

Hydrogen Projects – Business at Usual?

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This paper looks at advances in process safety knowledge gained from recent Hydrogen trials.

Process Safety practices have evolved over the decades, adapting to new findings from industrial incidents, regulatory change and the emergence of new technologies. Industry is on the horizon of major change once more as global efforts focus on reducing emissions of greenhouse gases and plotting a course to Net Zero by 2050. The UK's independent advisor on tackling climate change, the Climate Change Committee, has advised that the 2020s will be crucial in mainstreaming Net Zero solutions. There is no doubt that changes to industry, as well as a move away from gas-fired power generation, will be necessary for further reduction in emissions. Part of the identified solution is the use of low-carbon hydrogen as a fuel source.

The practice of using Hydrogen as a fuel source is in its infancy, and recent hydrogen trials such as HyDeploy and HyNet are providing advances in knowledge; informing operators, regulators, and industry bodies alike. This paper shares a typical process safety lifecycle that was followed for recent hydrogen trials, where installing temporary modifications to existing facilities was necessary, and new infrastructure had to be provided to enable a safe and controlled trial period whilst maintaining the flexibility to give meaningful trial data and results.

The paper looks at the inherent properties of hydrogen to pinpoint how those properties could introduce major hazards to an installation, whilst looking at potential solutions for addressing them in the design. The paper discusses the differences between an innovative hydrogen trial project vs. a more well-established natural gas project. It highlights the need to follow a rigorous hazard identification and risk assessment process, and looks at the tools available to a process safety engineer to provide reassurance that the correct steps have been taken, that best practice has been followed, and the necessary documentary evidence generated. The intent of this paper is to share insights gained from being responsible for the process safety deliverables on recent hydrogen projects. It discusses the challenges faced with trying to comply with natural gas industry standards when delivering a hydrogen project, and demonstrates that allowing for process safety from the earliest concept stage of a project onwards can save time and money.

The objective is to demonstrate that by applying known and established techniques of hazard identification, risk assessment, risk analysis and best industry practice, you can: apply the familiar to the unfamiliar; give confidence to owners, operators, regulators and investors; and deliver a project where the hazards are identified, the risks are understood, and all the right safeguards have been delivered

Historical Gas Provision in the United Kingdom

The 1960s and '70s saw nationwide change to the United Kingdom energy supply network. Prior to this large-scale conversion project, 'town gas' was used for industrial use, as well as domestic cooking and heating services. 'Town gas' constituents include methane, hydrogen and carbon monoxide, with the hydrogen content typically being above 50% and up to 65% v/v[6].

In 1964, Great Britain passed the Continental Shelf Act, sparking the exploration of the North Sea for exploitable hydrocarbon deposits. Gas was discovered off the East Anglian Coast in 1965. This changed the landscape for energy provision in the United Kingdom, with the new source of gas being perceived to be cheaper and cleaner than that produced in gas works as a product from heating coal or coke.

Current Gas Safety (Management) Regulations, introduced in 1996, ensure the safe management of the gas network in Great Britain, placing strict limits on the quality of gas entering the network. Natural gas is predominantly methane, and the current limit of hydrogen in the natural gas supply is 0.1% (molar)[4] according to the regulations.

The changeover from 'town gas' to natural gas took nearly 10 years to complete and converted 13.5 million domestic and 650 thousand commercial and industrial consumers[9]. In the pursuit of low-carbon, or carbon neutral energy sources in the 21st Century, parallels can be drawn with the monumental scale of this past conversion and lessons can be taken, both from the UK's historical abilities to safely transport and use high percentage hydrogen gases, as well as the challenges and investments required to move to a more sustainable UK.

The Drive for Change

It is clear from the global trend in weather patterns and extreme climatic events, that the current international energy status quo is not sustainable.

Key messages issued jointly from the United Nations and the World Metrological Organisation[11] include that;

> "*There is a growing chance of annual global mean near surface temperature temporarily exceeding 1.5 °C above the 1850–1900 pre-industrial level, being ~20% in the 5-year period ending in 2024"; and*

> "*The Emissions Gap in 2030 is estimated at 12–15 Gigatonnes (Gt) CO2e to limit global warming to below 2 °C above pre-industrial levels by the end of this century. For the 1.5 °C goal, the gap is estimated at 29–32 GtCO2e, roughly equivalent to the combined emissions of the six largest emitters.*".

The UK have committed to becoming 'Net Zero' by 2050 – this means that the amount of greenhouse gases that the UK will add to the atmosphere will be balanced by that taken away from the atmosphere. The scale of the task is not insignificant in terms of the commitment in investment, the scale of the required infrastructure change, ensuring favourable public perception, and the demonstration of safety.

The Climate Change Committee published the Sixth Carbon Budget in 2020[2], advising government ministers on the volume of greenhouse gases the UK can emit during the period 2033-2037. The advice published describes a blueprint for a fully decarbonised UK. The goals include a 78% reduction in emissions by 2035 and estimates low carbon investment must scale up to £50 billion each year, which will, in time, be balanced out by the savings from cleaner and more efficient fuel. The report includes the necessity of developing the role of hydrogen, with a metric of low-carbon hydrogen production increasing from <1 TW h in 2019 to 105 TW h in 2035 and 225 TW h in 2050.

In 2021 the government published the UK Hydrogen Strategy[3]. The UK's ambition is for 5GW of low carbon hydrogen production by 2030. It summarises the role of hydrogen in the government's plans:

> *"Hydrogen is one of a handful of new, low carbon solutions that will be critical for the UK's transition to net zero. As part of a deeply decarbonised, deeply renewable energy system, low carbon hydrogen could be a versatile replacement for high-carbon fuels used today – helping to bring down emissions in vital UK industrial sectors and providing flexible energy for power, heat and transport"* [3]

The strategy document acknowledges the successful hydrogen research and innovation to date, committing to provide safety assurance and to address risks with new and emerging technologies. It aims to put the initial network regulatory and legal framework in place by the mid 2020's; with the necessary regulations, codes and standards in place by the end of the decade.

The Requirement to Demonstrate Hydrogen Safety

The previous nation-wide use of majority hydrogen gas in British homes during the times of town gas distribution and the long-term experience of industrial use in refineries and in steam methane reforming (SMR) provide a sound and valuable basis for our understanding of hydrogen and hydrogen safety. Having said this, it remains vital that a thorough safety case for hydrogen, based on demonstrations and compilation of data, in conjunction with the regulators, is demonstrated in order to gain acceptance within the wider public.

Recent ground-breaking hydrogen trials such as HyDeploy and HyNet are providing advances in knowledge; informing operators, regulators, and industry bodies alike. These trials are giving us the evidence we need and therefore the confidence to move forward with the UK hydrogen strategy. Without the data and results from these vital projects, securing the

necessary investment and commitment to go forward would prove to be far trickier. These trials are likely to be the foundation from which a low carbon energy solution can be built and net-zero achieved.

Figure 1: HyDeploy Site at Keele University

Safe Production and Use of Hydrogen

"Will it be safe?" is a reasonable question to be asked when starting a conversation on the change from natural gas to hydrogen or hydrogen blends. For some, memories of past incidents; such as the explosion in an electrolytor plant at LaPorte Industries (1975)[5], or the Hindenburg disaster (1937), or incidents from the nuclear industry; may disproportionately colour their perception of the true risk profile.

Hydrogen production by steam-methane reforming has been underway since the early part of the 20th century. This industrial experience over many decades, in conjunction with the learning taken from incident investigation and published research, has led to a comprehensive understanding of how to safely produce, handle, store and use hydrogen. Distribution of hydrogen on a much larger scale and the use of hydrogen for heating and transport in commercial and domestic settings may be less well understood in more recent times, but the key premise has been there since the days of 'town gas'.

Where new hydrogen projects are started, the key to preventing future accidents is identifying and understanding the risk, i.e., it is no different to conventional good practice for any other project. The established methods of hazard identification, risk assessment, and applying the hierarchy of controls to ensure the overall risks are at a broadly acceptable level, or as low as reasonably practicable (ALARP), are still applicable.

In the UK, the primary regulations that will govern the handling of hydrogen and the associated infrastructure are Dangerous Substances and Explosive Atmospheres Regulations (DSEAR), Control of Major Accident Hazard Regulations (COMAH), Pressure Equipment (safety) Regulations (PER) and the Carriage of Dangerous Goods and Use of Transportable Equipment Regulations (CDG); all of which originated from implementation of EU Directives. As the government have indicated in their Hydrogen Strategy[3], it is likely that these regulations are augmented by codes and standards more specific to hydrogen, and in particular low-carbon hydrogen. At the time of writing, there are three threshold values for hydrogen inventory that should be taken into account if considering the transition to hydrogen as a fuel source:

1. The controlled quantity of hydrogen for The Planning (Hazardous Substances) Regulations 2015 is 2 Tonnes.
2. COMAH regulations specify hydrogen as a named dangerous substance.
    a. The threshold quantity is 5 Tonnes (lower tier).
    b. The threshold quantity is 50 Tonnes (upper tier).

These threshold quantities will primarily affect sites or projects where gaseous or liquid storage is being considered. Reaching these inventories at a facility is less likely if hydrogen is provided by distribution pipeline.

Designing for Hydrogen

Understanding the inherent hazards associated with hydrogen is a good starting point to enable comprehensive risk assessment and ensure the design and operation of facilities will prevent, control or mitigate against hydrogen hazards.

Hydrogen's inherent physical properties, much like other flammable compounds such as natural gas, can be safely managed through lifecycle management of a facility – from design to operation and modification. A designer can use the known properties of hydrogen to influence design considerations. The earlier the identification of risks, the more time-efficient and cost-effective the solution.

As discussed, gaseous hydrogen is in common use in refineries and other industrial facilities, and there is a wealth of experimental and anecdotal evidence of the properties that might be useful to consider early on in the design.

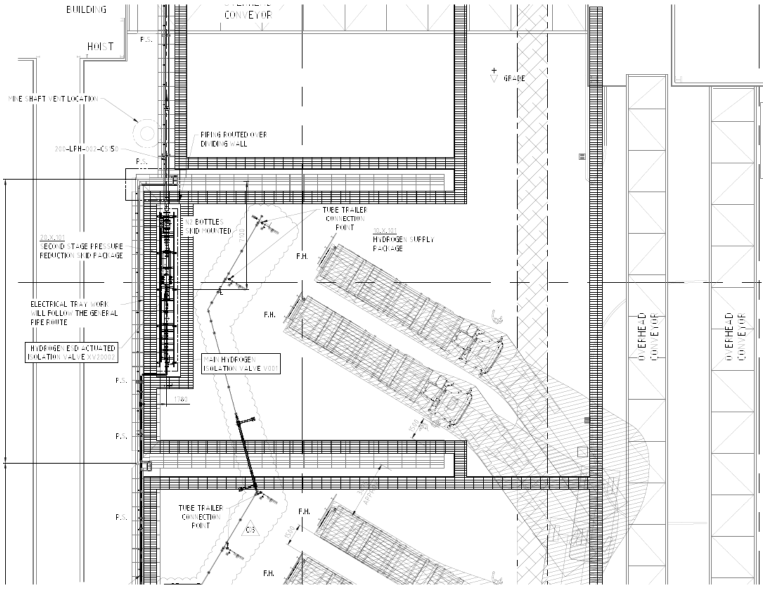

Figure 2: Layout Considerations on the HyNet Fuel Switching Project

Property		Implication	Design and Operation Solutions
Appearance and Odour	Colourless, odourless, and tasteless.	Difficult to detect.	Provision of appropriate types of gas detection equipment – fixed, portable and personal.
Toxicity	Non-toxic, however, does not support life and may act as an asphyxiant.	Large clouds may cause oxygen deficiency if not ignited, and affect the ability to escape.	Appropriate layout should be considered. Confined or congested spaces providing an opportunity for gas build up should be avoided. Preferentially facilities and equipment should be located outdoors. If indoors, good ventilation should be ensured. Potential leak points should be identified and appropriate inspection and maintenance regimes should be put in place.
Flammability	Extremely flammable in air.	Potential for fires and explosions.	Identify loss of containment scenarios for pressurised pipework and equipment and ensure adequate layers of protection are in place. For 'expected' small leaks, such as those covered by hazardous area classification, appropriate extents of zones should be calculated, potential ignition sources identified, and eliminated or controlled as appropriate. Emergency response plans should be put in place.
Ignition	Ignition energy is lower than methane and it burns in air with a very hot and almost invisible flame.	Pure hydrogen and high percentage hydrogen flames are difficult to see. Fires or flames may be harder to detect.	Tight control of ignition sources is necessary. Thermal imaging cameras (fixed) or portable may aid staff to detect an incident and avoid/escape the area.
Detonation	Greater propensity to detonate in mixtures of	Deflagration to detonation transition	The design should consider where oxygen-hydrogen boundaries exist, such as vents to

Property		Implication	Design and Operation Solutions
	air than more common flammable fuels. Maximum burning velocity of a hydrogen-air mixture is about eight times greater than those for natural gas.	is more likely than with a methane or natural gas explosion. Blast overpressure will be higher than for a deflagration detonation and the effects may extend over larger areas.	atmosphere. Appropriate detonation arresters should be fitted. Vent line design should be targeted where detonation may be a concern. This will include minimising fittings and bends and accommodating a higher diameter to length ratio where practicable. Consequence assessment and perhaps QRA modelling may be required to fully understand the consequences from a detonation event, especially if consequences are likely to extend beyond the site boundary.
Density and Viscosity	Low density and low viscosity.	Leak prevention is difficult. Hydrogen is likely to pool at high points, such as roof apexes.	If a hydrogen leak occurs in an open or well-ventilated area its diffusivity and buoyancy will help to reduce the likelihood of a flammable mixture forming in the vicinity of the leak. Ensuring good ventilation and no 'dead spots' is key. Hydrogen leak detection should be placed accordingly.

Table 1: Physical Properties of Hydrogen Gas

Having looked at gaseous hydrogen, it is also appropriate to consider the properties of liquid (cryogenic) hydrogen (LH2). As you would expect, some of the more significant properties are shared with other cryogenically stored gases. Applications involving liquid hydrogen present additional fire and explosion hazards to those arising from use in gaseous form. Again, there is significant experience with these types of behaviour in the UK, for example, at large scale LNG terminals.

Hazard		Design and Operation Solutions
Boil Off Gas	Cold boil-off gas, as well as the liquid hydrogen, can produce severe burns upon contact with the skin.	Segregation of people and equipment. Identification of likely leak points. Well documented inspection and maintenance procedures, including details of correct personal protective equipment (PPE).
Rapid Phase Transition (RPT)	Liquid Hydrogen carries a potential for rapid phase transition (RPT) explosion – this is when cold liquid comes into contact with a liquid that is above the boiling temperature (-253°C for LH2 at atmospheric pressure) of the cold liquid.	Keeping potential loss of containment points away from pools of water where possible. This may include the requirement for avoidance of entry into water pools or directly into rainwater drainage. Drainage.

Hazard		Design and Operation Solutions
Liquid Spills	The release of gaseous hydrogen from a spill would be initially very cold, denser than air and start accumulating at low level. All gases will be condensed and solidified should they be exposed to liquid hydrogen. Leaks of liquid hydrogen in air will cause oxygen to preferentially condense out leading to oxygen enrichment of the solidified material. Oxygen-enriched air reduces the ignition energies, increases the combustion rate of flammable and combustible materials and increases the likelihood of a detonation. Spills of liquid hydrogen can result in air condensing out in and around the pool of liquid. This can result in the formation of zones in the pool, containing an explosive mixture of liquid hydrogen and solidified oxygen-enriched air. These mixtures are shock-sensitive and can detonate with a yield similar to an explosive.	Placement of gas detection at low level around areas of potential liquid spills. Ensuring low occupancy in areas identified with potential for LH2 loss of containment incidents.
Material Degradation	Liquid hydrogen presents severe challenges to the materials it comes into contact with, due to low temperature exposure and hydrogen embrittlement. The thermal expansion and contraction of equipment when exposed to temperature fluctuations of ambient to LH2 temperatures can cause wear and premature failure.	Selection of correct materials of construction. Pipe stress analysis. Inspection and maintenance regimes.

Table 2: Physical Properties of Liquid Hydrogen

Hazardous Area Classification

Work carried out by Health and Safety Laboratory, Buxton (HSL) for the HyDeploy Trial at Keele University looked at concentrations of up to 20% hydrogen blended in Natural Gas (NG). The results showed that volumetric release rates could be up to 10% higher for the blend than NG, and dispersion distances (to ½ LFL) could be up to 15-25% further for the blend. HSL proposed pragmatic, conservative modified criteria to be applied at HyDeploy to the Natural Gas Standard IGEM/SR/25[7] for the blend. Further work will be required to allow these criteria to be used outside the HyDeploy Project.

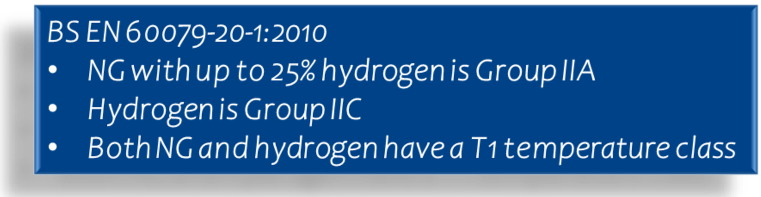

Figure 3: Hydrogen Classification to BS EN 60079-20-1:2010[1]

In contrast, standards addressing Hazardous Area Classification for pure hydrogen or hydrogen blends above 20% are in wide use already. The Energy Institute (EI) Model Code of Safe Practice EI 15[10] guides that any mixture containing above 30% volume hydrogen should be treated as hydrogen. The corresponding EI representative fluid category is G(ii). The HSL tool, Quadvent[8], is also recommended for classifying zones and calculating extents.

Industry Codes and Standards

A number of organisations provide internationally recognised codes with respect to Hydrogen, including; the European Industrial Gases Association (EIGA); the National Fire Protection Association (NFPA) and; the American Compressed Gas Association (CGA). In the UK there is the British Compressed Gases Association, and a number of compressed gas suppliers have their own internal standards. These are particularly useful for identifying requirements for provisional separation and segregation distances for hydrogen storage during FEED.

Hydrogen Design Project Lifecycle

The Plan

One of the first tasks on a project is to produce a programme against deliverables, and that is as true for Process Safety deliverables as it is for the more 'traditional' disciplines. Putting together a list of requirements allows the project to set realistic expectations and allow key individuals to schedule blocks of time for key safety activities such as hazard studies and layer of protection analysis (LOPA) workshops. In order to develop the list of process safety deliverables there are some key decisions to be made by the wider project team;

- What regulatory requirements need to be met?
    - This could include planning permissions, Construction (Design and Management) regulations 2015 (CDM), COMAH, DSEAR, CE or UKCA marking, or Environmental Permits
- Which organisation is responsible for obtaining any permits?
    - What data or other support do they need, how long does the permitting process usually take?
- What codes, standards, and procedures need to be followed?
- When does management of change begin on the project, how is it to be implemented, who needs to sign off?
- Is the project going to use the full suite of hazard studies?
    - Identify a facilitator early in the project and get them on board.
- Are there likely to be safety instrumented systems (SIS)?
    - Start the SIS Lifecycle plan as early as possible and put in place key roles and responsibilities.

This can seem like a lot of hard work and an investment in time and resources, but agreeing all of the above information, deliverables, schedules and responsibilities at the outset can aid the project to proceed far more smoothly. A well-run project wants to avoid any surprises or misconceptions that can cause costly redesign late in the schedule, and maintain good working relationships through the project team.

Process Safety Lifecycle Concept

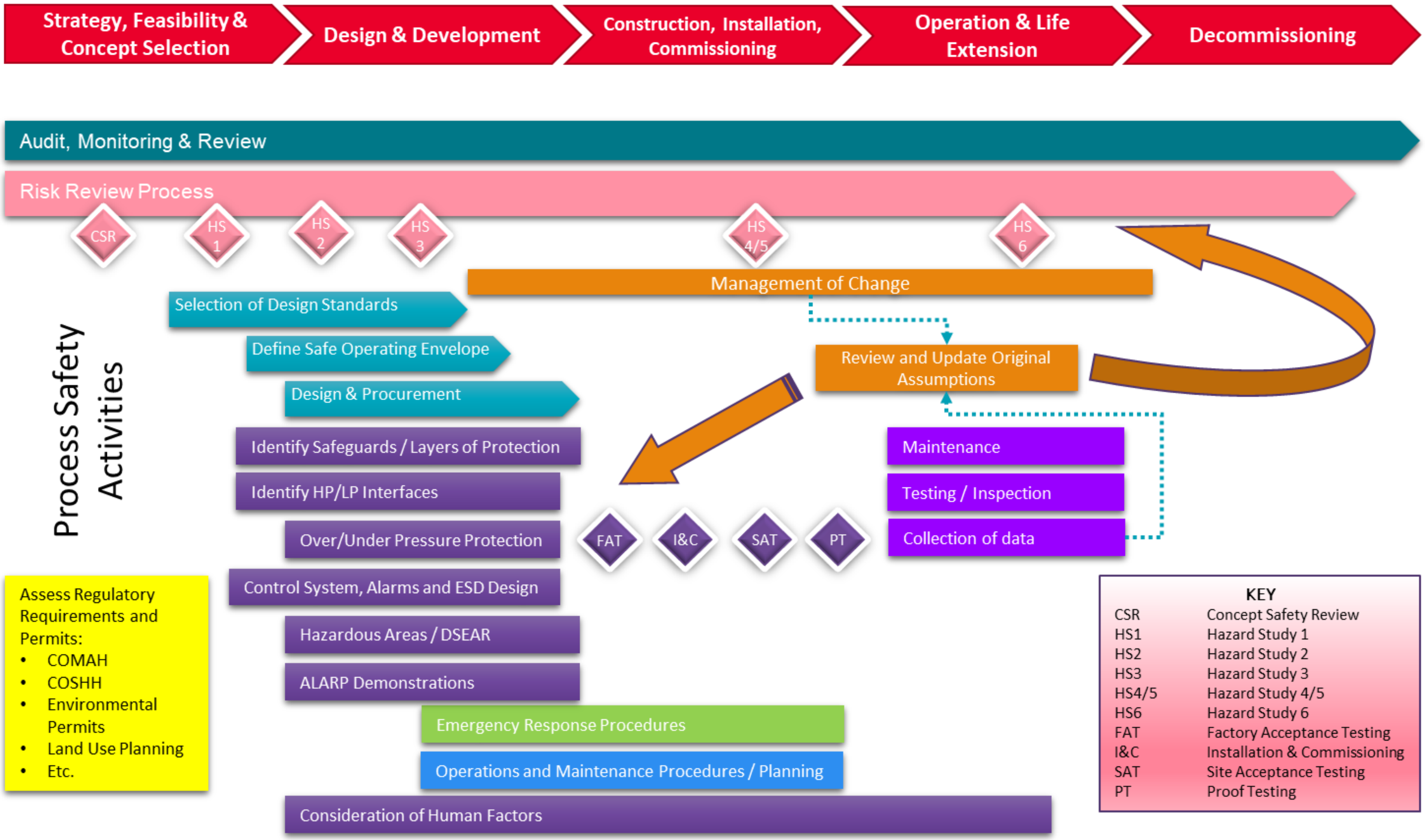

Figure 4: Example of Key Process Safety Activities During the Lifetime of a Project

Key Activities

The Basis of Safety document is a 'live' document which is a focal point for what can be rather disparate process safety deliverables. This is particularly important where a COMAH Safety report is not required, as it is a summary of key studies that will or have been completed, a document map to all the other process safety deliverables, and a repository for ALARP evidence and demonstration. More importantly, perhaps, it is the location for the list of Major Accident Hazards (MAH) or Major Accidents to the Environment (MATTE) that have been identified, along with brief details of potential initiating events and the main safeguards. If this is maintained throughout the lifecycle of a plant, it can be used as a useful tool in staff training as well as documentary evidence of management of risks at a facility. It is useful to start this document early in the project, with a preliminary issue around hazard study 1 or 2, and further issues as the design becomes fixed.

Hazard identification is also something that should begin early in the life of a project, with hazard studies 1 and 2 being recommended. These studies provide early sight of hazards, and provide a focus to the design, spotlighting areas of concern in process. Late identification of hazards may lead to design changes, the requirement for extra safeguards, new equipment or changes to layout. Avoidance of this is key to maintaining schedule and budget. Hazard study 3 can be tricky to schedule; too early and the design is incomplete, leading to inefficient workshops, high numbers of actions and potential for rework under management of change and an administrative burden on the project; too late may mean purchase orders have already been made for long lead items, making the design impracticable to change. This can be alleviated by identifying hazards early in HS1 and 2.

Further more rigorous risk assessments may be required should any high unmitigated consequence hazards be identified. To aid the identification of such hazards, especially if the hazard and operability study (HAZOP) is large, it is recommended that risk ranking is done at HS2 and HS3. This may include, LOPA, Bow-Ties, Fault Trees, Event Trees or Quantitative Risk Analysis (QRA).

DSEAR assessment has already been discussed, but it should be mentioned here that hazardous area classification (HAC) is an iterative process through the design phase. In early revisions, final equipment may not have been fully identified, or the layout may not have been fixed, however, order of magnitude hazard zone extents are needed to progress with selection of components. It is probable that the early revisions are overly conservative and area extents may become less onerous as design decisions are made.

The identification of pressure interfaces is, of course, as important in hydrogen projects as it is in any other.

The Challenges

So far, the discussion around finding design solutions, planning a project and key process safety activities, clearly point to the fact that new energy projects utilising hydrogen are no different to anything else that anyone working in the UK process safety field is familiar with. That is not to say that there have been no challenges, but these have been overcome and it is worth sharing those experiences.

Exemptions to GS(M)R

As previously stated, the current limit of hydrogen in the natural gas supply is 0.1% (molar)[4] according to the regulations. For any project wishing to exceed these limits, official exemption must be granted by HSE. This entails significant effort on the part of the project to demonstrate the safety case to the regulator, as can be expected. The expertise and knowledge to do this kind of demonstration is limited to a few organisations within the UK, and may include laboratory and pilot scale experiments, gas industry experience, experts in the field of explosion sciences, as well as reliability modelling experts.

With the excellent data from trailblazing projects such as HyDeploy proving the safety case for hydrogen blends and the government's commitment to the hydrogen strategy, it could be reasonably foreseen that the GS(M)R regulations will need to be updated to widen the limits of hydrogen in the gas supply in the future.

Gas Industry Best Practice

It seems obvious to say that gas industry standards and practices are tailored to the definition of natural gas as mandated by the GS(M)R regulations. In working with the gas companies, it is natural that they wish to apply their own standards, which give a high level of confidence both in the quality and safety of a build. However, there is little leeway in some of these standards to account for a hydrogen or hydrogen blend. If taking these standards literally, some of the more prescriptive elements are difficult to meet. This requires good communication and relationships between the operators and the designers to come up with an agreeable and safe solution, based on a more flexible interpretation.

Trials and Demonstrations

The very nature of a trial or demonstration project means it is temporary and time limited. This comes with the need to find creative and innovative solutions. The challenges are:

- Physically fitting new equipment into an existing facility, finding the best layout solutions.
- Planning for equipment and plant that can be removed at the end of a trial.
    - Reinstating the plant to its 'as-was' condition.
    - Potentially moving trial equipment to another location or 'mothballing' for later use.
- Installing and commissioning without affecting current production throughput or quality.
    - Potentially narrow and fixed windows during a planned shutdown.
- Sourcing a temporary hydrogen supply.
- Getting the trial results within the allocated window – there is little time to 'tweak' or optimise during a commissioning phase.

Summary

In the author's opinion, based on experiences to date, a hydrogen energy project can and should be treated like any other with regards to the process safety elements. Following best practice, scheduling the appropriate risk assessments, allowing for inherent properties within the design and planning for the right deliverables will get you most of the way to delivering a safe, high-quality project. It is true that the early trials and demonstration projects may have a few extra challenges, but nothing insurmountable if you are creative and have a good working relationship with the wider project team. Over the next decade, as the hydrogen roadmap is achieved, I fully expect hydrogen projects to become, "business as usual".

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