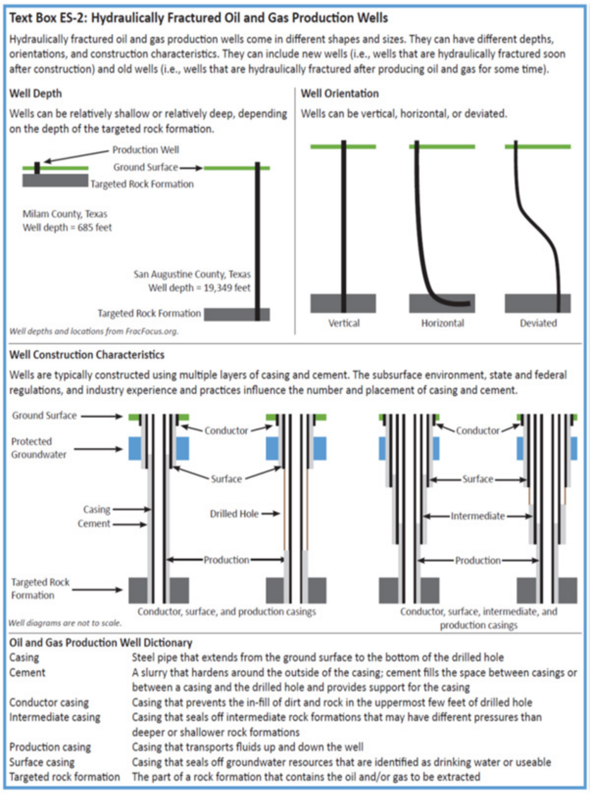

Figure 3 Hydraulically fractured oil and gas production wells (FracFocus.org).

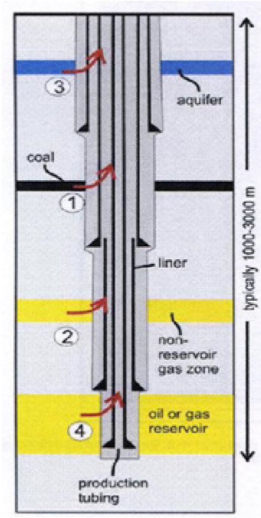

Figure 4 Schematic diagram of typical sources of fluid that can leak through a hydrocarbon well: 1 – gas-rich formation such as coal; 2 – non-producing, gas- or oil-bearing permeable formation; 3 – biogenic or thermogenic gas in shallow aquifer; and 4 – oil or gas from an oil or gas reservoir.[7]

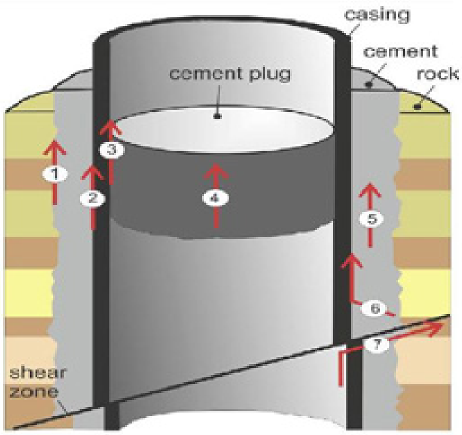

Figure 5 Routes for possible fluid leaks in a cemented wellbore: 1 – between cement and surrounding rock formations; 2 – between casing and surrounding cement; 3 – between cement plug and casing or production tubing; 4 – through cement plug; 5 – through the cement between casing and rock formation; 6 – across the cement outside the casing and then between this cement and the casing; 7 – along a shared wellbore.[7]

By judicious selection of the cement zones in relation to natural geological barriers, the well can be sealed but in the end it must be accepted that in a 3000m deep well with two such barriers, 80% of the vertical annulus between the casing and the rock is not cemented and is just mud filled. This may be a significant factor as one of the sources of gas at the surface is fugitive emissions which in some areas is found to occur in 6 to 40% of fracked wells.[3] and is attributable to loss of well integrity.[8]

Wells are not drilled straight, usually due to rock irregularities and have curvature "dog legs" in them.[9] that can be 10 degrees per 30m, which can have an effect on stresses in the well casing when fracturing pressures are applied, and hence affect well integrity.[10,11]

Once the well drilling and cementing of the annuli in the well and the well into the hole are complete and verified by downhole instruments, the drilling wellhead and it's BOP is removed and replaced by a fracking wellhead Possible failure hazards in a fracking wellhead are described in Figure 6.[12]

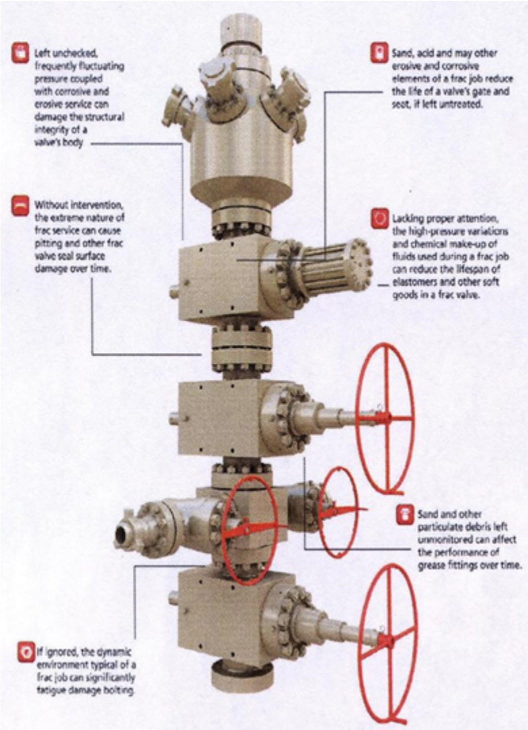

Figure 6 Possible failure hazards in a fracking tree.[9]

Main hazards during drilling phase: If, during drilling, a gas reservoir is suddenly encountered at depths less than the expected well depth (so-called "shallow gas"), that might be quite near the surface and quite highly pressurised, then that pressure will be felt by the well and the mud in it and the pressure "kick" that occurs will be a signal to the drilling crew of an impending danger of blow-out. In such a case, extremely strong hydraulic rams in the BOP stack will be operated to shear off the drill string and seal the well. (Firstly the mud specific gravity (SG) is increased to hydraulically seal the well and, as a last resort, the blowout preventer (BOP) shear rams are activated). The BOP stack has additional rams just below that are designed to grab the drill string to stop it falling down the hole.

To make the well safe again, high density mud (Barite, specific gravity 4.5) will be pumped down the hole via a side (or wing) valve, down the annulus and up the well bore so that the gas pressure is securely held by gravity. Alternatively the high density mud can be driven directly (bull-headed) down the well bore.

If the BOP stack fails to seal the well, the flammable well hydrocarbons will come out of the top of the drill string above and arrive at the drill floor where the drilling operators are and, if ignited, will cause an explosion, jet fire or fireball depending on the nature of the release. In such an event fatalities are likely and the worst accidents in USA at fracking / drilling sites have been from this cause.

The process of borehole construction and installation of casing also carries the risk of 'over-break' fragmentation of the rock formations penetrated; and there are no techniques for grout-sealing within the damaged zones which would ensure complete protection against migration of contaminants.

Hydraulic fracturing phase

Figure 7 depicts the stages of the hydraulic fracturing water cycle and Figure 8 shows a typical drilling phase on a fracking site.

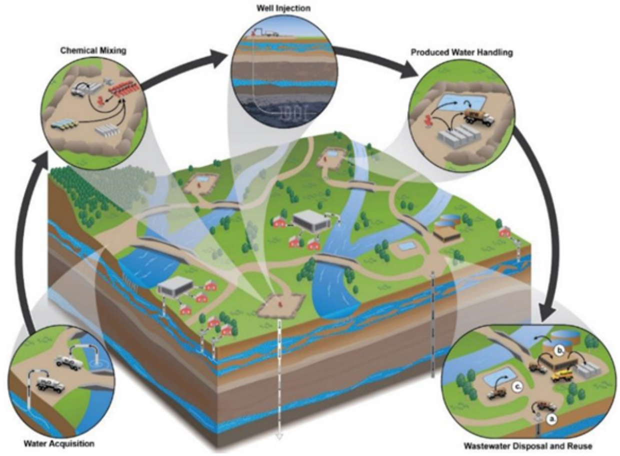

Figure 7 Stages of the hydraulic fracturing water cycle.

Figure 8 Drilling phase on a fracking site.

For hydraulic fracturing phase the drilling rig is removed, a manifold is set up and connected to the well and a number of mobile pumping trucks and chemical tanks are brought in as shown in Figure 9.

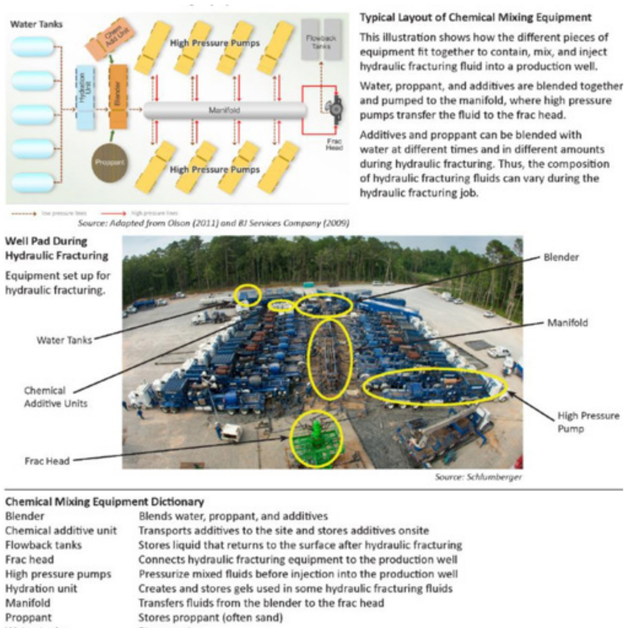

Figure 9 Site of chemical mixing (adapted from Olson and BJ Services Company).

A single site may have three or four wells as shown in Figure 10. There are a large number of flowlines into each site production string to allow injection of the different chemicals required: including biocide, friction reducer, acid, scale inhibiter, iron control, corrosion inhibitor and 13% sand.[2] In addition, oxygen scavengers and radioactive isotopes may be injected, different ones into different parts of the producing zone to help identify the effectiveness of the fracturing activity.[2] Each well requires 10000 to 25000 tonnes of water, so a very large volume of chemicals and sand is used overall. Injection pressure is typically 700bar.

Figure 10 Three wellheads on a multi-well pad connected to the piping used for hydraulic fracturing injection (photo credit: DOE/NETL).

It is necessary to include biocide in the injection water to prevent the growth of sulphate reducing (anaerobic) bacteria (SRB) which produce H2S as a bi-product which "sours" the oil and gas and any produced water. It also results in increased corrosion of pressure containing equipment (Figures. 11&12). The effects of SRB's in exploration drilling for hydrocarbons are long term and build with time.

The biocides and some of the other chemical additives can be highly toxic to aquatic organisms, wildlife and people, so great efforts should be made to keep biocides reliably separate from aquifers and life. In UK only glutaraldehyde biocide is currently allowed and is currently classified as non-hazardous but it should be noted that it may not be as effective as a biocide as some mixtures used in USA. It is likely that the number of additives used in UK will increase if and when pilot production starts in earnest and may be required for a fully effective pilot production. (Figure 11&12)

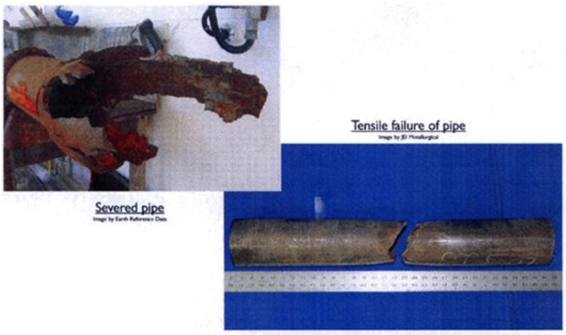

Figure 11 Examples of pipe rupture: Ruptured corroded pipe and tensile failure of pipe.

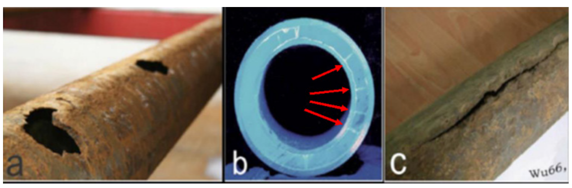

Figure 12 Examples of tubing corrosion (figure a), cracks in cement (figure b) and erosion in casing (figure c).[7]

The proppant and additives are transported to site and injected by a series of mobile fracking trucks with fluids transferred to the wellhead via a pipe manifold which would be to the right of the view in Figure 10. The fracking fluids are either fed directly down the production casing or down production (coiled) tubing. This flow line can be a continuous tube down through the production string to the reservoir. The surface facilities are extensive during fracking.[2] shows a typical fracking site in USA after the drilling rig has been removed and the fracking wellheads have been mounted on top of the wells.

Considering the use of proppants, these will hold the fissures open for a limited time only as the granules tend to punch into the shale, which is subject to the large weight of over-burden which may be 3000m thick. This loss slowly reduces the area of pore paths formed. The flow of oil and gas then slows and it is then necessary to re-frack the well, or in a different location along it to push the fissures open again or to push open new fissures or perhaps to drill a new well.

The production from each well and fracking exercise will commence with back-flow up the well of 25 to 75% of the original injection water and its admixtures, for disposal elsewhere. Hazards associated with waste water are described in Figure 13.

Figure 13 Illustration of storage of flow back water on-site short term (adapted from Olson and BJ Services Company).

In general the fracturing extends about 300m from the well bore and this means that exploitation of a gas or oil reservoir will require a very close spacing of well sites in a field development. Full field development require numerous fracking sites with relatively small separation distances (Figure 14). The fracturing can however extend more than 2km locally in some cases (depending on geology and pre-existing fault lines). The oil or gas flow between fracking exercises might last only a matter of weeks or 6 months. This is due to rapid decay of the flow. Flow is usually measured in terms of its "half-life", i.e. the time it takes for the flow to attenuate to half its rate.

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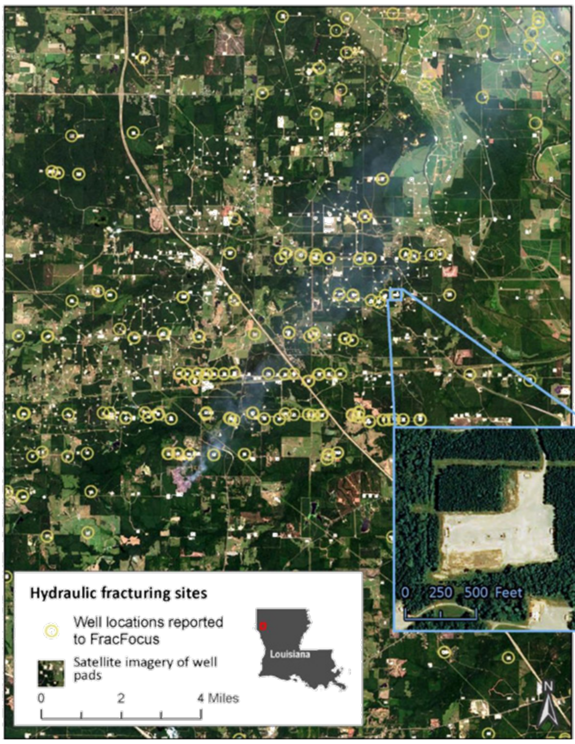

Figure 14 Landsat photo showing hydraulic fracturing well sites (imagery from USGS Earth Resources Observation and Science, Landsat & Operational Land Imager (scene LC80250382014232LGN00) captured 8/20/2014, accessed 5/1/15 from USGS's EarthExplorer (http://earthexplorer.usgs.gov/). Inset imagery from United States Department of Agriculture National Agriculture Imagery Program (entity M 3209351_NB 15_1_20130703_20131107) captured 7/3/2013, accessed 5/1/2015 from USGS's EarthExplorer (http://earthexplorer.usgs.gov/). FracFocus well locations are from the EPA FracFocus 1.0 project database (U.S. EPA, 2015c).

The gas and oil content of returns will gradually increase and these need to be separated out from the water and additives. Disposal of the toxic returns is a problem requiring the use of another disposal site. Reduction of fluid transport to a disposal site is facilitated by having 3 to 4 wells at each well site and reinjecting in one well while producing another (simultaneous operations or SIMOPS). Effects of damaged wells is described in Figure 15.

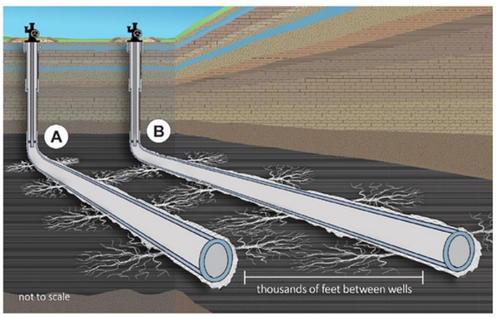

Figure 15 Effects of damaged wells. This image shows a conceptualized depiction of the fractures of a newly fractured well (Well A) intersecting the existing fracture network created during a previous hydraulic fracturing operation in an offset well (Well B). Evidence of this interaction may be observed in the offset well as a pressure change, lost production, and/or introduction of new fluids. Depending on the condition of the offset well, this can result in fluid being spilled onto the surface, rupturing of cement and/or casing and hydraulic fracturing fluid leaking into subsurface formations, and/or fluid flowing out through existing flaws in the casing and/or cement. (Figure is not to scale.).

Explosion risk during hydraulic fracturing phase: In cases where hydraulic fracturing takes place on one well while production is undertaken on other wells at the same site, the potential consequences of hydrocarbon vapour leak from producing wells and production equipment are increased. This is because the cloud of leaked vapour could entrain the nearby highly congested fracturing equipment. Explosion probability will be significantly increased due to the high level of ignition risk associated with the pumping equipment, which will usually be diesel powered. Delivery vehicles for water additives and proppant are an added ignition hazard. Explosion risk in the fracturing equipment is further exacerbated by the fact that the fracturing equipment is connected to hydrocarbons in the reservoir, albeit protected by non-return valves.

Confinement is not necessary for high explosion pressures to occur: the equipment congestion alone is sufficient.

[13]Contains a hazard review for explosion and fire at hydraulic fracturing sites and highlights a number of specific hazard areas. An issue not present with conventional onshore and offshore oil and gas exploitation is the proximity of containers of highly toxic chemicals and tote tanks of concentrate. These may be subject to explosion overpressures and will usually be of plastic.[14] This brings in the risk of severe environmental pollution and toxic release onto persons, especially if high pressure piping is breached while pumping equipment is running.

Environmental pollution is therefore a potential consequence of explosion – and this needs to be considered as part of the explosion consequence analysis. This risk is not usually present offshore, or is much less.

Once the fracking exercise on the wells is complete, there is normally little surface equipment left. The only explosion risk remaining is from blow-outs or fugitive methane emissions coming up in the ground around the well site, getting into confined spaces and igniting. The risk overall is to the drilling and fracking crew who move in an itinerant way and are constantly exposed to periods of maximum risk. This possibly explains the high fatality rates mentioned in the Introduction Chapter. See.[13] for more information.

Risk of well damage due to fracturing pressure and temperature: Experience in USA and China has shown that the proportion of well failures, leading to upward migration of methane or water additives in aquifers or to the surface, is of great concern. These failures are thought to be due to damage to the wells during fracturing: the combination of very high pressures and significant differential temperature (~60 to 200^{o}C) between the fracking water and surrounding rock, which can be found at depth, are believed to be the cause.[15,16] The studies showed the effects, are exacerbated by dog-legs in the wells.[9]

The effects on the well of fracturing are circumferential shrinkage cracking of the cement in the annuli and between the well casing and the rock and potential casing structural damage. Compared to conventional wells (on which current design guidance is based) the following factors resulting from the action of fracking can conspire to reduce well reliability:

I. The action of high injection pressures coupled with thermal shrinkage of low permeability rock strata.
II. Radial shrinkage forces which exceed the tensile strength of the cement grout used to seal the well.
III. Limited lengths of cementing to the annulus between the outer casing and the rock, (usually limited to about 300m gross above each casing stop point). Above this zone the annulus is mud filled, through which upward migration of fluid is possible, especially methane.

IV. The fact that working stresses in casings during fracturing are routinely close to the allowable limit (yield/1.25).[17] and may be sustained for days or weeks and yield to ultimate tensile stress (UTS) ratios at around 0.9, are higher than with conventional casing material. Note that steel strengths are reduced when the tensile stress is sustained.

V. The high strength steels used are more prone to cracking (hydrogen or step-wise) induced by any H2S, and the corrosion rate is enhanced when the rock is hot (e.g. 200^{o}C) or CO2 is present.

VI. Erosion of the casing due to proppant injection or returns can cause thinning of the steel wall and hence the deterioration of its strength.

VII. The larger number of wells in a particular field development, compared to conventional hydrocarbon developments, means that target reliability for each well would need to be raised to meet overall risk criteria.

The current UK well guidelines.[17] provide little coverage on specific requirements for fracked wells and do not allow for the more severe operating conditions for such wells compared to conventional ones. These guidelines need to be updated in respect of allowable stresses and the required number of barriers in well design.

Research published in Duke university[18] concludes than all casings, regardless of steel quality, may eventually fail and grout seals are vulnerable to shock-fracturing. The only protection is total avoidance of aquifers and fault zones.

Risk of blow-out during fracturing: Blow-outs occur occasionally during Hydraulic Fracturing phase and are reported in the literature..[19] is a case history by the "Wild Well Company" (formerly Red Adair). The wellhead blew-off when the pressure applied beneath it rose due to failure of the fracking tube a short way below the wellhead, coupled with inadequate welding of the fracking tree to the top of the well. Many thousands of tonnes of fracking water and some hydrocarbons were ejected at very high pressure and the spread of environmental damage was wide. Fatalities can occur in such incidents and health problems for persons soaked by fracking fluids during the blow-out. When such an event occurs, specialist emergency intervention is required and in reality there is only one company worldwide that can do this and it is based in USA. Figure 16 shows an unignited blowout resulting from wellhead failure.

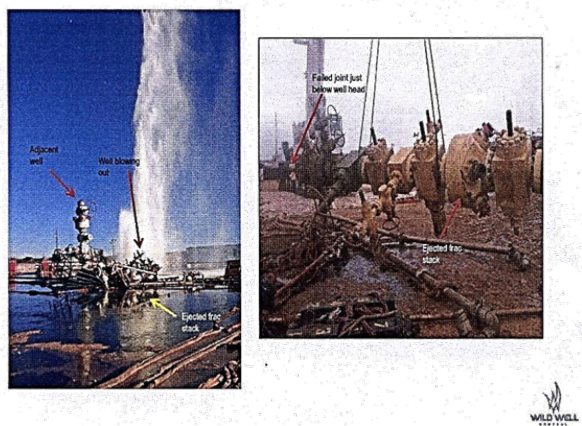

Figure 16 Unignited blowout resulting from wellhead failure (Wild Well).

Potential consequence of earthquakes caused by fracturing operations: On occasion, ground movements (usually, but not always, very small) may occur because disturbing the strata hydraulically and fracturing the shale may reduce frictional engagements between rock layers. Residual ground shear stresses and strains can then be released suddenly and one section of rock can slip relative to an adjacent one.[15] The risks with earthquakes are that pre-existing or new fault lines may open up allowing migration of fluids up towards the surface or to other abandoned wells. In addition slips that occur between rock layers can cause shear deformations or failures of wells. Causes and consequences associated with faulting, seismic events and fracking are further addressed in ***Faulting, Seismic Risks and Fracking and Environmental Risks*** Chapters.

Production phase

After production has started and settled down, the fracturing equipment and operating team move to another well site until a further fracturing exercise is undertaken (if required). There are two production phases: pilot and full. It is a bit difficult to perform a pilot production test without full processing equipment to enable produced hydrocarbons to be used rather than burnt thereby contributing to greenhouse gases. This means that a pilot production activity is not really possible without full production equipment and this will in all probability be leased or hired in, in which case it will not have been subject to bespoke design and the risk reduction that goes with it..[14] is a website which is navigable vertically and horizontally and shows the range of production equipment likely to be used.

Full production involves many separate individual well pad sites. The close spacing of well sites (each of which will have been fracked) is a result of the fact that fracturing only reaches out about 300m from the well bore. Given a typical horizontal leg length for the well of 3km, the exploited area for each well is only 1.8km^2 so that for 3 or 4 wells per site a field will need one well site for each 5 to 7km^2 area.

Also part of a full field development would be a gathering site where oil and gas would be taken in from the well sites, (mostly by pipeline) and processed for onward transmission of purified products into energy infrastructure and other reject products to disposal sites. This would be an extensive facility (Wytch Farm facility covers 18ha).

A gathering site will be part of a full development scheme as shown in Figure 17. It is likely to include the same equipment functions as an onshore oil or gas production facility or North Sea oil or gas production platform, plus some additional elements, as follows:

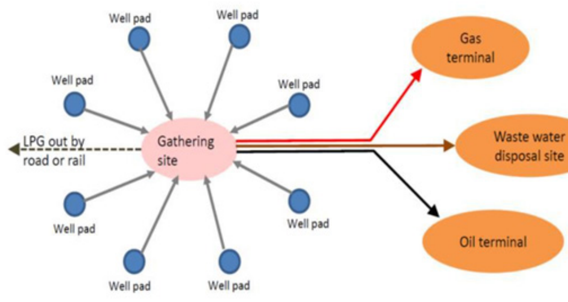

Figure 17 Schematics of a full field development.

i. Slug catchers for incoming 3-phase flow;
ii. Fiscalisation metering;
iii. Flare burner farm in place of a flare tower;
iv. Storage vessels for LPG (butane and propane);
v. Water treatment and sand washing facilities;
vi. Marshalling yard for LPG trains or lorry loading facilities;

vii. Marshalling yards or lorry loading facilities for hazardous waste water;

viii. Sand silos and lorry loading for transport to other fracking sites;

ix. Large pits and storage tanks for waste products including spent fire-fighting foam which is hazardous to water resources; and

x. Facilities for local fire brigade emergency response teams.

If production is sent from the gathering site by 3-phase pipeline to an existing onshore receiving terminal for processing, albeit modified, then the gathering site will need significantly less facilities. The downside to this is that there will be a tariff to pay to the receiving terminal and the pipeline owner for their processing activity (usually a high price) which will reduce substantially the sales revenue for the hydrocarbon produced at the well sites. This would be a significant problem given the weak economics for fracked oil and gas.

Another problem is that an integrated recycling exercise for waste water and sand in conjunction with well sites will involve much more lorry transportation and infrastructure consequence, with hazard implications.

Decommissioning and potential for carbon sequestration use

Decommissioning.[20] requires the well bore to be sealed, the well to be capped by a welded steel cover and full documentation of the well's geometry and data logs and history to be kept in order to allow future interception in case problems come to light after abandonment. This last requirement could be invoked by applying Building Information Modelling (BIM).[21] to onshore wells. To be effective the BIM database should be started at the start of drilling because it is at drilling phase that the Barriers are set up and their effectiveness verified. Further information is required after fracking (which can damage the Barrier system) and prior to closure for abandonment.

The effectiveness of the decommissioning process as a means of preventing future poisoning of aquifers or fugitive methane emissions.[3,20] depend partly upon whether the reservoir at termination has raised or lowered pore pressure compared to prior to any exploitation or is likely to become so after abandonment. Fugitive methane emissions can indicate that a flow conduit up to the surface has occurred, e.g. in the annulus between the casing and the rock, which is for the most part not cemented (see ***Drilling Phase*** Chapter above). This is a form of well integrity failure. This up-flow of gas will act like a gas-lift process that could facilitate transport of other contaminants upwards to surface aquifers and can be permanent.

Given the historic frequency of fugitive emissions.[3] as an indicator of well integrity failure, fracked wells should not be used for carbon capture and storage. CO2 injection increases the subterranean pore pressure and an overpressure could in time enhance the drive of pollutants up to surface aquifers or to atmosphere.

From the environmental standpoint, upwelling of CO2 causes acidification of ground water which results in leaching out of mineral salts which would render aquifers poisonous on a long term, even permanent basis. This is a most important issue given the potential quantities of CO2 considered for a carbon sequestration exercise. CO2 is poisonous to humans in larger concentrations (e.g. 7%) and so is potentially hazardous in its own right. It is heavier than air (unlike methane) and does not disperse naturally, and this is a problem for large leaks in still wind conditions as large clouds can migrate to populated areas or roads.

Faulting, seismic risks and fracking

Fracking is the only known way of extracting oil or gas from compacted, or "tight" shale rocks, which are carbon rich. It has come to prominence since around 2003 in the USA, and many other countries, several European. In consequence they are now actively investigating their previous locked-up gas reserves, for shale is a very common rock type.

Geologies vary between sites in terms of age and rock type and they reveal faulting – evidence of structural weakness. The high pressure generated by the fracking process could activate existing geological faults and initiate seismic disturbance, disrupting the rock formations and creating pathways for the dispersion of toxic gases and fracking fluids. An example of pre-existing ground fault line is shown in Figure 18. Figure 19 depicts examples of ground movements,

Figure 18 Example of pre-existing ground fault line (the surface of it without vegetation).

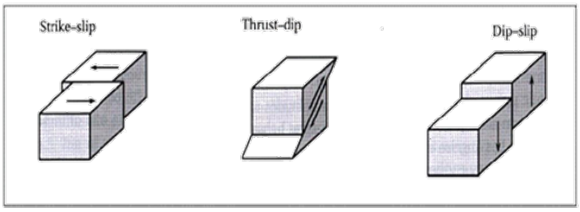

Figure 19 Examples of ground movements.

A geological fault is a crack in the earth's crust resulting from the displacement of one side with respect to the other. Faults cannot necessarily be "seen" in advance of drilling, for example using geophysical methods, and indeed it is common for exploration wells to drill through a fault zone without it even being spotted.

The exploratory and production sites may feature water-bearing rocks (aquifers) throughout the stratigraphic sequence. Some of these may be at relatively shallow depths and support abstraction for local public supplies, supplies for industry and infrastructure, and agriculture including irrigation. There may also be natural reservoirs for springs and seepages feeding the headwater 'basewater' of rivers and wetlands.

One of the technical fields associated with fracking is determining whether or not geological faults in any particular area will seal-off a potential oil or gas reservoir, or will act as a conduit. The default industry position on fault seal risk (which means that risk of the oil or gas being trapped – the desired outcome) is that faults do not normally act as seals.

No authoritative study that mentions the fault seal problem in connection with horizontal fracking (sometimes also referred to as

Citation: Brewerton RW, Medonos S, Warren GD. Hazards to water resources and life safety from exploitation of onshore wells by hydraulic fracturing. *Int J Petrochem Sci Eng.* 2023;6(1):42–63. DOI: 10.15406/ipcse.2023.06.00130

slickwater, high volume fracking, or super fracking, to distinguish it from other methods of fracking which can safely be used) seems to exist. A leaky fault is a fast-track back to shallow groundwater and to the surface for methane and other gases, as well as for the contamination of water resources by fracking chemicals. In France fracking has been banned partly because of this risk, which was pointed out in 2011 by geologists from the University of Montpelier.

In NW Germany, a thorough study of fracking risks has been carried out by academic experts (but funded by Exxon Mobil), which includes the question of fracking through faulted zones. One of the main conclusions of the study is that fracking in fault zones must be banned.

Fracking operations have been banned in France, Germany, Austria, the Netherlands and Spain. In England, by comparison, nothing of substance on effects of geology faults and fracking has been published. Evidence submitted by the Geological Society of London and the Petroleum Exploration Society of Great Britain to the Royal Society stated under the heading *Groundwater Contamination from Hydraulic Fracturing:*

Another possible cause for both methane and fracking fluids leaking and migrating into groundwater supplies is the fracture stimulation process intersecting with open or unstable natural fractures and faults in the subsurface that extend upwards from the deeper prospective layers towards the surface where groundwater supplies might exist. The current UK policy is that it *"will not support fracking until the science shows categorically that it can be done safely*".

Advocates of fracking will point to its long history in the USA (more than 70 years). But until around 2000 this involved relatively low pressure technology developed primarily for recovering 'worked-out' gas and oil fields; and without the complex suite of toxic chemicals. High pressure fracking is little more than 15 years old, and most of the episodes of serious environmental contamination date from this period.

The work carried out in USA cannot be applied to Europe, because the European geology is very different. The English shale basins, for example, are 10 to 100 smaller in area than the main US basins, but the shale deposits are 10 times thicker. Faulting is almost non-existent in the US basins, whereas it is a fundamental and important feature of the basins in England, the south of France and NW Germany – all areas which are or have been considered for fracking.

Pennsylvania State Agency has established 209 cases in which home owners' water supplies were contaminated from nearby drilling since 2008. The Proceedings of the National Academy of Sciences (of the USA) published a research article which proves, from a case history in Pennsylvania, that faults and/or fractures can and do act as a conduit from fracked shale to contaminate drinking water.

Most of the American experience pre-dates the recent high pressure injection technique adopted only 15 - 20 years ago. There is also a very low density of geological faults compared with the UK and European sites and, also, for most of the period, there has been no formal obligation on the operators in the US to monitor or report pollution incidents. US case studies do not therefore constitute reliable information for operations outside US.

There are concerns regarding effective treatment and disposal of flow-back water with examples of bad practice in US, including re-injection of oil and gas waste, which in some instances have been identified as the cause of large earthquakes; an environmental risk "as old as the industry itself". A forecast of the flow-back estimated the annual flow-back in the UK of 108 million cubic metres; all requiring treatment. This amounts to a substantial burden on the existing waste-water treatment capacity.

The development of fractures or re-activation of faults in the base of an aquifer can also result in a reversed hydraulic gradient which would in turn create a groundwater drain and consequent loss of storage.

Hazards associated with exploitation of shale hydrocarbons

A hazard is a potential source of harm. The description of hazard often includes the cause of the hazard, or the causes of hazards are described individually and separately from each other. For example, the hydrocarbon fluids produced from shales are explosion and fire hazards all the way from wells to the gas plant or refinery, and to the infrastructure.

Hazards are identified in Hazard Assessment studies, which are collective studies facilitated by study 'Chairmen'. They usually include semi-quantitative estimations of risks in the application of a Risk Matrix to determine the ranking of the risk. Figure 20 shows an example of Risk Matrix and the ALARP triangle. A risk is the combination of the likelihood of occurrence of harm and the severity of the consequence of that harm materialising. The traditional definition of risk combines three elements: it starts with a potential event and then combines its probability with its potential severity. A high risk event would have a high likelihood of occurring and a severe impact if it actually occurred.

CONSEQUENCE SEVERITY									
Personnel Injury	Asset Damage	Environm. Damage	Schedule Delays / Loss of Production	Publicity Damage					
Extremely Serious (>10 fatalities)	Euro20M	10T spill	180 days	Internat'l	ALARP	ALARP	Intolerable	Intolerable	Intolerable
Critical (several fatalities)	Euro5M	1T spill	90 days	National	ALARP	ALARP	ALARP	Intolerable	Intolerable
Major (single fatality)	Euro1M	200kg spill	30 days	Prosecut'n	Broadly Acceptable	ALARP	ALARP	ALARP	Intolerable
Moderate (lost time injury)	Euro200K	50kg spill	7 days	Local	Broadly Acceptable	Broadly Acceptable	ALARP	ALARP	ALARP
Minor (non lost time injury)	Euro20K	1kg spill	1 day	Company	Broadly Acceptable	Broadly Acceptable	Broadly Acceptable	ALARP	ALARP
					Insignific'nt 10E-5 or less	Remote 10E-5 to 10E-4	Unlikely 10E-4 to 10E-3	Possible 10E-3 to 10E-2	Probable 10E-2 to 10E-1
					OUTCOME ANNUAL FREQUENCY				

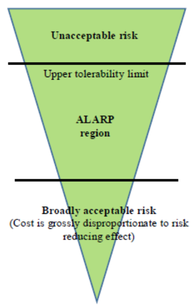

Figure 20 Examples of Risk Matrix and ALARP Triangle.

The Chairmen are required to have a high level of knowledge of the facility being studied, its environment and infrastructure. Details are provided by the studies' participants.

The shown example is of a detailed 5x5 Risk Matrix, which includes risks to Personnel, Assets, Environment, Schedule Delays (Loss of Production) and Publicity. This is based on recent practical experience. Including all these types of risks is convenient as Causes, Barriers and recommended Actions may be the same, and can all be addressed in one Hazard Assessment study where the personnel responsible for subject risks can interact. This conveniently results in optimized solutions at lower design and operational costs, and improved solutions. The Consequence Severities and Outcome Annual Frequencies are project specific. Smaller Risk Matrices down to 3x3 have also been used, but for not more than one risk type and without any quantification.

The Hazard Assessment identifies the Hazard, during which phase (of the project) it occurs, the Cause and Consequence(s) of the hazard materialising, Barriers (and Safety and Environment Critical Elements), Risk Type and Ranking, and recommended Actions.

Citation: Brewerton RW, Medonos S, Warren GD. Hazards to water resources and life safety from exploitation of onshore wells by hydraulic fracturing. *Int J Petrochem Sci Eng.* 2023;6(1):42–63. DOI: 10.15406/ipcse.2023.06.00130

Barriers are physical or non-physical means to prevent, control or mitigate undesired events or accidents. Barrier systems may be classified according to several types, for example as passive or active barrier systems, and as physical, technical, or human / operational barrier systems.

Safety and Environment Critical Elements (SECEs) are parts of an installation and such of its plant (including computer programmes), or any part of those-

a) the failure of which could cause or contribute to an accident or incident; or

b) a purpose of which is to prevent, or limit the effect of an accident or incident.

The nature and seriousness of the accident or incident that SECEs are provided for are dependent on the relevant legislation, location and installation. A SECE can be a form of mitigation.

Figure 21 depicts the Bow Tie Analysis (BTA) for discussions on Barriers and SECEs in Hazard Assessment studies.

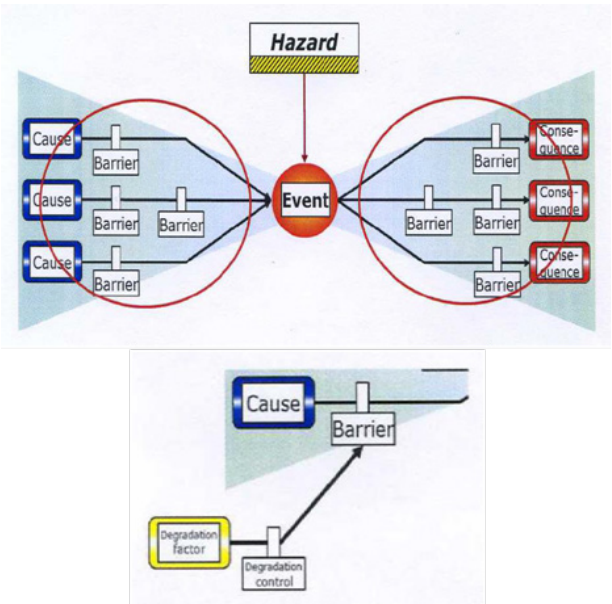

Figure 21 Schematics of Bow Tie Analysis (BTA) for discussions on Barriers and SECEs in Hazard Assessment studies.

Data on the integrity of items of equipment subjected to accidental loads and effects of fire protection are useful for discussions on the Barriers and SECEs during the Hazard Assessment studies. They may be found in references such as.[22]

The unacceptable risk is in the right upper part of the Risk Matrix. The lower left part represents broadly acceptable risk. The diagonal area between the two parts are risk scenarios which should be reduced to the ALARP level.

'ALARP' is short for 'as low as reasonably practicable'. SFAIRP is short for "so far as is reasonably practicable". The two terms mean essentially the same thing and at their core is the concept of 'reasonably practicable'; this involves the weighting of a risk against the effort, time and money needed to control it. Thus, ALARP describes the level to which it is expected to see workplace risks controlled.

Hazard Assessment studies combined with ALARP provide a semi-quantitative assessment of risk, identification of major accident hazards (MAHs) and identification of risk scenarios that require some form of prevention, mitigation and/or protection against, and hence also the determination of fire and explosion loadings. The most common definition of a Major Accident Hazard comes from UK legislation where a MAH is defined by:

A. any event arising from work activity involving death or serious personal injury to five or more persons on the installation or engaged in an activity in connection with it;

B. a fire, explosion or the release of a dangerous substance involving death or serious personal injury to one or more persons on the installation or engaged in an activity on or in connection with it; and

C. any other event involving major damage to the structure of the installation or plant affixed or the loss of stability of the installation or major environmental impact(s).

The Royal Society and Royal Academy of Engineering report.[23] recommends risk assessments to be carried out for both technical safety and for the protection of the environment. Harm to operating personnel, general public and the environment may originate from the same events. Hence SECEs and Barriers may also serve to provide the prevention, mitigation and protection against the same events.

Examples of MAHs are:

a) Sites with high congestion of the fracking equipment and the proximity to the wells. Explosions exacerbated by equipment congestion are a major issue especially during simultaneous operations (SIMOPs) when production of one or more wells is taking place during fracturing of an adjacent well. This means that leak risk is present nearby in conjunction with high congestion and high levels of ignition risk.

b) Full field developments that require numerous production and fracking sites with relatively small separation distances would also be MAH. Concurrent activities in many of the neighbouring sites, with the number of personnel working in each, are SIMOPs considered with respect to risks of explosions and fires as one plant.

c) MAH of a gathering site in Figure 18 where oil and gas is taken in from the well sites, (mostly by pipelines) and processed for onward transmission of purified products into energy infrastructure with reject products sent to disposal sites. A gathering site is an extensive facility containing a relatively large number of vessels and pipework with flammable inventories. It is therefore required to be treated as a potential Major Accident Hazard site.

d) Major Accident Hazards of gas and oil terminals (Figure 17) typically contain large numbers of vessels and pipework with flammable inventories, large numbers of potential leaks and considerable numbers of potential sources of ignition of leak flammable fluids.

e) It should be noted that current experience is from the United States, where distances between the sites and general public, housing and infrastructures may be far larger than in the UK. I.e. the risk to the general public, housing and infrastructures in the UK would be higher than those in the US but this may not account for potential impact on water resources in those countries.

In accordance with Table 1, the most frequent fatal events in the US oil and gas extraction industry between 2003 and 2015 were in transportation (42%), contact with objects / equipment (25%) and fire / explosions (14%). It is to be noted that current UK regulations for

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preparing Environmental Impact Assessment do not require accidental events to be considered. This is problematical with hydraulic fracturing because the majority of risks are associated with accidental events. Hazards and failure mechanisms associated with wells are addressed in detail in Chapter of ***Hydraulic Fracturing, what is it?***.

Transportation risks

The transportation considered is by road trucks from the drilling and/or production site to the location of the disposal of the waste material in the following time-phases:

A. Connection, loading and disconnection within the operation site fence;

B. Vehicle manoeuvring and management within the operators site;

C. Transport from the site to outside of the disposal site;

D. Connection, unloading and disconnection within disposal site fence; and

E. Decontamination of transport vehicles.

Table 3 gives a summary of the risk occurrence phase, hazards / causes of the risks and very brief descriptions of risk consequences. It only gives the initiating event and final consequence. Human failure includes fatigue, which according to is the main contributor to risks associated with transportation. Causes of risk of failures in site management practices are included in the causes by human factors.

Risks of contact with objects / equipment

Table 4 provides an overview of deaths and injuries associated with contact with objects and/or equipment between 2011 and 2015 inclusive.[4]

Table 1 Most frequent fatal events in US oil & gas extraction industry, 2003-2015[4]

Event Type	Transportation	Contact with Object/Equipment	Fires / Explosions	Exposure to Harmful Environments	Falls	Other	Total
No of Deaths	597 (42%)	354 (25%)	202 (14%)	126 (9%)	116 (8%)	27 (2%)	1422

Table 2 Basins with assessed shale oil and shale gas: Estimates of technically recoverable shale gas resources (trillion cubic feet (tcf)) based on 48 major shale formations in 32 countries (The Royal Society and Royal Academy of Engineering 2012)

Country	Recoverable Shale Gas Sources (tcf)	Country	Recoverable Shale Gas Sources (tcf)
Algeria	231	Libya	290
Argentina	774	Mexico	681
Australia	396	Norway	83
Brazil	226	Pakistan	51
Canada	388	Paraguay	62
Chile	64	Poland	15
China	1276	South Africa	485
France	180	UK	20
India	63	USA	862

Table 4 Overview of deaths and injuries associated with contacts with objects and/or equipment 2011 – 2015 [4]

Description	Deaths	
Struck by Object / Equipment	99	(82%)
powered vehicle, non-transport (17 deaths)		
falling object or equipment (52 deaths)		
discharged or flying object (4 deaths)		
swinging object (8 deaths)		
Caught in Equipment or Machinery	7	(6%)
Caught in Collapsing Structure / Machinery	4	(3%)
Other / Unknown	11 (9%)	
Total		121

Fire and explosion risks

Barriers and SECEs have to be designed for accidental events, which are different to operational conditions. SECEs also have operational functions, hence they have to be designed for operational conditions too. A Barrier or SECE must be available when an accident happens, and available, functional and reliable throughout the duration of the accident.

UK safety legislation is based on a goal setting risk-based cautious best estimate approach. Cautious best estimate is an approach with careful attention to risk that is reasonably foreseeable, where all consequences are considered with due care. A cautious best estimate approach is not based on a worst case scenario. Dismissing foreseeable high consequence low probability events would result in a potentially optimistic (low) risk based decision that could require a costly retro-active action in the future. When a cautious best estimate approach is employed, the most serious consequences should be considered and, if required, modelled. Barriers should be identified to prevent or mitigate such consequences. The selection of barrier measures should be made by informed bodies. Analysts should report results with confidence levels for both probability and consequence.

This enables good freedom to optimise prevention, mitigation and protection with resulting improved safety and environment protection level at reduced costs; provided that the work is carried out by personnel with adequate expertise.

Required functionality times must be longer than those required for facility personnel to escape and evacuate from the facility. Depending on the Safety and Environment Protection Philosophy of the facility, this may also include protection of assets (i.e. buildings, machinery and equipment).

It should also be noted that acceptance criteria for risks to technical safety associated with the exploitation of shale hydrocarbons are different from those for the oil and gas industry offshore and onshore as the risks associated with exploitation of shale hydrocarbons are to the general public, in addition to the operation personnel. This article does not address any acceptance criteria.

Time-dependent consequences, response and actions following accidental release of flammable gas or liquid in gathering sites and well pads to be considered are described in Table 5.

Table 5 Scenarios to be considered following accidental release of flammable gas or liquid in gathering sites and well pads

Time (minutes)	Event	Consequences and / or Response
0 – 2	The escaping gas or oil may reach a point of ignition and ignite. A fire will result (rather than explosion, because an explosion would require some time for a flammable gas cloud to form.	Systems: The detection system activates the alarm and shutdown of the plant. Process safety valves and depressurising system are activated. The heating-up of plant equipment and supporting structures starts. Personnel: Fatalities and injuries of personnel in the plant exposed to high heat radiation if they are in the vicinity of fire. The escape routes should go through areas where the likelihood of escalation is low. Personnel on the Control Room continue to control the accidental event.
4 – 20	The escaping gas has reached the point of ignition and ignited. Gas cloud explosion (which may be followed by fire).	Systems: Due to explosion overpressure: Equipment is lifted-off their supports or over-turned, resulting in additional leaks, which ignite from the explosion, resulting in additional fires. Structures are excessively deformed, resulting in excessive deformation of the pipework the structures support, resulting in new leaks, which ignite from the explosion, resulting in additional fires. Control and instrumentation systems are damaged, resulting in the loss of plant control. Personnel: Personnel have made their workplace safe and are escaping to the Muster Point. Some or all personnel may have escaped to a location behind blast wall or explosion-rated fire wall. They may therewith be protected from the effects of explosion overpressure, i.e. knocking them down (injury) or fatal injury.
10 – 20	Escalation of fire – loss of tightness of flanges.	Systems: Bolted flanges: Nut(s) sliced-off due to the combined effects of thermal expansion of the flange body and the loss of strength of the nut due to its elevated temperature, resulting in the loss of tightness, resulting in new leaks, resulting in additional fires, which ignite from the original fire. Clamp flanges: Rapid loss strength of the bolts due to their elevated temperature, resulting in the loss of tightness, resulting in additional fires, which ignite from the original fire. Personnel: The escape routes should go through areas where the likelihood of escalation is low.
2 – 20	Escalation of fire – fire-induced stress concentrations and loss of strength of pressure vessels.	Systems: Un-insulated vessel nozzles (and pipes) rapidly heating-up and conduct heat into the insulated or fire-protected vessel. Thermal gradients develop, which may result in ductile ruptures of the vessels, new leaks and additional fires. Personnel: The escape routes should go through areas where the likelihood of escalation is low.
	Escalation of fire to the loss of strength of pressure vessels and new fires, or to boiling liquid evaporating vapour explosion (BLEVE).	Systems: Transfer of heat from the flame onto a vessel surface, heat conduction through the vessel wall, heat transfer from the inner vessel wall into the vessel contents. Heating-up of the 2 or 3-phase (oil, gas and water (if present)) vessel contents, thermal expansion of the hydrocarbon (HC) liquid and water (if present) and increase of the stresses in the vessel wall. Reduction of the load

Table 5 Continued...

Time (minutes)	Event	Consequences and / or Response
		bearing capacity of the pressure vessel due to its rising temperature. The applied stress due to the vessel pressure becomes higher than the reducing vessel strength. These effects also include pipes and flanges, and the loss of their tightness. This results in loss of pipe joints tightness and / or vessel explosion resulting in new fires; leading to a pressure wave from the explosion travelling through the plant, flying fragments of the exploding vessel and fire escalation through the plant. (Investigations of accidents and full scale tests show that the flying fragments may have a high mass and speed, travel up to 500m and damage storage and pressure equipment; resulting in new leaks and fires within and also outside plant fence, damaging facilities, infrastructure, buildings and housing, and causing fatalities of the general public.) The temperature rise of unprotected structures affected by fire may cause the structure collapsing (or a part-collapse) causing losses of pipework supports, loss of pipework flanges tightness, new leaks and fires. Local structural deformations should be acceptable, however, providing that key pipework strengths are maintained ensuring adequate supports to prevent additional leaks. Personnel: The escape routes should go through area where the likelihood of escalation is low. General Public: The potential escalation of explosions and fires beyond the plant fence should be included in emergency plans for the general public, such as the public Fire Brigade.
30 – 240	Escalation of fire / and or explosion to collapse of a storage tank	Systems: Overfilling of hydrocarbon (HC) storage tank causes overspill of the HC contents into the tank bund. The HC liquid in the bund evaporates and the vapours may find an ignition point and ignite, resulting in a bund fire. It may take some time before the flammable vapours come in contact with a source of ignition, in which case there may be a sufficient time to form a gas cloud that would explode. The explosion would damage the storage tank, cause additional spills, which would result in a massive combined bund / tank fire. The fire, explosion or the combination of explosion and fire would cause the storage tank to collapse, leading to a cataclysmic fire and explosion escalation through the tank farm. Personnel: Fatalities and injuries of personnel in the plant exposed to high heat radiation if they are in the vicinity of fire. The escape routes should go through areas where the likelihood of escalation is low. Personnel on the Control Room continue to control the accidental event.
10 – 240	Escalation of fire between neighbouring process buildings.	Systems: Ignited medium and large releases of flammable gas may result in fire with flames of such a length that the flame may affect the process equipment and structures of the neighbouring plant buildings. Additional leaks may form, which will ignite from the original fire. Due to the effects of structural deformation additional leaks may also form away from the fire. These leaks may form flammable clouds, which will ignite with a delay causing explosions. The escalation therewith propagates through the plant. This is sometimes called as a "domino effect". Personnel: The escape routes should go through areas where the likelihood of escalation is low.

It should be noted that the pipework and equipment inventories may consist of oil, gas, harmful chemicals and waste water, where the latter itself will contain harmful chemicals. It has to be considered that any releases or explosions prior to and within the time of separation may result in harmful effects on humans, wildlife and environment, and fire.

Details on managing fire and explosion hazards from shale hydrocarbon sites can be found in articles in.[13] and[24.]

For the design of Barriers and SECEs,.[25] and.[26] provide guidance on protection of piping systems subject to fires and explosions, fire loadings and structural response. The prevention, mitigation, protection and fire and explosion loadings can be wholly or partly determined using a probabilistic approach, which has been used for offshore oil and gas installations in the past. HSE document.[27] gives guidance on accounting for congestion of equipment or trees for explosion pressures estimation. Without this the explosion pressures would be seriously under-estimated.

Detailed Quantitative Risk Assessments (QRAs), or updates of existing ones (due to additional equipment associated with production of shale hydrocarbons), may be required for gas and oil terminals and refineries. Statistical leak frequency data needed for such purposes may be found in databases which were originally developed for and used in the QRAs of offshore oil and gas facilities. This is where equipment and components used for the exploitation of shale hydrocarbons are similar to those of traditional oil and gas facilities. There may be situations where only low amount of statistically available failure data may be found. In these cases the quality of failure frequencies used in QRAs may be assessed by the computation of confidence intervals in the Poisson model (see.[28] for an example).

Environmental Risks

Environmental risks and risks to humans: Hydraulic fracturing may cause:

1) Ground movements and cause earthquakes, which may open-up pre-existing or new fault lines;
2) Slips to occur between rock layers, which can cause shear deformations and/or failures of wells;
3) Both above causing migration of fracking fluids and/or methane up to the surface or to abandoned wells;
4) Methane may ignite causing explosion and/or fire; and
5) Fracking fluids may contaminate the land, aquifers and surface bodies of water.

Geological faults provide a fast-track for the migration of fracking fluids, fugitive methane and naturally occurring radioactive materials. This include migration into overlaying aquifers and surface bodies of water. Existing faults may be exacerbated by ground movements caused by hydraulic fracturing.

Fracking fluids can contain up to 200 chemical constituents, many known to be toxic and carcinogenic. Other are associated with acute conditions of the respiratory, gastro-intestinal and central nervous systems. Regulators should require from operators full disclosure of fracking chemicals and they should not permit use of hazardous chemicals.

Water demand and assessments: An example of the estimate of water consumption for fracking operation can be seen in.[29] with respect to current population, population growth, environmental sustainability and climate change. The estimate is from US experience based on field development in Texas where water availability is a key issue. Also, spills of the fracking water and produced oil within the operation fence, transportation and at the disposal site may pollute the land aquifers and surface bodies of water.

An example of environmental impact assessment of shale gas and oil extraction can be seen in.[30] Assessments were undertaken for to 12 objectives, namely:

1. Biodiversity
2. Population
3. Health
4. Land use, Geology & soils
5. Water
6. Flood Risk
7. Air Quality
8. Climate Change
9. Waste
10. Resource Use
11. Cultural Heritage
12. Landscape

Assessments under each objective were rated according to a scale of 5 alternative “effects”:-

- Significant Positive (beneficial)
- Minor Positive
- Neutral (no overall effect)
- Minor Negative
- Significant Negative (adverse)

Assessments for the most critical stages of exploratory drilling, testing, development and production have rated 10 of the 12 objectives as demonstrating a predominantly negative impact with Population rated as neutral and Flood Risk as “uncertain”. No positive assessments were recorded and a separate cumulative impact assessment produced significant negative effects for 9 of the 11 objectives (with Flood Risk excluded).

Control of additives to fracking water and hazards to water supply: Hydraulic fracturing is an efficient process for recovering natural gas from rock deep underground. Natural gas is cleaner-burning than coal or oil, so it can be better for the environment than those other fossil fuels. However, fracking brings its own environmental problems.

Beginning in 2010, many US states started to regulate hydraulic fracturing, obliging operators to disclose the substances used in their fracturing fluids. In fact, the US Environmental Protection Agency (EPA) reviewed and synthesized the evidence concerning the impact of hydraulic fracturing on US water resources and concluded in its 2016 report that there are instances of surface water contamination related to local leaks and spills, but did not identify widespread or systematic contamination.

The main innovation of the study of the environmental impact of hydraulic fracturing in.[31] (2021) was the large-sample, statistical approach. Still, the relationship among harmfulness of chemicals used, spill locations and sizes, and activities associated with hydraulic fracturing is not fully understood and require further research.

In an analysis of more than 1,000 chemicals in fluids used in and created by hydraulic fracturing, Yale School of Public Health researchers found that many of the substances have been linked to reproductive and developmental health problems, and the majority had undetermined toxicity due to insufficient information.[32] While they lacked definitive information on the toxicity of the majority of the chemicals, 240 substances were analysed and concluded that 157 of them chemicals such as arsenic, benzene, cadmium, lead, formaldehyde, chlorine, and mercury – were associated with either developmental or reproductive toxicity.

An important consideration is the control and monitoring of injection additives, especially biocides. The biocides can be highly poisonous to aquatic life, wildlife and people and must be reliably kept separate from aquifers and life. A breakdown of examples of hydraulic fracturing fluids can be seen in Table 6.

Examples of effects on environment and humans

Exposure to benzene and related compounds: The cancer risk of exposure to BTEX (benzene, toluene, ethyl benzene and xylenes) compounds: These chemicals have a role in fracking, which means they can leak into the air or into groundwater. Many other fracking chemicals pose risks if they get into the air, soil, or water.

Toxic waste storage: Fracking produces heavily contaminated water that is often stored above ground in pits, The chemicals in that toxic waste are not always identified, because of intellectual property laws, but the chemicals that are known can cause a variety of health problems if the fracking waste leaks.

Excessive use of water: Fracking uses huge amounts of water mixed with various synthetic chemicals. The water sources can be the same one that the general public use for drinking and bathing, as well as for agriculture. Natural water sources that are key parts of the ecosystem can be severely reduced by the demand for water. The problem is compounded in areas where water is relatively scarce.

Safety risk to workers from well blowouts: Explosions and toxic gases are environmental hazards, and real safety hazards at well sites. Aside from any air pollution that might result, the explosions may kill or injure workers at the well sites.

Ozone pollution from wells: The EPA considers 75 parts per billion (ppb) the safe limit for ozone exposure. Recordings of ozone levels up to 124ppb were made on some drilling sites.

Workers exposed to toxic chemicals: The health risks from breathing traces of toxic chemicals or ozone are exacerbated for people who work at the fracking sites. Those workers are going to have elevated risk of respiratory illness and cancer because of their exposure. Air pollution is not the only environmental health hazard either. The solvents and other liquids can cause skin rashers and other, more serious health problems even if they are not ingested.

Wastewater disposal: The contaminated water that a fracking well has is to be disposed of eventually. Much of that water gets dumped into waste disposal wells, some of which are well constructed but other are not.

Exposure to silica dust: Crystalline silica (sand) particles are extremely irritating to the lungs and nasal passages. Chronic exposure can cause a variety of serious respiratory illnesses, including an incurable lung disease called silicosis. Sand is a key ingredient in fracking fluids.

Smog Production: Fracking wells release nitrogen oxide and sulphur dioxide. These compounds lead to smog formation. Smog is a long-term threat to human health.

Volatile organic compounds: The leftover fracking chemicals tend to be dumped in open pits, where chemicals in the water outgas. Some of these volatile organic compounds are likely unhealthy to breath, at least for anyone directly downwind of the storage pits.

Groundwater contamination: A single well can produce one million pounds of contaminated water. Fissures or cracks underground, or just porous sections of rock, allow fracking compounds to leak into water. The water table some of that contaminated water ends up in surface water or in wells, where humans or wildlife drink it.

Contamination of wells: The groundwater contamination is a problem in general, but more worrisome when it ends up in wells that rural residents use. Solvents and methane gas leak into wells, rendering them unsafe and possible dangerous. The health effects of consuming many of those chemicals in small amounts are not known. Other chemicals, like benzene are known to be highly toxic.

Soil contamination from waste pits: Volatile organic compounds are only one issue with waste disposal pits. The waste products contain chemicals like benzene and toluene that are also harmful when they leach into the soil. A spill can naturally dump a large amount of the dangerous chemicals, which then drain into the topsoil.

Methane gas emissions: Methane is a greenhouse gas, which has twenty-five times the heat trapping power of carbon dioxide. Therefore, a massive degrease in CO2 emissions could be offset by a relatively small increase in atmospheric methane.

Risks to wildlife: Fish and birds can be put at risk by fracking activities in a couple of ways:

Spills of fracking fluids or waste water contaminate streams and ponds.

Even chemicals that are not immediately dangerous can cause health problems that inhibit the ability of exposed wildlife to reproduce. A 2011 review of 632 chemicals used in fracking, drilling and processing found many that pose risks to humans and wildlife.

Toxic air near fracking sites: Polycyclic Aromatic Hydrocarbons (PCHs) are useful in forcing natural gas out of the ground, but those compounds are also toxic.

Prevention, detection, control, mitigation and emergency response

Planning permissions should not be granted for drilling at sites known to feature geological faults. Given that, irrespective of the outcome, no authorisation for extraction could follow. To proceed otherwise, would be to impose an unnecessary costs and pose a threat to the environment and the region's vulnerable water resources; with implications for the quality of life of the affected communities.

There is no technology that can ensure adequate warning; once a seismic event is triggered there is nothing that can be done to halt or in any way control its further progress, or ameliorate its impact on the community. There can be no reliance on the competence or integrity of operators. There is no methodology that can monitor the impact of fracking with sufficient accuracy to predict future seismic responses.

As the underground effects caused by hydraulic fracturing are not visible and they have permanents effects that are difficult to mitigate, effective regulations are required, which require 24 hour, uninterrupted monitoring and supervision by the regulators to ensure full compliance with the conditions of the licenses and consents. The monitoring and supervision have to be carried out by personnel with adequate experience using adequate methods. It should be noted that lack of adequate quality information is also a risk.

Appropriate regulators should have powers of entry, at any time and without notice, by an independent inspector, to any site for purposes of assessing installations, equipment, materials and processes; and to order the immediate cessation of any operations deemed to constitute a material environment or public health threat. The regulations should make explicit that the well examiner for onshore operations must be independent of the well operator or ideally employed by the appropriate regulator.

The following measures were identified by the UK Government to control the risk of seismic activity:

a) Preliminary assessment of stress fields and historic seismicity to identify stress faults;

b) A hydraulic fracturing plan, identifying how seismic risks would be addressed, ensuring no fracturing near active faults (the term "active faults" was not defined, however);

c) Maintain seismic monitoring before, during and following fracking; and

d) Implement a "traffic light system" with a trigger-stop facility.

The Government considers groundwater contamination as the 'biggest environmental risk'. They may not permit the use of hazardous substances in the fracking process and should exercise their powers to order full disclosure of chemicals. They also may not permit fracking near aquifers or active faults.

Even assuming a total enforceable ban on the use of hazardous chemicals, there still is a threat from methane, brine and NORMs (Naturally Occurring Radioactive Materials) from the re-activation of geological faults, coupled with poor well construction and failure of casings and grout seals. Also, no provisions are envisaged for protecting the integrity of aquifers from drainage by fracturing associated with the re-activation of faults.

Concerning abandoned wells, the operator should be required to notify the regulator of abandonment and the operator should remain liable for the well and expected to remedy any subsequent problems.

Design for response to accidents

Any facility or plant should be designed for,-

- its availability on demand, should it be for normal operation and protection of plant personnel and plant itself in case of an accident;
- functionality;
- operability;
- reliability and
- survivability

which improves by periodical inspection and maintenance. The drilling is normally completed within a few days and the facility operates for 10 years up to 4 decades, which may require a plant life extension.

The design for safety is usually described in the facility Safety Strategy. The plant, SECEs and Barriers in accidental events should be harmonised with the response of facility personnel. This is illustrated in Table 5.

The actions of facilities and response of personnel can be simulated by time-dependent computations including,-

✓ Prevention;

✓ Detection;

✓ Control;

✓ Mitigation; and

✓ Emergency response;

o in this time sequence, and incorporating,-

✓ leaks of harmful chemicals and flammable fluids;

✓ effects of the chemicals on humans, wildlife and environment;

✓ fire and explosion scenarios and loadings;

✓ heating-up of equipment and associated fluid dynamics of the facility inventories;

✓ strength response of the facility and its availability, functionality and survivability;

✓ the actions of personnel and general public; and

✓ survivability of infrastructures.

Prevention

The prevention of an accident can be achieved by reducing the number of potential leaks, such as the use of compact flanges (Figure 22). Referring to Figure 20, the reduction of number of potential leaks moves the risk in the direction from Intolerable to As Low as Reasonably Practicable to Broadly Acceptable. This reduces the likelihood of harm of humans, wildlife and environment from potential leaks of fracking chemicals.

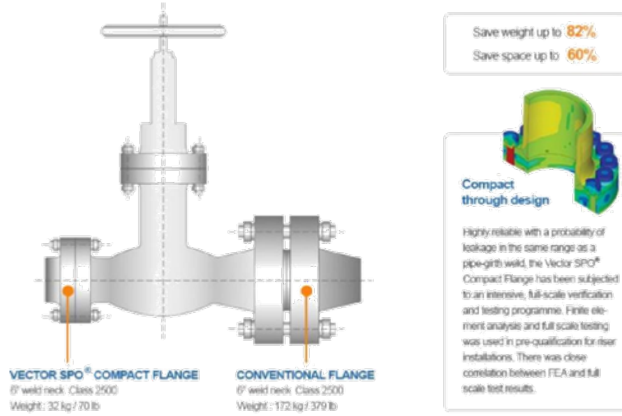

Figure 22 Illustration of a difference between a compact and conventional flange.[21-23]

Detection

The locations of detectors should provide a reliable early detection of accidental leaks.

Control

The control is provided by emergency shutdown and rapid depressurisation of equipment. The control equipment has to be available and functional throughout the accident.

Mitigation

The mitigation involves the reduction of harmful effects, such as temperatures and stress. This can be achieved by a combination of rapid depressurisation and fire protection coatings of vulnerable equipment.

Emergency response

Escape routes should located such that they can be quickly reached by the plant personnel and enable the plant personnel to get quickly to areas of relative safety, from which they should be able to evacuate to a safe location. The safe location may be outside the facility fence, which would require a coordination with the safety facilities of general public, such as the Fire Brigade.

Solutions to the problems described in this article may be examined by making and investigating changes to the design and their effects on the emergency response. Due to the operational and in-

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accident interactions between plant and its SECEs and Barriers, any modifications, upgrades and plant life extensions should be reviewed as a whole, to all details including selection of construction materials.

This article uses the example of fire response of the hydrocarbon plant separator limited with the assumption that the plant will survive and remain functional following initial structural dynamics effects of explosion. The example includes all the complexities of multi-physics thermodynamic behaviour of the separator inventories affected by impinging fire with the final results of computed stress distribution within the separator vessel and its comparison with separator vessel strength at the high vessel temperature. Many cases in the industry may not involve these complexities and the decision on equipment behaviour may be made on the level of temperature. Such cases may be assessed on the basis of a simplistic spreadsheet-based calculation of transient temperature involving,-

- thermal load in the form of time-dependent heat flux from the fire or flame temperature;
- heat transfer from the thermal load by thermal radiation and convection;
- conduction of the heat through the material affected by the thermal load;
- possible transfer of heat between materials being in contact with each other; and
- heat transfer from the "cold" side of the equipment to the environment.
- It should be noted that, despite its simplicity, this calculation requires the data of convection heat transfer, emissivity, absorptivity, thermal conductivity and heat capacity temperature-dependent. This also includes the possible time-dependency on the value of rate of leak and depressurisation.[22,26]

The heating-up of the separator in the shown example is by an impinging hydrocarbon jet fire (Figure 23). The effects of the fire on the separator are summarised in Figure 24.

Figure 23 Gas jet flame impinging on separator vessel.

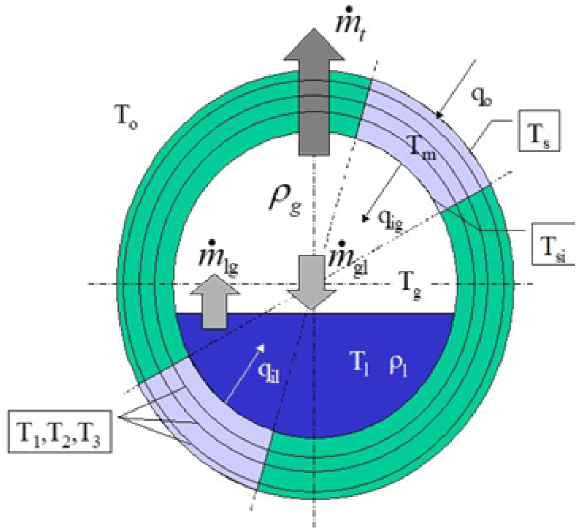

Figure 24 Processes of heat transfer and strength in the pressure vessel affected by fire as simulated by computational dynamic analysis incorporating:

- Heat transfer from the fire onto the vessel shell, the surface of fire protective coating, thermal insulation or protective shield.
- Heating-up of and heat transfer through the fire protective coating, thermal insulation or protective shield (if present).
- Heating-up of and heat conduction through the vessel shell with resulting temperature distribution.
- Reduction of material strength with rising temperature.
- Heat transfer from the inner vessel surface to the vessel contents.
- Thermodynamics of the vessel contents.
- Variation of pressure in the vessel due to depressurisation counter-acted by the increase of the pressure due to evaporation, boiling and expansion of vessel contents.
- Strains and stress in the vessel shell.
- Thermodynamics in the depressurisation pipework.
- Variation of properties of heat transfer and all materials with time and temperature.

The above capabilities are available in the computer program VessFire, which is a system for simulation of fire response of process equipment. It simulates time-dependent heat conduction and stresses of fire response of process vessels. Simultaneously the system simulates the vessels inventory by treating the gas phase and liquid phase separately. The two phases are linked through evaporation, condensing, heat transfer and depressurisation (emptying (blowdown) simulations) of pressurised equipment. The whole system is linked together to a multi-physics simulation and its performance was verified by full scale tests.[33]

Figure 25 shows the time-temperature history of the heating-up of the vessel shell from computer simulation using VessFire. Note the temperature gradient through the vessel shell and the segregation between the liquid and vapour spaces during progressive evaporation of the liquid.

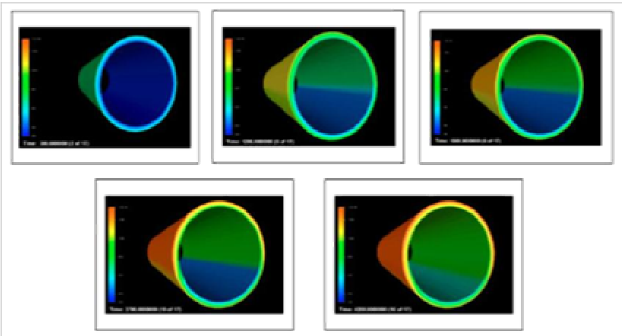

Figure 25 Time-dependent temperatures through cross section of the separator pressure vessel engulfed by fire obtained from computer simulation.

Figure 26 shows the time-dependent variation of temperature, stresses and masses in a process vessel containing oil, gas, water and steam affected by fire. The pictures in Figure 26 were obtained from a thermodynamic mechanical simulation of the separator vessel without and with fire protective coating using VessFire. The vessel without fire protective coating burst within 5 minutes after the start of the fire, which was found inadequate for the plant personnel to escape. Various thicknesses fire protective coatings were applied and the analysis re-run until the vessel burst at approximately 83 minutes (in the top graph) after the start of the fire when the applied stress became greater than material yield stress (which was the failure criterion). The simulation assumed that the vessel process safety valve (PSV) opened on fire detection at time = 0 (refer to the starting slope of the green applied stress curve), while blowdown valve (BDV) opened some time (seconds) after that (the green curve slope shows a higher sloping gradient downwards from the time when BDV opens – the total depressurisation orifice is that of PSV + BDV from that point in time).

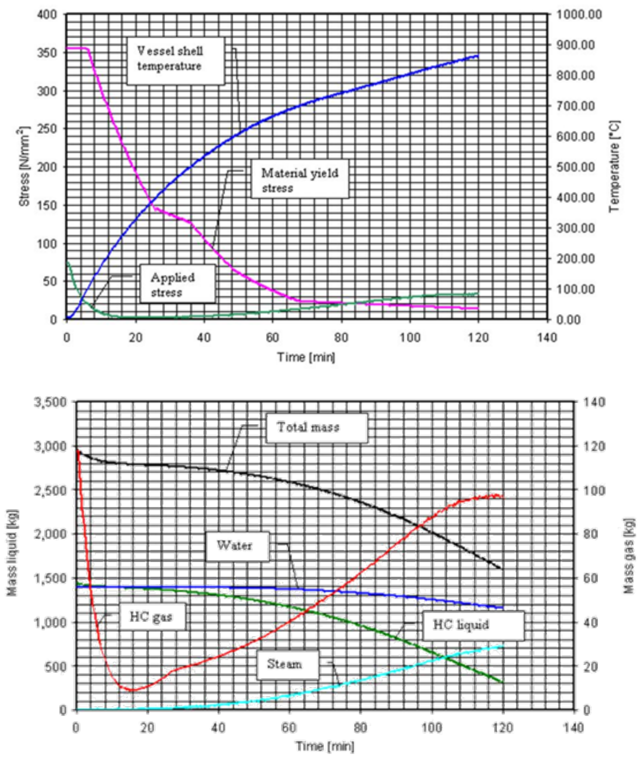

Figure 26 Time-dependent processes in the separator pressure vessel containing oil, gas, water and steam (2 graphs).

Figure 27 shows another scenario: Boiling liquid expanding vapour explosion (BLEVE) from a fire ball (bottom left picture) on a pressure vessel and examples of vessel fragments following the BLEVE.

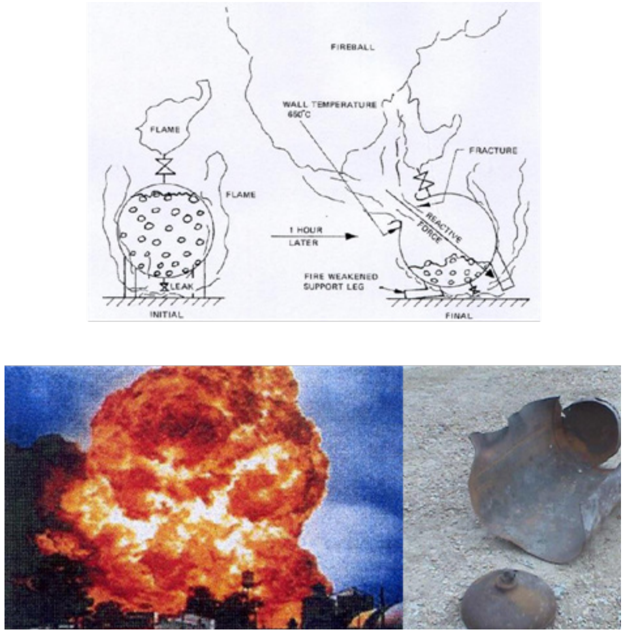

Figure 27 BLEVE from a fireball on a pressure vessel and fragments of the exploded vessel (the time of 1 hour may be much shorter).

Missiles, fragments and rocketing vessel parts can be ejected very far from a BLEVE-d vessel. Figure 28 below shows a map of the plant and neighbouring housing with the landing points of fragments of the site of Mexico City BLEVE catastrophe.

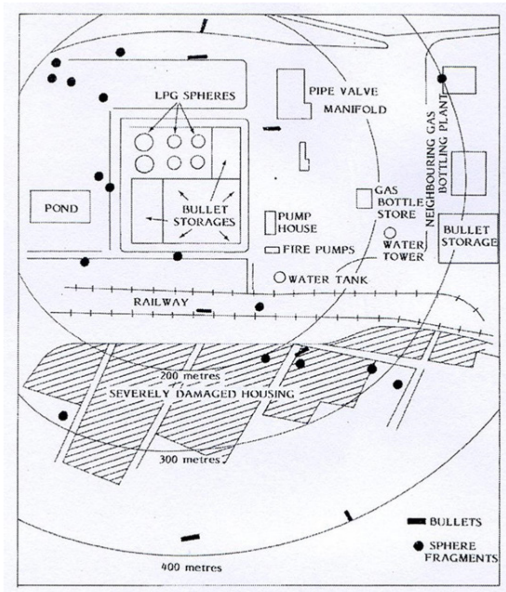

Figure 28 Site of the Mexico City BLEVE catastrophe.

The behaviour of equipment and structures affected by accidents changes with time and temperature. This is simulated by the application of verified computational methods, including material changes with temperature. Actions of site personnel and public emergency services are determined iteratively with the time-dependent behaviour of equipment and structures. Figure 29 illustrates the designed harmonised response in accident between facilities, site personnel and public emergency services.

Citation: Brewerton RW, Medonos S, Warren GD. Hazards to water resources and life safety from exploitation of onshore wells by hydraulic fracturing. *Int J Petrochem Sci Eng.* 2023;6(1):42–63. DOI: 10.15406/ipcse.2023.06.00130

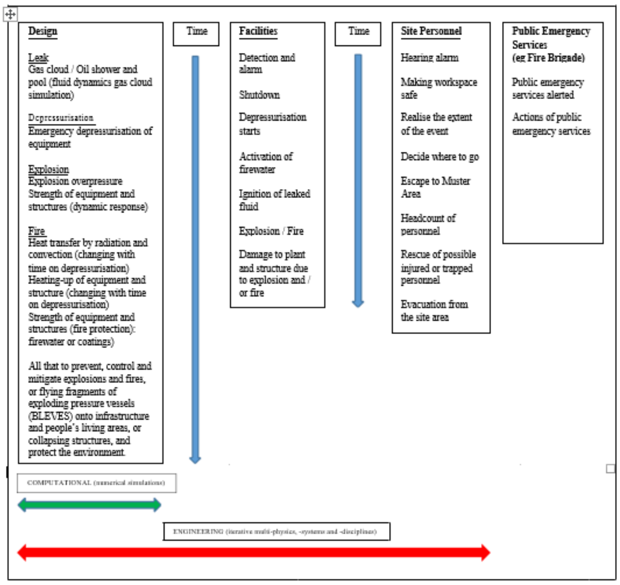

Figure 29 Illustration of designed harmonised response in accident.

Typical changes used for reducing risk levels are,-

A. Reviews of preventive inspection and maintenance;

B. Reducing the numbers of potential leaks of harmful fluids by using less-leaks-prone equipment;

C. Increasing the capacity, speed of activation and operation of depressurising equipment;

D. Increasing the capacity of firewater system;

E. Installing fire protection coatings, blankets or jackets;

F. Reducing the number of staff present in areas of live plant with many potential leak sources;

G. Reducing the number of points of potential ignition;

H. HAZOPs carried out from conceptual and then updates through to detail design, modifications and decommissioning.[34] of the facility, including the identification and updates of hazards and remedial actions (these should include involvement of all disciplines involved).

The harmonised actions between facilities and personnel should be part of PFEER (Prevention of Fires, Explosions and Emergency Response) reviews. Response to accidents by operating companies and public organisations and facilities, such as the Fire Brigade, should be mutually coordinated, including the provision of adequate training to public organisations. Public organisations should participate in the PFEER reviews.

Value of computational methods

This article addresses risks of damage to surface and ground water, and risks to safety of operating personnel and the general public associated with hydraulic fracturing used for the extraction of shale oil and gas. Organisations operating in this industry are to carry out their work as formally regulated in areas of their operations, to valid standards, used in their own guidance and operational experience. Equipment and structural design and their use for normal operations are prescriptive. However, for the protection of safety and environment specific practices may be used as described in operators' safety and environment philosophy, which may be both deterministic and also based on probabilistic methods.

For an accident situation, the facility must be designed such that it enables a safe escape, evacuation and rescue of plant personnel, adequate protection of the general public and the provision of infrastructure for both. This is done by safety and environment critical elements (SECEs) and barriers, which have to provide, in the following sequence of priority, adequate prevention, detection, control, mitigation and emergency response. It should be noted that some systems and components that are required for normal operations also have functions of SECEs and / or barriers.

In the event of an accident, the SECEs and barriers have to be available, functional and reliable, and have the ability to survive the accident from its start to end, whereby at the end all personnel are in the area of safety and the general public is adequately protected against the accident's effects. This is to be achieved by safety design and engineering through the whole history of the accident, as illustrated in Figure 29, and requires a holistic approach involving multi-physics of materials and fluids; -systems and -disciplines, and consideration of the capabilities and behaviour of escaping and evacuating personnel.

For example, permanent local structural deformations not allowed for normal operations, such as the one shown in Figure 30, are permissible in case of accident because it provides adequate support for the escape route in the area above the ceiling.

Figure 30 Example of allowable local deformation of structural support of compartment ceiling.

Similarly, as illustrated in the top graph in Figure 26, the thermodynamic mechanical analysis of pressure vessel affected by fire confirmed that adequate fire protection is provided for, as the vessel would burst 83 minutes after the start of fire. This was the time adequate to shut and depressurise the plant with all personnel and the rescue team evacuated to a safe location and with general public and infrastructure located away from effects of the accident. This has been achieved by the application of numerical time-dependent multi-physics, thermodynamic and stress analysis of the pressure vessel with oil, gas, water and steam inventory.

As another example, the determination of loadings from gas explosions require the application of fluid dynamics, statistical plant failure data and the application of probabilistic methods because the design of process plants and structures using worst-case methods are not realistic.

These capabilities have been developed and qualities of their results verified during the last 50 years of developments of finite element and other numerical methods in systems such as VessFire, FAHTS, USFOS, FLACS, Ansys and Abaqus.

This article uses information obtained from these types of time-dependent non-linear analyses of heat transfer, determination of loads, strength analyses, statistics of failure data and fatal accidents, fracture mechanics and others in safety design and engineering, the methods of which and quality of results have been verified for risk assessments in the petrochemical industry.

The computation of risks associated with operation of plants such as the gathering site and gas and oil terminals is a regulatory requirement in some countries. Risk is defined as the likelihood and consequence of occurrence of a hazard, where a hazard definition in safety is any source of potential damage, harm or adverse effects on something or someone. A hazard can be an object, situation, or behaviour that poses an unacceptable level of danger. Risk computations require statistically obtained failure data of the operating plant, structure and their components and systems.

Conclusions and Discussion

Conclusions

The following conclusions are reached on the basis of this article:

Hydrocarbon recovery by hydraulic fracturing is a high-risk undertaking, with implications for site personnel, general public, environmental quality, property and infrastructure; and the processes involved are, for the most part, carried out at depth and out of sight.

Hydraulic fracturing is a risk to safety of personnel, environment, safety of general public, property and infrastructure. The hydraulic fracturing operation itself is a major cause of well integrity failures that are not normally present in conventional onshore oil and gas exploitation sites. This difference is not well covered in existing UK guidance and significant amendments are proposed in this article.

The risk is considered at the oil and gas extraction well sites, sub-surface environment, transport to disposal site, disposal site and cleaning of fracturing and produced water. The article describes the physics of materials, including geology, actions of systems, facilities and humans in their inter-action, as this is the holistic approach resulting in optimised design and operation not well publicized in the media. The facilities behaviour is time-dependent, which is represented as such in the design by application of verified computerised methods covering various operational and accidental scenarios. The successful design, however, is selected (based on the computer analysis results) by engineers as it involves the inter-action between facilities and humans.

The above risks occur in all phases of exploitation of shale hydrocarbons; drilling phase, hydraulic fracturing phase, production and decommissioning. They are described in detail in the article.

Remediation of contaminated groundwater can be a lengthy, expensive and sometimes fruitless operation; and major pollution events must often be accepted, for all practical purposes, permanent and irreversible.

Effective regulation is therefore required with, as a minimum, continuous 24 hour monitoring and control of all operations, both surface and down-hole, by competent, independent specialist inspectors to ensure full compliance with the relevant consent or license conditions. The statutory regulators may not have the necessary staffing levels with adequate experience and resources to ensure compliance by the operators.

However comprehensive and sophisticated the monitoring regime, there are no means by which any regulator can guarantee or anticipate the re-activation of a geological fault and the subsequent escape of contaminants. A technology that can ensure adequate warning does not exist. Once triggered, there is no action that can be taken to halt or in any way control its progress or ameliorate its impact.

Large areas may need to be seen as hydrological entities, with a high dependence on groundwater, and with their major aquifers vulnerable to seismic disruption. All the sites identified for exploratory drilling and shale gas or oil extraction should be assessed collectively as a measure of the likely cumulative environmental and public health impact.

Given the historic frequency of fugitive emissions as an indicator of well integrity failure, fracked wells should not be used for Carbon Capture and Storage. CO2 injection increases the subterranean pore pressure and an overpressure could in time enhance the drive of pollutants up to surface aquifers or to atmosphere.

The highest risks associated with hydraulic fracturing are of transportation, contact with equipment and fires / explosions. The effect of hydraulic fracturing on geology faults or loss of well integrity are causes common to leaks, which may be flammable (methane) or contaminating. The consequences can be explosions and fires, or contamination. Environmental pollution is a potential consequence of explosion due to the proximity of containers of highly toxic chemicals and tote tanks of concentrate, which can be severely damaged.

Preventative, detection, control and mitigation measures may be the same or similar for several consequences resulting from one cause. The most suitable method for assessments of all the risks associated with the exploitation of shale hydrocarbons is, therefore, multi-physics, -systems and -disciplines (‘holistic’) collective Hazards Assessment study, which is described in this article. Such a study should include semi-quantification with the application of a Risk Matrix.

The holistic Hazard Assessment usually results in optimised solutions of improved technical safety, safety of the general public and protection of environment, property and infrastructure at reduced overall costs.

For all new designs, retrofits and upgrades, always all are to be considered, reducing the probability of failure, and / or reducing the loads and / or strengthening, and their combinations.

The most comprehensive experience with exploitation of shale hydrocarbons is in the United States. That can be used only very selectively and with caution due the differences in geology and the density of population and infrastructure.

The current policy in the United Kingdom is that it ‘will not support fracking until the science shows categorically that it can be done safely’. This moratorium puts back exploitation in the UK but exploitation of fracking overseas may continue, especially in China, which has major water stress problems and where the pressure to reduce their 70% reliance on coal for energy is very strong.

Discussion

The fatal accident rate within the industry in USA is 7 times the USA industrial average. While regulation in UK would improve the situation, it is realised that the methodologies applied and standards will be similar so that a significant reduction in accident and pollution rates cannot be expected without change in these areas. The risk reduction will be none at all in countries that do not have an effective regulatory regime.

Comprehensive baseline monitoring of groundwater, soil and surface water quality were considered in the past with the purpose being to provide standards of reference for the detection of any pollution arising from fracking operations. However, most instances of contamination will originate at depth, and there may be a long delay (weeks or months) before any evidence can be recorded at the surface; by which time, most of the damage will have been done.

The issue of water supply must also be addressed insofar as the demand on resources under drought conditions could prove prohibitive for extended fracking operations.

The yields of shale hydrocarbon wells are significantly lower than with conventional wells, so that, for a given production level, many more wells are required for the former and this affects the economics. Also affecting the economics of fracked wells, is that the wells have to be designed for high injection pressure and they are more complicated than conventional wells. In USA and China the onshore oil and gas industry is supported by state subsidies.

The Hazard Assessment study records the phase of the project when the hazards occur, the Cause and Consequences of the hazard materialising, Risk Type and Level, Barriers, SECEs and recommended Actions. Hazard Assessment studies combined with ALARP provide a semi-quantitative assessment of risk, identification of major accident hazards and identification of risk scenarios that require prevention, detection, control, mitigation and emergency response (in this sequence of priority), and hence also the methods of determination of associated loadings.

The holistic approach in safety design and engineering involves the use of computational methods of time-dependent analyses of explosions, fire, heat, temperature and strength of the SECEs and Barriers for their availability, functionality, reliability and survivability. The determination of explosion loadings and level of risk associated with plant operations require statistical failure data.

The Royal Society and Royal Academy of Engineering report prepared on the request of UK Government recommends risk assessments to be carried out for both technical safety and for the protection of the environment. To date, only Environmental Impact Assessments have been carried out. There is a body of expert opinion which opposes fracking in geological fault zones, and bans or partial bans are now in place in France, Germany, Austria, Spain and the Netherlands.

This article uses information obtained from numerical analyses of heat transfer, determination of loads, strength analyses, statistics of failure data and fatal accidents, fracture mechanics and others in safety design and engineering, the methods of which and quality of results have been verified for risk assessments in the petrochemical industry

Recommendations

The following recommendations are reached on the basis of this article:

It is recommended that any activities of the exploitation of shale hydrocarbons should only commence after a proper assessment of all risks associated with these. This may include a considerable amount of research and science, and changes to current practice and guidance.

The risks associated with effects of hydraulic fracturing on geology and contamination of water resources are of high importance. Effective regulations should be developed. Existing regulations may be used as the basis, but they should be revised for applicability to the exploitation of shale hydrocarbons. The revised regulations should include the requirement of comprehensive geological and hydrological analysis of the effects for hydraulic fracturing on water resources an example of which may be found in.[26].

The revised regulations should include the requirement of 24 hour, uninterrupted monitoring and supervision by the regulators to ensure full compliance with the conditions of the licenses and consents.

The monitoring and supervision have to be carried out by personnel with adequate experience using adequate methods. It should be noted that lack of adequate quality information is also a risk.

Appropriate regulators should have powers of entry, at any time and without notice, by an independent inspector, to any site for purposes of assessing installations, equipment, materials and processes; and to order the immediate cessation of any operations deemed to constitute a material environment or public health threat.

The regulations should make explicit that the well examiner for onshore operations must be independent of the well operator or ideally employed by the appropriate regulator.

For fracked wells, allowable casing stresses should be reduced and Barrier redundancy requirements increased. Given that fugitive CO2 emissions underground can lead to acidification of aquifers and leaching of poisonous minerals and given the potential similarities to fracking operations, the planned techniques for carbon sequestration should be thoroughly investigated to demonstrate that the practice can be applied safely.

In countries which consider the exploitation of shale hydrocarbons, past experience from international activities should only be applied with caution and with respect to the local conditions.

The UK guidance should be made up-to-date with respect to the experience with the exploration of shale hydrocarbons to date and consideration of the risks described in this article.

The risks identified in the article can be used as a template for assessment of risks associated with hydraulic fracturing on the safety of personnel, damage to the environment, safety of general public, property and infrastructure.

An assessment of likely water resource impact of hydraulic fracturing should be made prior to any drilling. The assessment should be carried out on the basis of structural geology and hydrology. The information on structural geologies and hydrology should be on the basis of detailed information on the geologies within and close to the areas of drilling, and as far as the wells are located underground. This information should include aquifers, public water supplies, agricultural and other water abstractions, and stratigraphy..[26] can be used as an example of the assessment required.

Results of the assessment of likely impact of hydraulic fracturing on water resources should be one of the inputs to the Hazards Assessment mentioned in Chapter of ***Hazards Associated with Exploitation of Shale Hydrocarbons***.

It is recommended that the thread of computational intelligence be interrupted by audit points, at each of which, the parallel safety management system (SMS) can control and amend the parameters of the thread. This is to cover for inherent risk uncertainties identified in the SMS process.

Conflicts of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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