YRKESHÖGSKOLAN
NOVIA

Fire Safety in Hydrogen Processing Facilities - Design Considerations

Dick Söderholm

Bachelor's Thesis

Civil and Construction Engineering

Raasepori, 2023

DEGREE THESIS

Author: Dick Söderholm
Degree Programme and location: Civil and Construction Engineering, Raasepori
Specialisation: Structural Design
Supervisor(s): Johan Degerlund, M.Eng. (Novia UAS)
Simon Nyman, M.Sc. (Ramboll)

Title: Fire Safety in Hydrogen Processing Facilities - Design Considerations

---

Date: 18.10.2023 Number of pages: 91 Appendices: 7

Abstract

Lately, there has been a growing demand for green hydrogen as a fuel source, recognized as an alternative in mitigating CO_2e emissions arising from the usage of fossil fuels. The purpose of this bachelor's thesis was to provide an overview of fire safety in hydrogen processing facilities, with a focus on building design. The goal was to compile a comprehensive summary of fire safety design considerations, including relevant legislation and risks as wells as methods for fire protection and suppression. The work was conducted as a literature study.

The study identified several risks associated with hydrogen handling, with the most significant being hydrogen's flammability and tendency to leak. By understanding these fundamental principles related to hydrogen and fire safety, it is possible to control these properties and mitigate the hazards through various design and technical solutions.

Leak detection in combination with appropriate ventilation can be considered one of the most important safety measures, and the first line of defence. In confined spaces, hydrogen can accumulate, posing an explosion hazard, which should be considered in the design through explosion relief measures and structural solutions. Additionally, since hydrogen is generally stored under high pressure, it further increases the risks, and consequently, jet fire is a constant hazard. Hence, it is crucial to protect essential processes, safety devices, and load bearing structures with active and passive fire protection methods, considering the risk of jet fire along with other types of fire hazards. In addition, a fire detection system is critical and should be designed to detect hydrogen fires along with other types of fires; thus, the use of correct detection technology is essential. Safety distances between different processes and structures is vital when mitigating consequences and propagation of accidents. Consideration should also be given to facilitate access for emergency responses and firefighting.

The study was commissioned by Ramboll, Industrial and Global Services, and the information gathered in the thesis can provide an introduction for designers to the topic of fire safety and related concerns in facilities handling and producing hydrogen. This study helps to understand the fundamental principles regarding fire safety in relation to hydrogen, and in addition, it can function as a checklist or an aid in the design process.

Language: English
Key Words: Hydrogen, fire safety, fire prevention, fire protection, fire suppression

EXAMENSARBETE

Författare:	Dick Söderholm
Utbildning och ort:	Ingenjör (YH), byggnads- och samhällsteknik, Raseborg
Inriktning:	Konstruktionsplanering
Handledare:	Johan Degerlund M.Eng. (Novia) Simon Nyman, M.Sc. (Ramboll)

Titel: Brandsäkerhet i vätgasanläggningar - planeringsaspekter

---

Datum: 18.10.2023 Sidantal: 91 Bilagor: 7

Abstrakt

En växande efterfrågan på grön vätgas har observerats, eftersom vätgas ses som ett potentiellt alternativ för att minska CO_2e-utsläpp som härstammar från användning av fossila bränslen. Syftet med detta ingenjörsarbete var att ge en överblick inom ämnet brandsäkerhet i vätgasanläggningar, med fokus på byggnadsplanering. Målet var att sammanställa en helhet som sammanfattar det som bör beaktas gällande brandsäkerhet vid planering av en vätgasanläggning, och samtidigt även presentera relevant lagstiftning, risker och brandbekämpningsmetoder. Arbetet utfördes som en litteraturstudie.

Arbetet identifierade flertalet risker som hänförs till hantering av vätgas samt egenskaper hos vätgas som leder till en förhöjd brandrisk, varav de mest betydelsefulla kan anses vara vätgasens lättantändlighet och benägenhet att läcka. Genom att förstå de fundamentala principerna som associeras med hantering av vätgas i relation till brandsäkerhet, är det möjligt att kontrollera och minimera riskerna.

Läckageupptäckt i kombination med korrekt anpassad ventilation kan anses vara en av de viktigaste säkerhetsåtgärderna i en vätgasanläggning. I slutna utrymmen kan vätgas ackumuleras, vilket leder till en förhöjd risk för explosion, och bör således även beaktas i designen genom explosionsskyddande åtgärder och -konstruktioner. Eftersom vätgas vanligtvis förvaras under högt tryck, ökar det ytterligare riskerna, och således är även jetbrand en konstant risk. Följaktligen är det ytterst viktigt att essentiella processer, säkerhetsanordningar samt bärande konstruktioner skyddas genom aktiva och passiva brandbekämpningsmetoder, så att risken för jetbrand beaktas i kombination med andra brandscenarion. Branddetektionssystem är en kritisk del av säkerhetsarrangemangen och bör planeras för att upptäcka vätgasbränder tillsammans med andra typer av bränder; således är användningen av korrekt detektorteknologi väsentlig. Säkerhetsavstånd mellan olika processer och byggnader är avgörande för att mildra konsekvenserna samt för att förhindra eskalering av olyckor. Hänsyn bör även riktas mot att underlätta tillträde för nödinsatser och brandbekämpning.

Detta examensarbete är uppgjort i samarbete med Ramboll, Industrial and Global Services, och den information som samlats ihop i studien kan fungera som en introduktion för designers till ämnet brandsäkerhet och relaterade frågor i anläggningar som hanterar och producerar vätgas. Samtidigt som studien hjälper att förstå de grundläggande principerna kring brandsäkerhet relaterat till vätgas, kan den även fungera som en checklista eller användas som ett hjälpmedel i designprocessen.

Språk: engelska

Nyckelord: vätgas, hydrogen, brandsäkerhet, brandskydd, brandförebyggande åtgärder

OPINNÄYTETYÖ

Tekijä:	Dick Söderholm
Koulutus ja paikkakunta:	Insinööri (AMK), rakennus- ja yhdyskuntatekniikka, Raasepori
Suuntautumisvaihtoehto:	Rakennesuunnittelu
Ohjaaja(t):	Johan Degerlund, YAMK (Novia)
	Simon Nyman, M.Sc. (Ramboll)

Nimike: Vetykaasulaitoksien paloturvallisuus - rakennussuunnittelussa huomiotavat asiat

Päivämäärä: 18.10.2023 Sivumäärä: 91 Liitteet:7

Tiivistelmä

Viime aikoina on todettu kasvava kysyntä vihreälle vedylle, sillä vety nähdään potentiaalisena vaihtoehtona CO_2e-päästöjen vähentämisessä, jotka aiheutuvat fossiilisten polttoaineiden käytöstä. Tämän insinöörityön tarkoituksena oli antaa yleiskatsaus paloturvallisuuteen vetykaasulaitoksissa, erityisenä painopisteenä rakennussuunnittelu. Tavoitteena oli koota kattava yhteenveto vetykaasulaitoksen suunnittelussa huomioon otettavista paloturvallisuuteen liittyvistä seikoista, mukaan lukien asiaankuuluva lainsäädäntö, riskit sekä soveltuvat palosuojausmenetelmät. Tutkimus toteutettiin kirjallisuuskatsauksena.

Tutkielma tunnisti useita vetykaasun käsittelyyn liittyviä riskejä, joista merkittävimmät ovat vetykaasun syttyvyys ja vuotoalttius. Ymmärtämällä näitä vetykaasuun ja paloturvallisuuteen liittyviä periaatteita, on mahdollista hallita näitä ominaisuuksia ja minimoida riskejä.

Vuotojen havaitseminen yhdistettynä asianmukaiseen ilmanvaihtoon voidaan katsoa yhdeksi tärkeimmistä turvallisuustoimenpiteistä vetykaasulaitoksessa. Suljetuissa tiloissa vetykaasua voi kertyä, aiheuttaen räjähdysvaaran, ja tämä tulisi ottaa huomioon suunnittelussa räjähdysturvallisuustoimenpitein ja -rakentein. Lisäksi, koska vetyä yleensä varastoidaan korkeassa paineessa, se lisää edelleen riskejä, ja näin ollen myös suihkupalo on jatkuva uhka. Siten on äärimmäisen tärkeää suojata olennaiset prosessit, turvallisuuslaitteet sekä kantavat rakenteet aktiivisin ja passiivisin palosuojausmenetelmin, ottaen huomioon sekä suihkupalon uhan että muut palotilanteet. Myös palonilmaisujärjestelmä on kriittinen osa turvallisuusjärjestelyjä ja sen tulisi olla suunniteltu havaitsemaan vetypaloja yhdessä muiden palotyyppien kanssa; siksi oikean havaitsemisteknologian käyttö on olennaista. Turvavälit eri prosessien ja rakennuksien välillä ovat tärkeitä onnettomuuksien seurausten lieventämisessä ja niiden eskaloitumisen estämisessä. Samalla on huomioitava myös pelastajien pääsy kohteeseen hätätilanteissa ja palontorjuntaan.

Insinöörityön toimeksiantajana toimi Ramboll, Global and Industrial Services, ja tutkielmassa kerätty tieto voi toimia johdantona suunnittelijoille aiheeseen paloturvallisuus ja siihen liittyvät huolenaiheet vetyä käsittelevissä ja tuottavissa laitoksissa. Tämä tutkielma auttaa ymmärtämään periaatteet, jotka liittyvät vedyn käsittelyyn ja paloturvallisuuteen, ja samalla sitä voidaan käyttää myös tarkistuslistana tai apuvälineenä suunnitteluprosessissa.

Kieli: englanti
Avainsanat: vety, Vetykaasu, paloturvallisuus, palosuojaus, palontorjunta

Table of Contents

Acknowledgements

Abbreviations

1 Introduction and Background 1
  1.1 Thesis Purpose 2
  1.2 Research Methodology 2
  1.3 Research Constraints and Scope 3
  1.4 Thesis Structure 3
2 Hydrogen 5
  2.1 Use in Industrial Applications and Green Hydrogen 6
  2.2 The Production Process 7
    2.2.1 Electrolysis 8
    2.2.2 Steam-Methane Reforming 9
    2.2.3 Thermochemical Cycles 10
  2.3 Storage 11
  2.4 Green Hydrogen Production Facilities 13
3 Fire Safety and Phenomena Relevant to Accidents 16
  3.1 Flammability 17
  3.2 Hydrogen Release 19
  3.3 Health Hazards and Environmental Considerations 22
4 Fire Dynamics 24
  4.1 Fire scenarios in Industrial Environments 28
  4.2 Explosion 31
    4.2.1 Boiling Liquid Expanding Vapor Explosion 34
5 Relevant Regulation and The Legal Framework in Finland 35
  5.1 Decree of the Ministry of the Environment on Fire Safety in Buildings 36
    5.1.1 General Principles 36
    5.1.2 Building Components and Fire Compartments 37
  5.2 Act on the Safety of Handling Hazardous Chemicals and Explosives 40
  5.3 Requirements for Industrial Handling and Storage of Hazardous Chemicals 40
    5.3.1 Placement of the Production Facility 40
    5.3.2 Placement Within the Production Facility Area 42
    5.3.3 Requirements for Buildings and Structures 44
    5.3.4 Emergency Preparedness 46
  5.4 Standards and Guides 47
6 Fire Protection, Prevention and Suppression 50
  6.1 Active Fire Protection 50

6.2 Passive Fire Protection 54
6.3 Explosive Atmospheres (ATEX) 56
7 Fire Safety Considerations and Mitigating the Hazards in the Design 61
7.1 Fire Safety Philosophy 61
7.2 The Design Process 64
7.3 Siting 66
7.4 Facility Area Layout 68
7.5 Buildings, Structures, Ventilation and Fireproofing 70
7.5.1 Fireproofing 72
7.5.2 Explosion Relief 73
7.5.3 Ventilation 74
7.5.4 Control Room 76
7.5.5 Substations 76
7.5.6 Office spaces, social facilities, and other occupied buildings 77
7.6 Fire Detection and Suppression, Smoke Control, and Leak Detection 77
7.7 Considerations for Evacuation and Rescue Services 82
8 Conclusion 83

Appendices

Acknowledgements

I would like to thank Ramboll, Industrial and Global Services, for the opportunity to write this thesis, and especially all my colleagues at Ramboll for all the encouragement and collaboration. Special thanks to Simon, Mikko, Sami and Nicklas.

I would also like to thank Western Uusimaa Department of Rescue and all my colleagues at Western Uusimaa Department of Rescue, for the support and flexibility during my years of study.

Additionally, I would like to thank Novia UAS and its faculty members, for the collaboration, flexibility, and support received during the years.

I would as well like to thank my extended family for all the support.

Sincerely,

Dick Söderholm

Siuntio, 18.10.2023

Abbreviations

ATEX	Explosive Atmosphere (atmosphèes explosibles)
BLEVE	Boiling Liquid Expanding Vapor Explosion
CO_2e	Carbon Dioxide Equivalent
DDT	Deflagration-to-detonation transition
ESD	Emergency shutdown system
EU	European Union
FERA	Fire & Explosion Risk Assessment
g/m^3	grams per cubic meter
HAZID	Hazard Identification
HAZOP	Hazard and Operability
H_2	Hydrogen
IEA	International Energy Agency
I-S	Iodine-sulphur cycle
kPa	kiloPascal
kW/m^2	kiloWatt per square meter
LFL	Lower flammability limit
LH_2	Liquified hydrogen
LNG	Liquified natural gas
mJ	millijoule
NTP	Normal temperature and pressure
P2X	Power to X
PFP	Passive fire protection
POX	Partial oxidation
QRA	Quantitative Risk Assessment
RPT	Rapid phase transition
SIL	Safety Integrity Level
SMR	Steam-methane reforming
SR	Steam reforming
TFC	Total final energy consumption
TUKES	The Finnish Safety and Chemicals Agency
TWh	Terawatt hours
UFL	Upper flammability limit
UV	Ultraviolet

1 Introduction and Background

As the world continues to battle the climate change, hydrogen fuel produced from renewable energy sources, is seen as a potential alternative in mitigating CO_2e emissions that arise from the usage of fossil fuels. The International Energy Agency (IEA) emphasises the significance of hydrogen in its Net Zero Emissions by 2050 scenario and predicts that hydrogen's share of total final energy consumption (TFC) will increase from 0,1% in 2020 to 10% by 2050. (IEA, 2021, p. 20)

With the growing demand for (green) hydrogen, it is of most significance to recognise the importance of fire safety when producing and handling hydrogen. It is widely acknowledged that hydrogen presents some challenges in terms of fire safety, and probably one of the most renown demonstrations of the dangers regarding fire safety of hydrogen, is the explosion of the airship Hindenburg in 1937. An accident such as a fire or an explosion in any industrial facility can be devastating; not only result in injuries or even death, but it can also lead to severe economic and social challenges. A fire in a hydrogen facility also presents a great challenge for the rescue department, and in addition, also a great risk to firefighter's health. Hence, it is vital to mitigate the risk that such an event will ever occur.

This bachelor's thesis has been commissioned by Ramboll Finland, Industrial and Global Services, to present an overview over fire safety in hydrogen processing facilities. At Industrial and Global Services, the rapid growth of green hydrogen facilities in the Nordic countries has been recognised, and consequently, also the need for an overview of the topic fire safety in facilities handling and producing hydrogen.

Ramboll is an international planning, design and consultancy company founded in Denmark, operating worldwide with over 18000 experts and presence in 35 countries as of 2023. Ramboll is a member of the global compact act and strives for net zero emissions. In addition, Ramboll aims to be the global leader in the green energy transition and has in the last two and a half years been involved in over 150 hydrogen-related projects. Ramboll also sees strong growth in the green energy and hydrogen market. (Ramboll, 2023)

In addition to experience as a structural engineer, the writer also possesses over a decade of operational rescue task experience as both a firefighter and rescue diver but also experience as a fire inspector. This experience not only aids in understanding the topic, its complex phenomena, and the importance of fire safety, but also reflects a deep fascination and genuine passion for the topic.

1.1 Thesis Purpose

The objective of this thesis is to provide an overview of the essential design considerations regarding fire safety and prevention in facilities handling and producing hydrogen. The thesis will explore relevant fire safety phenomena and hazards related to hydrogen, and furthermore, the thesis will present the legislation and legal framework in Finland concerning fire safety in buildings, with a focus on industrial environments. In addition, standards applicable to the design of a hydrogen facility will likewise be presented, and the thesis will also introduce various possibilities for fire prevention and fireproofing in hydrogen and other similar industrial processing facilities.

Although the focus of this thesis is on fire safety in hydrogen processing facilities, the concepts presented in this thesis can broadly be applied to other facilities that processes flammable gases with similar properties. However, it is important to recognize, that a separate risk assessment must be conducted for each distinct case.

1.2 Research Methodology

The research methodology of the thesis is a qualitative literature study, which means that the aim is to understand the subject matter. This is achieved by utilizing literature, research studies, Eurocodes, standards, and regulation, as well as manufacturer's data and industry best practice. The information obtained from these sources will be gathered into a coherent whole topic area.

Key words: Hydrogen, fire safety, fire prevention, fire protection, fire suppression.

1.3 Research Constraints and Scope

The primary focus of the thesis is on (green energy[1]) hydrogen production facilities, but the concepts can of course be applied to other facilities that produces and handles hydrogen. The thesis is constrained to Finnish legislation and regulation. The thesis will present fundamental principles and properties regarding hydrogen but will not explore these topics in a great depth as the focus is on fire safety.

The scope of this thesis will be restricted to include considerations for the design of the facilities structures, siting and layout, safety related equipment and other equipment directly associated with fire safety. This thesis will not discuss the safety issues related to equipment associated with the hydrogen production or process itself.

The thesis will only discuss fire safety issues related to hydrogen and will not consider specific risks related other flammable liquids or gases, that also might be handled or produced in a hydrogen processing facility.

The thesis will also be constrained to the fire safety considerations of the hydrogen production facility and related structures, and will not consider the fire safety of the structures, technology or applications used to produce the energy required for the production of hydrogen.

1.4 Thesis Structure

The second chapter will briefly discuss hydrogen and its properties as well as usage and production.

Chapter three will present different phenomena associated with hydrogen and fire safety.

Chapter four will discuss fire dynamics and different fire scenarios in industrial environments.

Chapter five provides an overview of the legislation and regulation in Finland regarding fire safety in industrial structures and buildings, with a focus on industrial facilities that

---

[1] Green energy refers to energy produced through to renewable energy sources.

processes flammable gases and liquids. It will also present the most relevant standards applicable in the design of a hydrogen facility.

Chapter six aims to present the most relevant fire prevention and suppression technology used in industrial environments.

Chapter seven will explore safety considerations and ways to mitigate the hazards in the design of a hydrogen processing facility, in addition to presenting the safety design philosophy and the design process.

Chapter eight summarizes the topics discussed in previous chapters.

2 Hydrogen

Hydrogen is a colourless, odourless, and tasteless non-toxic gas. Hydrogen was first identified by Henry Cavendish in 1766, and the name (Hydrogenium) arrives from the Greek words “hydro” (water) and “genes” (from). A hydrogen atom consists of a single proton with one electron orbiting around it; thereby, it is the simplest element and very light, with a molecular weight of only 2,016g/mol[2] under normal conditions[3] (NTP). (Boudellal, 2018, p. 59)

Hydrogen is traditionally used in a variety of industrial applications, but lately has become of accelerating interest in the use as an energy source. Hydrogen is however fundamentally not an energy source, but an energy carrier. Compared to other fuel, hydrogen contains a lot of energy in proportion to its mass. The high amount of energy it contains is however, counterbalanced by the low density and large volume that follows. (Boudellal, 2018, p. 59)

Hydrogen is everywhere and account for 75wt% or 90 vol% of all matter. Although hydrogen is the most frequent element in the universe, it does not naturally occur as a free element (Sivill, et al., 2022, p. 131). Under NTP hydrogen exists as a diatomic gas. The energy content of hydrogen is 33,3 kWh/kg^{-1}, corresponding to 120MJ/kg^{-1}. When compared to other fuel such as methanol, gasoline or diesel, hydrogen demonstrates a much higher energy per unit weight, as seen figure 1. (Gandia, Arzamedi, & Dieguez, 2013)

Hydrogen has a melting point of -259°C, a boiling point of -253°C and a density of 0,07 in comparison with air (=1). Hydrogen is considered a very flammable gas and is the lightest of all gases. (Työterveyslaitos, OVA-Ohjeet, vety, 2022) Hydrogen displays some distinct properties which makes hydrogen challenging in terms of fire safety. These properties relevant to fire safety will be presented in chapter 3.

In addition, selected safety-related physical and thermophysical properties of hydrogen can be seen in annex 1. Comparison with other common gases can be seen in annex 2. Comparison with other fuel can be seen in annex 3.

---

[2] Molar mass is the mass of one mole of a substance and is expressed in grams per mole.

[3] Normal temperature and pressure (NTP): 20˚C and 1 atm (101.325 kPa) (University of Calgary, n.d.)

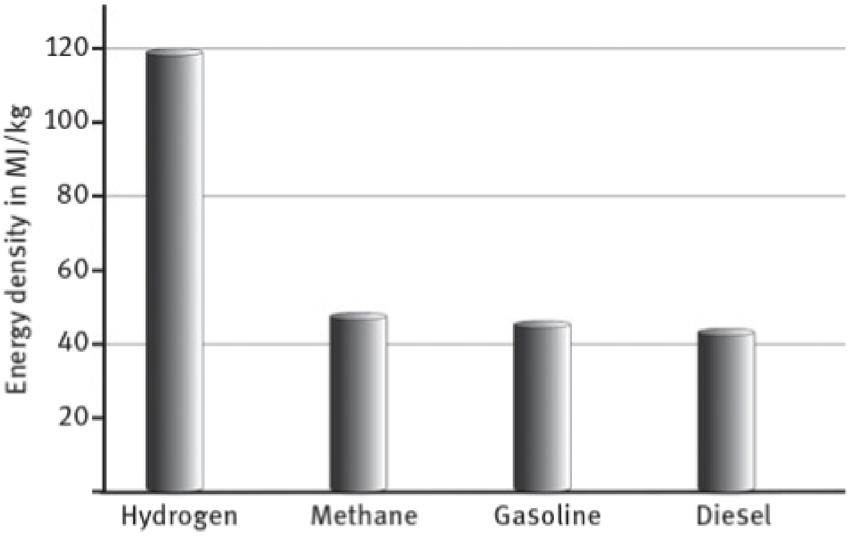


Figure 1. The energy density of hydrogen compared to methane, gasoline, and diesel. (Boudellal, 2018, p. 60)

2.1 Use in Industrial Applications and Green Hydrogen

Hydrogen is used for a variety of industrial applications such as manufacturing ammoniac, methanol and hydrogen peroxide. It is also used in the oil refinement and steel industry. Lately, green hydrogen as a fuel source, has been recognized as having a vital role in mitigating CO_2e emissions, and thereby an impact on the climate change. Green hydrogen refers to using renewable energy sources, such as solar or wind energy, to produce hydrogen (water electrolysis). This technology is often also referred to as “power-to-X” (P2X) or “power-to-gas”. As the technology advances and becomes more efficient in both ends, that is the production and the use stage, many countries including Finland, have been creating strategies or “road maps” for the involvement of hydrogen in becoming carbon neutral. (Laurikko, et al., 2020, p. 4) Green hydrogen will be further discussed in chapter 2.4.

In 2015 the total hydrogen consumption in the EU was 339 TWh and is predicted according to experts (Clean Hydrogen Joint Undertaking, 2023) to rise to 2250 TWh by 2050, with most of the growth coming from hydrogen use in transportation, heating and power for buildings, and industrial energy. (Laurikko, et al., 2020, pp. 9-10) Approximately 60% of the hydrogen production worldwide is based on steam reforming (see chapter 2.2.2) of natural gas or coal gasification. As a fuel, hydrogen has mostly been used in space programs, where properties such as high energy density benefits rocket propulsion. (Kotchourko & Jordan, 2022, p. 26)

The biggest consumer and producer of hydrogen in Finland is Neste refineries in Porvoo and Naantali, and over 99% of the hydrogen produced in Finland is produced by either steam reforming or partial oxidation. Currently, less than one percent is produced through water electrolysis. Figure 2 provides an overview over the hydrogen production in Finland, including the method of production as well as the location. (Laurikko, et al., 2020, p. 23)

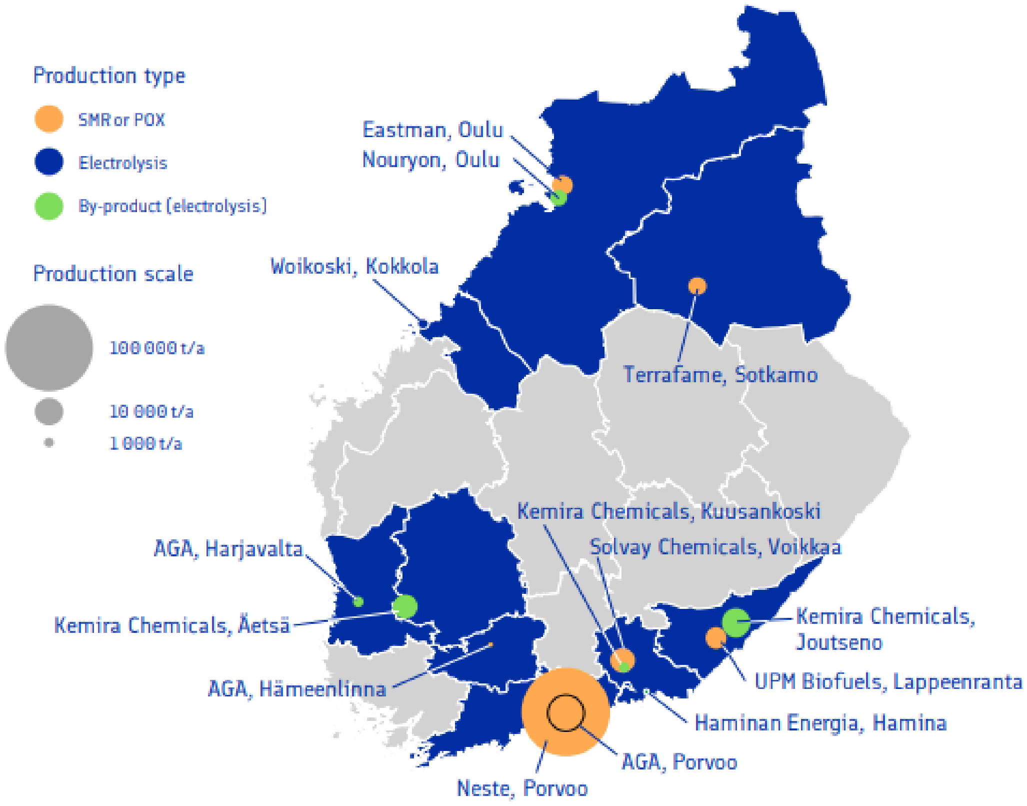


Figure 2. Hydrogen production in Finland. (Laurikko, et al., 2020, p. 23)

2.2 The Production Process

Hydrogen can be produced using a variety of energy sources (coal, natural gas, oil, renewables etc.), and therefore it is a very versatile fuel. It can also be produced in several different ways such as reforming, gasification, electrolysis, pyrolysis, and water splitting. Lately, colors have been assigned to hydrogen depending on the type of energy used in its production, for instance, green for renewable energy sources and blue for natural gas. (IEA, 2021, p. 14)

Currently, the most used methods to produce hydrogen is steam reforming, partial oxidation, thermochemical cycles, and electrolysis (Raunio, 2017, p. 5). Steam-methane reforming is the most cost-effective way of producing hydrogen, and only steam reforming and electrolysis are used in an industrial scale (Raunio, 2017, p. 10).

2.2.1 Electrolysis

Electrolysis or water electrolysis is a process where water (H_2O) is split into hydrogen and oxygen by using an electrical current (Gandia, Arzamedi, & Dieguez, 2013):

$$H_2O\ (l)\ \rightarrow H_2(g) + \frac{1}{2}O_2(g) \tag{1}$$

Electricity is transferred into the water through electrodes, where hydrogen is reduced by a cathode and oxygen is oxidized by an anode through the following reactions (Raunio, 2017, p. 6):

$$2H_2O\ + 2e^-\ \rightarrow H_2 + 2OH^- \tag{2}$$

$$2OH^-\ \rightarrow \frac{1}{2}O_2 + H_2O + 2e^- \tag{3}$$

Electrical and thermal energy is transformed into chemical energy that is stored in the hydrogen. As a by-product oxygen is produced. The hydrogen production is directly proportional to the amount of electrical charge transferred into the system. (Koponen, 2019, p. 18)

There are three main methods of electrolysis: Polymer Electrolyte Membrane Electrolysis (PEM), Alkaline Electrolysis, and Solid Oxide Electrolysis. The basic principle is the same for all three methods, with differences mainly in materials, such as the material of the electrolytes, and how the electrolyser is constructed. (Gandia, Arzamedi, & Dieguez, 2013, pp. 19-37)

It is possible to produce very pure hydrogen through water electrolysis, and depending on the energy source applied, it is also a pollution-free way to produce hydrogen; hence, used in the production of green hydrogen. The efficiency ratio usually is 80 – 85%, although it is possible to increase the efficiency by using higher temperatures. (Raunio, 2017, p. 6) However, the method presents some safety challenges, since hydrogen is in close proximity with oxidizers such as oxygen, in addition that there might occur electrical hot spots in the process (Kotchourko & Jordan, 2022, pp. 40-41). Figure 3 illustrates the water electrolysis reaction process.

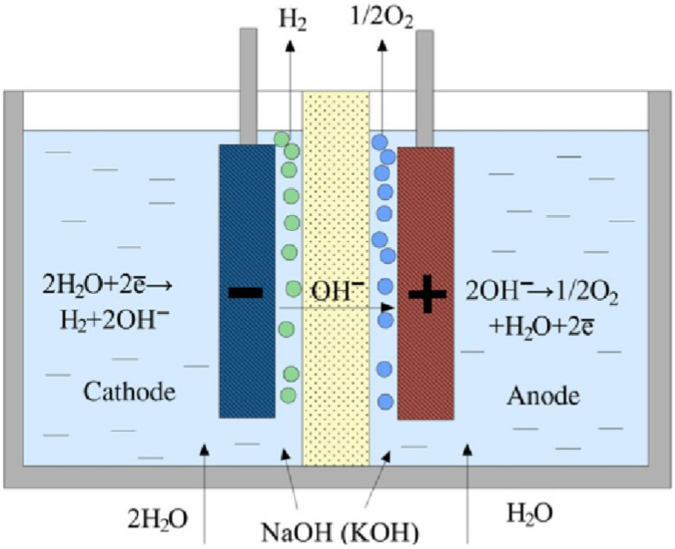


Figure 3. Hydrogen production through water electrolysis. (Gandia, Arzamedi, & Dieguez, 2013, p. 25)

2.2.2 Steam-Methane Reforming

Currently, steam-methane reforming (SMR) is the most used method to produce hydrogen. Steam reforming can be divided into three main methods: steam reforming, partial oxidation and autothermal reforming, of which steam reforming is the most utilized method. (Raunio, 2017, p. 4) As many of the steam reforming processes needs significant heat, it can in combination with the properties of hydrogen present a safety challenge. (Kotchourko & Jordan, 2022, p. 36).

The basic principle of **steam reforming** (SR) is that methane reacts with water, and as a result hydrogen and carbon dioxide are produced. Steam-methane reforming is an endothermic process, which means it needs heat; usually, the process requires a temperature of 500 – 800 ˚C. Steam-methane reforming is based on the following chemical reactions (Raunio, 2017, p. 5):

$$CH_4 + H_2O \rightarrow CO + 3H_2 \qquad - 206KJ/mol_2 \tag{4}$$

$$CH_4 + 2H_2O \rightarrow CO_2 + 4H_2 \qquad - 165KJ/mol \tag{5}$$

During these reactions methane reacts with water, and as a result hydrogen, carbon monoxide and carbon dioxide are produced. The synthetic gas produced from these reactions is then subjected to an exothermic shift-reaction, where carbon monoxide reacts with water to produce hydrogen and carbon dioxide (Raunio, 2017, p. 5):

$$CO + H_2O \rightarrow CO_2 + H_2 \quad +41KJ/mol \tag{6}$$

Partial oxidation (POX) is a process where methane and hydrocarbons in natural gas reacts with a small amount of oxygen. The oxygen is typically taken from air and is not enough to completely oxidize the hydrocarbons into water and carbon dioxide. Hence, the reaction produces hydrogen and carbon monoxide. Partial oxidation is an exothermic reaction, which means it produces heat. Partial oxidation is faster than steam reforming and requires a smaller reactor tank. The chemical reaction for partial oxidation is presented below (U.S department of energy, 2023):

$$CH_4 + H_2O \rightarrow CO + 2H_2 \quad (+Heat) \tag{7}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad (+Heat) \tag{8}$$

Autothermal reforming can be viewed as a combination of SR and POX, where the process combines the endothermic and exothermic reaction of the hydrocarbon steam and oxygen feed, so that no external heat is necessary. The method is often used in small or medium scale, where air instead of oxygen can be used which makes the method less complicated. The autothermal reforming chemical reaction for methane can be seen below (Kotchourko & Jordan, 2022, p. 34):

$$2CH_4 + 2H_2O + O_2 \rightarrow 2CO + 6H_2 \tag{9}$$

2.2.3 Thermochemical Cycles

There are hundreds of different thermochemical cycles, of which most used for hydrogen production is the iodine-sulphur cycle (I-S). The basis for the I-S method is the chemical reactions and chemical properties of water. First, sulphur-dioxide reacts with iodine, which is called a Bunsen-reaction, that produces sulfuric-acid and hydrogen iodine, a solution called HIx-solution: (Raunio, 2017, pp. 7-8)

$$SO_2 + 9I_2 + 16H_2O \rightarrow (2HI + 8I_2 + 10H_2O) + (H_2SO_4 + 4H_2O) \quad T = 120°\mathrm{C} \tag{10}$$

The HIx-solution and the sulfuric-acid is then separated, and the sulfuric-acid is further decomposed in high temperature into water and sulphate.

$$H_2SO_2 \rightarrow H_2O + SO_3 \qquad T = 600°C \qquad (11)$$

The sulphite is then decomposed further into sulphur-dioxide and added back into the Bunsen-reaction. From the HIx-solution hydrogen iodine is extracted and decomposed into iodine and hydrogen. (Raunio, 2017, pp. 7-8)

$$SO_3 \rightarrow SO_2 + \frac{1}{2}O_2 \qquad T = 800 - 900°C \qquad (12)$$

$$2HI \rightarrow I_2 + H_2 \qquad T = 200 - 400°C \qquad (13)$$

Basically, heat and water are introduced to the circuit, and hydrogen and oxygen are produced. The benefit of the method is that no carbon dioxide is produced. (Raunio, 2017, pp. 7-8)

2.3 Storage

A significant challenge regarding hydrogen is storage, due to its low density. This means that a much larger vessel is needed to store the same amount of energy in hydrogen in comparison with other fuel as seen in figure 5. Although various methods are under investigation, there are today four methods available for hydrogen storage: as compressed gas, as liquid hydrogen, as metal and chemical hybrids, and adsorption of different porous materials. (Gandia, Arzamedi, & Dieguez, 2013, p. 270). The methods are graphically illustrated in figure 4.

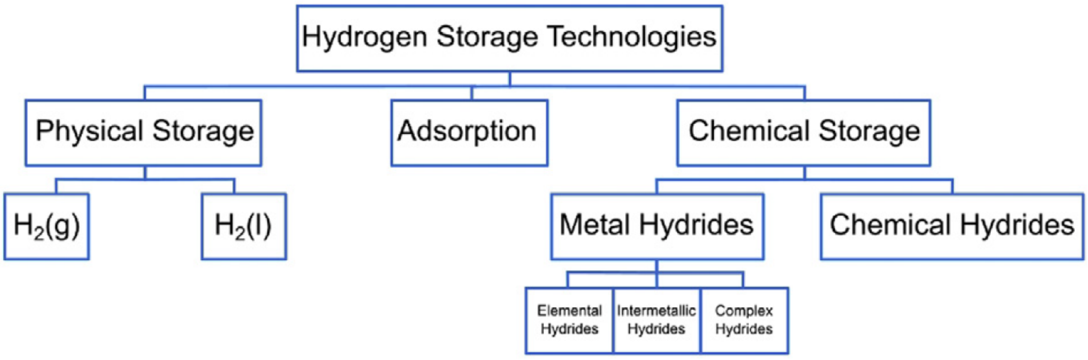


Figure 4. Methods for hydrogen storing. (Andersson & Grönkvist, 2019)

In Finland hydrogen is usually stored and transported as a compressed gas (Työterveyslaitos, OVA-Ohjeet, vety, 2022). Compressed hydrogen gas is normally stored in steel vessels under a pressure of 200-300 bar, although up to 700 bar is used. In mobile transportation, 350 and 700 bar carbon fibre composite vessels are a standard. (Kauranen, Solin, Törrönen, Koivula, & Laurikko, 2013, p. 18) The high pressure in addition to other properties of hydrogen leads to elevated safety hazards. (Kotchourko & Jordan, 2022, p. 50).

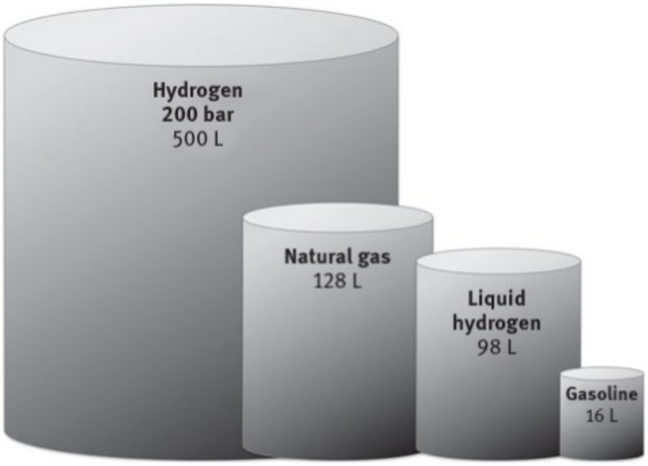


Figure 5. Same amount of energy stored in different fuel and the corresponding volume needed. (Not to scale) (Boudellal, 2018, p. 61)

Hydrogen can be stored as a liquid at a temperature of -253˚C in a vacuum insulated vessel, however, this method will use approximately 30% of the energy stored in the hydrogen. The benefit is that liquid hydrogen has a density of 70,9kg/m^3, which is significantly higher compared to hydrogen gas. Nevertheless, even if the vessel is very well insulated, some percentage of the hydrogen will continuously vaporize. (Kauranen, Solin, Törrönen, Koivula, & Laurikko, 2013) Hence, the method is most suited for short term storage, e.g., mainly mobile transportation (Motiva, 2023). Contamination with air or other impurities might lead to pipes, valves or armatures freezing, and thus result in safety issues. The cryogenic temperature may also condense air, which can lead to enrichment of oxygen. The solid oxygen can furthermore lead to ignition, and it may also oxidize normally inflammable materials. The extremely low temperature also puts a strain on the materials, and thus should the materials used, be carefully considered. Leaking cryogenic hydrogen might also be heavier than air, which means that the buoyant properties normally witnessed in hydrogen are absent and may lead to flammable mixtures forming on the ground. (Kotchourko & Jordan, 2022, p. 47)

It is also possible to store hydrogen in different materials such as metal hybrids, but the method is not widely used commercially. This method can be considered the safest way to store hydrogen, as no hydrogen leak occur. However, the method is not effective, for even the best metal hybrids can only store hydrogen of 10% of its mass. Additionally, heat, which corresponds to energy, is required for the extraction of the hydrogen. (Motiva, 2023)

2.4 Green Hydrogen Production Facilities

Green hydrogen refers to hydrogen produced utilizing renewable energy sources, such as wind or solar energy. The general idea is that the energy produced is stored in hydrogen. The energy transformation from renewable electricity to energy stored in hydrogen is generated through water electrolysis, discussed in chapter 2.2.1. Green hydrogen technology is especially beneficial when renewable energy sources produce excess electricity that is greater than the consumption. This surplus electricity can instead of being lost, be used to produce energy stored in hydrogen for later use. Hence, green hydrogen balances the energy system and functions as an energy storage. (Boudellal, 2018, p. 57) The hydrogen produced can either be used as pure hydrogen in various applications, or alternatively, it can be further refined into other chemicals, such as methane for use as E-fuel[4]. This processing can be achieved either on-site or off-site. (Ramboll, 2023) The whole power-to-gas value chain is presented in figure 6.

A key factor is the location of the hydrogen plant. As the process requires renewable energy, the location must be suitable for production of renewable energy or have access to renewable energy sources otherwise. The longer the distance from the energy and water sources, the more energy is lost on the way; hence, it is crucial that the facility is located close to both energy and water sources. This, in combination with the safety requirements, can thus present a challenge that needs proper planning. (Ramboll, 2023) For instance, the distance to the facility for the local emergency response, corresponding to emergency response time, must be considered when the designing the facility.

---

[4] Electrofuel is a synthetic fuel produced by using carbon dioxide in combination with hydrogen from renewable energy sources. (Ramboll, 2023)

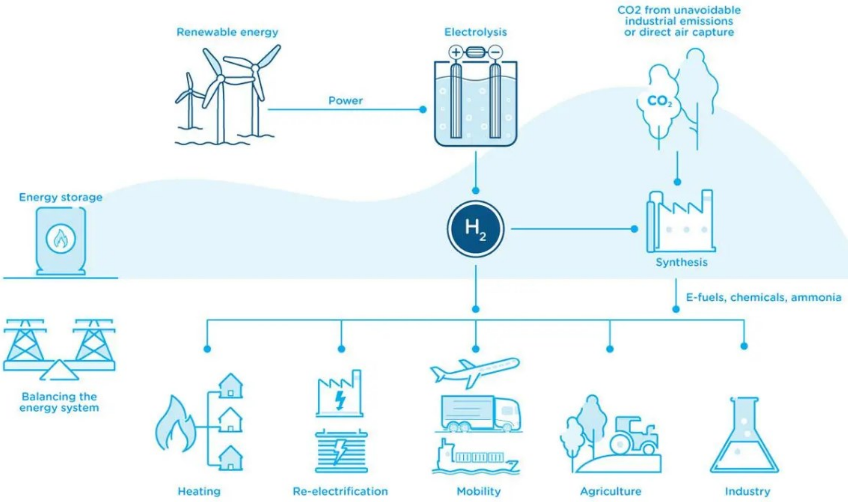


Figure 6. The Power-to-Gas value chain. (Ramboll, 2023)

The green hydrogen production process is illustrated in figure 7. The electricity generated from renewable energy sources is converted by transformers to meet the requirements of the electrolyser stacks. Water is introduced, and the electrolysers subsequently produce hydrogen (and oxygen) as explained in chapter 2.2.1. The hydrogen is then compressed and stored as a compressed gas or liquid; alternatively, the hydrogen can be distributed directly as a pressurized gas into the gas-grid system. Currently, the use of the natural gas-grid system for hydrogen distribution is under investigation, and the need for European standardization has been recognized (CEN/TR 17797:2022). The oxygen produced as a by-product can also be stored and used for various e.g., industrial, or medical purposes. Additionally, the heat generated in the process can be used for e.g., district heating. An example of a basic hydrogen plant layout can be seen in figure 8. (Noordende & Ripson, 2022)

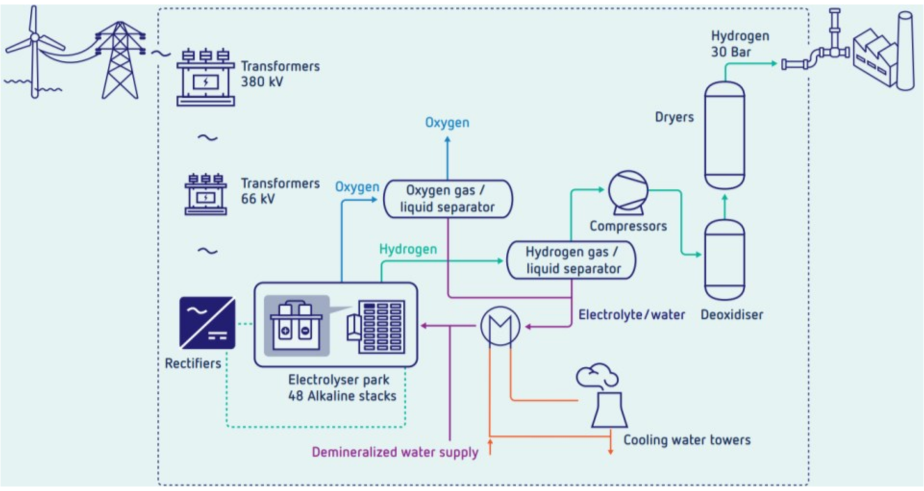


Figure 7. The fundamental principles of a green hydrogen plant. (Noordende & Ripson, 2022, p. 10)

Figure 8. A proposed layout for a one-gigawatt hydrogen plant. (Noordende & Ripson, 2022, p. 26)

According to YLE (Mäntylä, 2023), there are solely in Finland 23 different green hydrogen projects being planned, with a combined investment value of ten billion euros. In Finland, wind power is the most utilized method to produce the renewable energy required to produce hydrogen, but the energy source varies depending on the location and local conditions. (Mäntylä, 2023) A recently completed hydrogen plant located in Japan, that utilizes solar energy, can be seen in figure 9.

Figure 9. A hydrogen plant near Fukushima, Japan. (Lee A. , 2023)

3 Fire Safety and Phenomena Relevant to Accidents

The unique properties that hydrogen displays, presents some challenges in terms of fire safety when producing and handling hydrogen, even in respect to other flammable gases. These properties, in combination with the high pressure under which hydrogen is stored, can be very hazardous and must be carefully considered in the design and operation of the facility. The risks and issues regarding hydrogen can be divided into flammability, interactions between materials, molecular size, and storage procedure associated hazards e.g., high pressure or liquified hydrogen. Although the potential hazards related to hydrogen are universal, the way they present themselves are dependent on the condition of the hydrogen (gas or liquid). (ISO/TR 15916:2015, 2015, pp. 23-24)

Accidents in industrial environments related to hydrogen is often an explosion of some form, and usually is the last phase of a sequence that starts with a hydrogen release, that probably could have been prevented through various safety measures (Kotchourko & Jordan, 2022, p. 118). Various hazards and consequences related to hydrogen release are illustrated in figure 10. The way an accident develops depends on various factors, and by controlling these factors it is possible to mitigate the risks. Hence, it is crucial that these fundamental concepts that presents a hazard, and thus can lead to accidents, are fully understood when designing a hydrogen processing plant.

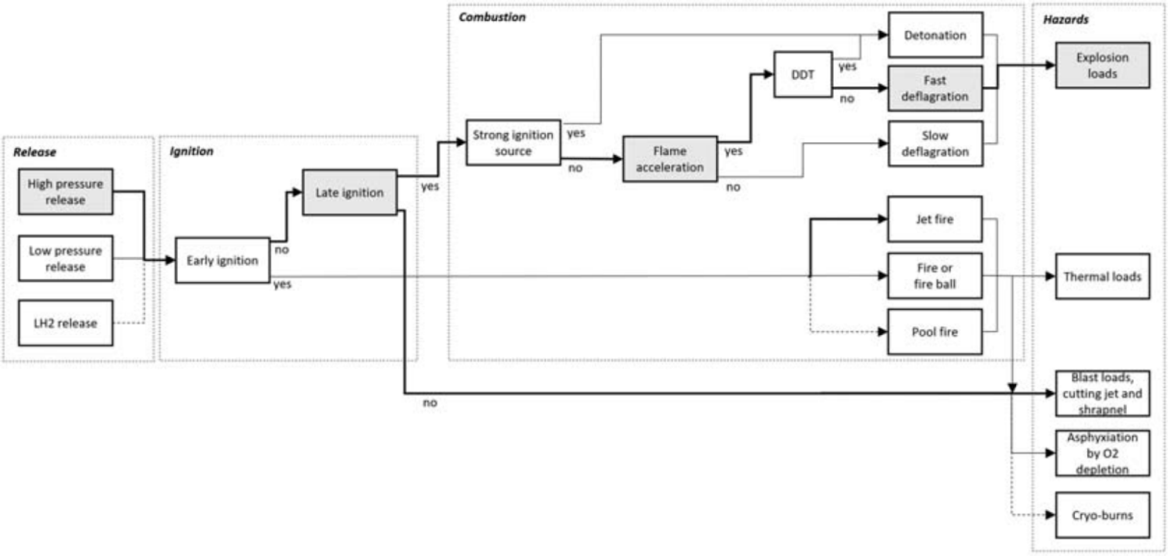


Figure 10. Hazards and consequences related to hydrogen release. (Kotchourko & Jordan, 2022, p. 282)

3.1 Flammability

Hydrogen is a very flammable gas, with a wide ignition limit. Hydrogen has an ignition limit ranging from 4 - 75,6% under normal conditions (NTP)[5]. (Työterveyslaitos, OVA-Ohjeet, vety, 2022) The ignition limit, also known as the flammability limit, refers to the concentrations of flammable substance in respect to air within it can ignite. It consists of a lower and upper limit; in the case of hydrogen the lower limit (LFL)[6] is 4% and the upper limit (UFL) is 75,6%. If the mixture has a concentration below the lower limit or above the upper limit, the substance cannot ignite under NTP. The ignition limit can also be presented in grams per cubic meter of air, whereas the ignition limit for hydrogen is 3,3 – 64 g/m^3. When assessing fire and explosion hazard, understanding the ignition limit is crucial. Generally, the wider the ignition limit, the greater the risk of an explosion. (Hyttinen, 2003, p. 34) The ignition limit also effects the amount of substance that burns, and thus, also the effect and pressure of an explosion (Fjellgaard Mikkelsen, Meraner, Sæter Bøe, & Stølen, 2020, p. 34). In comparison to other fuel, such as gasoline, diesel, methane and propane, hydrogen demonstrates a much wider ignition limit range, as can be seen in figure 11 (HySafe: international association of hydrogen safety, 2017). The National Fire Protection Association (NFPA) classifies hydrogen as a class 4 (severe hazard) chemical in terms of flammability, which is the highest degree of hazard in the classification. (National Fire Protection Association, 2022)

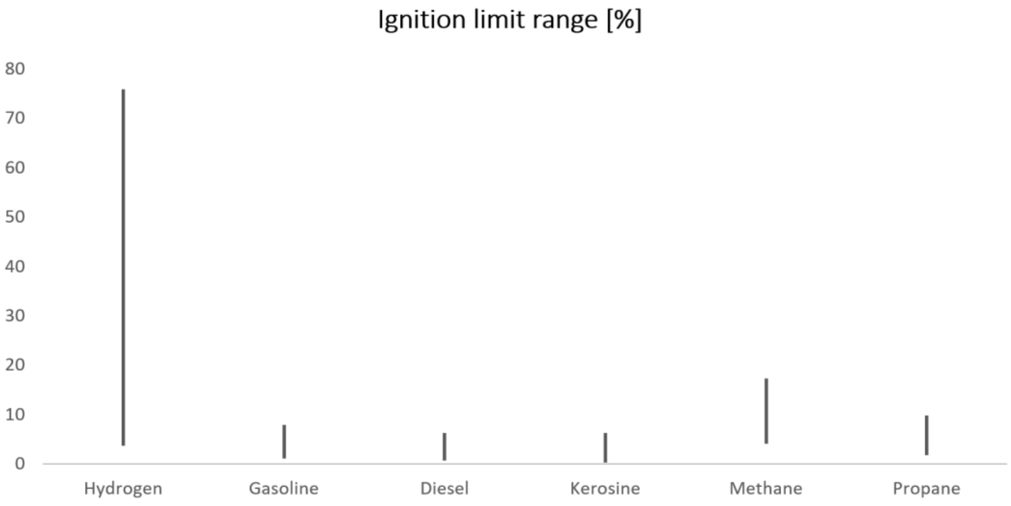


Figure 11. A comparison of the ignition limit range of different fuel. (OVA-ohjeet, 2022)

---

[5] Normal temperature and pressure (NTP) = 20˚C and 1 atm. (101.325 kPa) (University of Calgary, n.d.)
[6] Sometimes also referred to as LEL and UEL (Lower and Upper Explosion Limit)

Hydrogen also has a very low ignition energy of only 0,02mJ in a mixture with air. Ignition energy refers to the amount of energy needed for a substance to ignite. The energy required for hydrogen gas to ignite is so low, that even the static energy from a leak can cause ignition, which makes it seem that it can almost self-ignite. In general, static energy, sparks, hot surfaces, and flames can easily ignite hydrogen gas, but even some metals and rustic surfaces can cause ignition. (Työterveyslaitos, OVA-Ohjeet, vety, 2022) The low ignition energy required in combination with the wide ignition limit, makes hydrogen a very flammable and explosive substance (Fjellgaard Mikkelsen, Meraner, Sæter Bøe, & Stølen, 2020, p. 34).

A hydrogen fire or explosion is also dependent on the flame velocity (2.91 m/s) and energy density (120 MJ/kg). Because of the high energy density and flame velocity, the combustion process can become very intense and result in a phenomenon called deflagration-to-detonation transition (DDT). (Fjellgaard Mikkelsen, Meraner, Sæter Bøe, & Stølen, 2020, p. 35) Deflagration-to-detonation transition is phenomena where a rapid combustion (deflagration) turns into a supersonic combustion (detonation). The difference between a detonation and deflagration is the speed the flame front travels. The supersonic speed of a detonation will result in a shockwave with higher pressure, and thus lead to more severe damage compared to the subsonic deflagration. A DDT typically occurs in a confined space. (Hyttinen, 2003, p. 23) An explosion or detonation is always a hazard when hydrogen and air (oxidizer) are allowed to form a mixture within the flammability limit, either prior (premixed mixture) or after ignition, and can be considered as one of the most significant hazards when handling hydrogen. (ISO/TR 15916:2015, 2015, pp. 20-21)

A pure hydrogen-air flame burns with low thermal radiation, thus reduces the risk for thermal radiation related burns in comparison with other flames. However, as the flames energy is not “depleted” by radiation, the flame temperature is higher compared to other gas flames. A hydrogen flame may also be hard to detect by the human eye, as it burns with low thermal radiation and without soot, although other materials may contribute to the combustion reaction and consequently make the flame more visible. (Fjellgaard Mikkelsen, Meraner, Sæter Bøe, & Stølen, 2020, p. 36) A hydrogen flame can also melt most metals; hence, if the flame touches a pressure vessel, it can rupture within minutes (Työterveyslaitos, OVA-Ohjeet, vety, 2022).

Several different potential ignition sources exist in a hydrogen processing facility, of which the most significant are hot surfaces, electrical sparks, fused wires, incendiaries, adiabatic compression, catalytic materials, and shockwaves. In many hydrogen-related accidents that has been investigated, the source of ignition has remained unexplained, probably because hydrogen's ignition energy is so tremendously small. (Kotchourko & Jordan, 2022, pp. 135-138)

3.2 Hydrogen Release

Hydrogen is the lightest of all gases and much lighter than air, which will result in rapid rise of the hydrogen gas in the event of leakage. Indoors, the gas will therefore accumulate near the ceiling, which can lead to elevated risk of fire or explosion. Hydrogen is also highly diffusive, which means that the gas will rapidly mix with other mediums, such as air (HySafe: international association of hydrogen safety, 2017). Hence, outdoors the buoyant effect is not a problem, as the hydrogen gas will only dissipate into the air. (Fjellgaard Mikkelsen, Meraner, Sæter Bøe, & Stølen, 2020, p. 35)

As previously discussed, a hydrogen-related accident often starts with a discharge of hydrogen. There are of course many factors that can lead to a hydrogen release, but hydrogen releases can generally be classified accordingly:

- permeation, which means a leak through a material,
- jet release, which is a result of a breach in a material under pressure,
- pool vaporization, which is normally related to a spill of liquid hydrogen,
- explosive release, that is normally related to a total disintegration of vessel due to excessive pressure.

(Kotchourko & Jordan, 2022, p. 118)

Because of hydrogen's small molecular size and weight, as well as its low viscosity, hydrogen has a tendency to leak at larger molecular flow rate in comparison to other gases. Even diffusion through intact materials is possible in small amounts, which can lead to accumulation of hydrogen in confined spaces. In comparison, hydrogen has a leakage factor of 50 compared to water and a factor of 10 compared to nitrogen gas. As hydrogen is odourless and colourless, the detection of a hydrogen leak is difficult. Although it is possible to add an odour or colour to hydrogen, it is not practical in most cases. (HySafe: international association of hydrogen safety, 2017) Hydrogen's tendency to escape through materials and its small molecular size, elevates the risks in terms of fire safety when handling hydrogen (Rivkin, Burgess, & Buttner, 2015). Leakage frequencies for different types of fuel was estimated in a report by DNV GL, an independent expert in assurance and risk management, which shows that hydrogen in gaseous form has a significantly higher leakage frequency compared to other fuel such as gasoline, diesel or LNG, as illustrated in figure 12 (Fjellgaard Mikkelsen, Meraner, Sæter Bøe, & Stølen, 2020, p. 37).

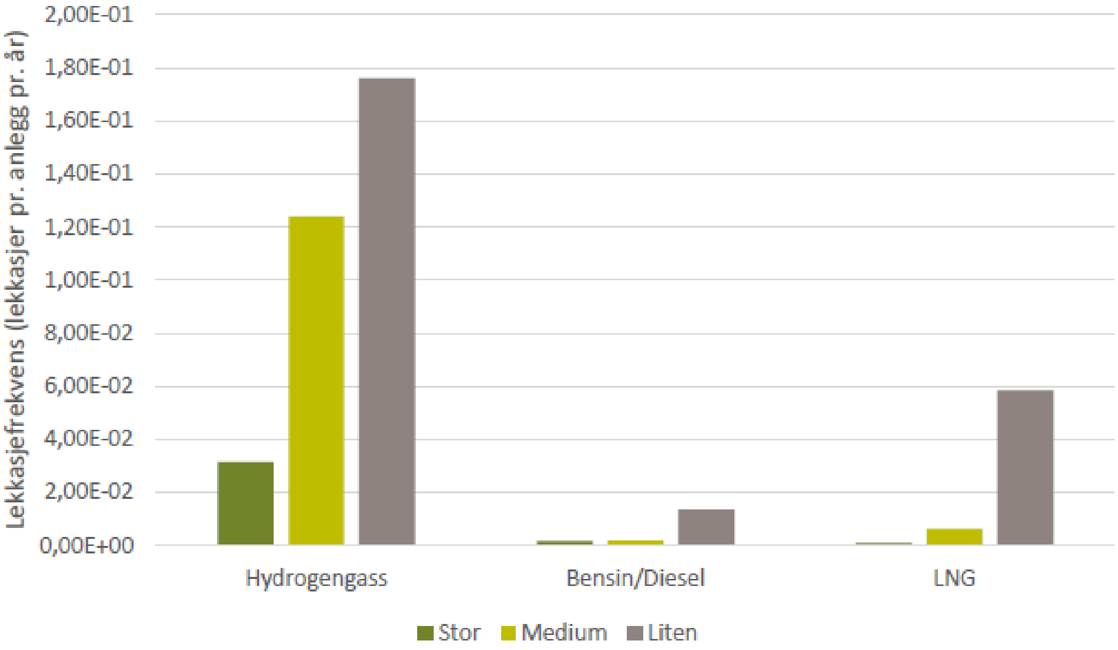


Figure 12. Leakage frequency of hydrogen in filling stations with aboveground tanks compared to gasoline, diesel and LNG. Leak sizes are categorized as large, medium, and small. (Fjellgaard Mikkelsen, Meraner, Sæter Bøe, & Stølen, 2020, p. 37)

As hydrogen due to its low density often is stored under high pressures, a jet release is always a hazard to be considered. A hydrogen jet release can ignite only due to the static electricity produced from the release, and depending on the pressure in the vessel a jet release can result in a jet flame up to 15 meters long. Jet releases can be expected in pressure tanks containing hydrogen in both its gaseous and liquid form. (Kotchourko & Jordan, 2022, p. 153)

Hydrogen also has the ability to damaged certain materials, mainly metals, even to a point of leakage. This phenomenon is called hydrogen embrittlement. (Rivkin, Burgess, &

Buttner, 2015, p. 3) The process of hydrogen embrittlement results in a decrease of the fracture toughness and ductility of metal due to the presence of hydrogen, which usually appears as sharp cracks, and ultimately can result in a devastating failure of e.g., storage vessels. Due to this phenomenon, it is vital that the materials used in the handling and storage of hydrogen is compatible with hydrogen. (Lee J. A., 2016, p. 1) Hydrogen compatibility with different materials as well as materials suited for hydrogen can be seen in annex 4.

Hydrogen also demonstrates a positive Thompson-Joule effect in temperatures above -80˚C, which means that the temperature rises as pressure decreases, which may result in ignition. However, the probability of self-ignition due to this effect is small, and it is more likely, for instance, that a static electrical charge would lead to ignition. (HySafe: international association of hydrogen safety, 2017)

When handling a hydrogen fire, a controlled burning until the hydrogen flow is stopped, is often an effective and safe approach. If a hydrogen fire is extinguished but the hydrogen flow continues, a dangerous combustible mixture is formed, and consequently, it can lead to an explosion if re-ignited. Thus, the most important emergency measure is to stop the hydrogen flow, shutdown the process and activate fail-safe mechanisms. (Kotchourko & Jordan, 2022, p. 332)

Equipment failure is the main cause of hydrogen-related accidents recorded in the H_2 incidents database, as shown in figure 13. As of 2023, 221 accidents involving hydrogen are reported in the H_2 incidents database, including 15 accidents resulting in loss of human life and 115 resulting in property damage. Equipment failure is the leading cause of accidents with 90 reported cases, followed by human error (52) and design flaw (32). Material incompatibility is reported as probable cause in nine cases. Piping (39) and valves (39) are the main cause of equipment malfunction leading to accidents. (Pacific Northwest National Laboratory, 2023)

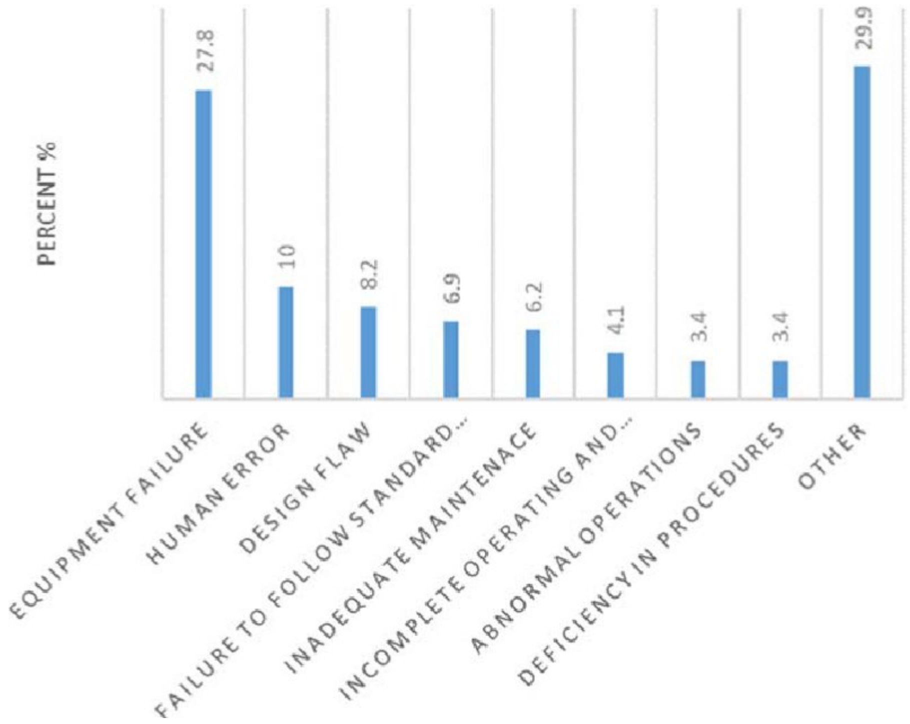


Figure 13. Causes of hydrogen-related accidents recorded in the H_2 incidents database. (Kotchourko & Jordan, 2022, p. 314)

3.3 Health Hazards and Environmental Considerations

Pure hydrogen is not toxic and therefore does not directly present any health hazards, although inhaling hydrogen will make the voice high-pitched. In high concentrates hydrogen displaces oxygen, which can lead to suffocation in enclosed spaces. Symptoms of oxygen deprivations can begin to appear when oxygen concentration drops below 18%. (Työterveyslaitos, OVA-Ohjeet, vety, 2022)

The cold temperature of liquid hydrogen or cold hydrogen gas can lead to severe injury in skin contact. Skin may also freeze onto surfaces and prolonged exposure to cold can lead to frostbite. Even small amounts of splashed liquid hydrogen or cold hydrogen gas into the eyes, can lead to severe and permanent injury. Prolonged exposure to cold can also lead asthma, lung injury or even hypothermia. (HySafe: international association of hydrogen safety, 2017) In addition, a burning hydrogen flame is also hard to detect and can cause severe burns. Furthermore, a rapidly burning hydrogen cloud (explosion) can cause severe burns to individuals inside the cloud. (Työterveyslaitos, OVA-Ohjeet, vety, 2022)

Hydrogen has not been found to have any negative effects on the environment, and therefore present no immediate danger to the environment. (Työterveyslaitos, OVA-

Ohjeet, vety, 2022) The combustion of hydrogen produces only water vapor, and thus has no impact on the environment or CO_2 emissions. It is also calculated that a leak rate of approximately 3% under the whole hydrogen energy chain can be presumed. This is however not a problem from an environmental aspect, as the oxidation of hydrogen only results in water vapor. (Kotchourko & Jordan, 2022, p. 18)

4 Fire Dynamics

A fire incident is an uncontrolled combustion event in which fire causes or threatens to cause damage. Fire is a chemical reaction, where a substance reacts with oxygen so rapidly (oxidation) that high heat, a light effect (flame) and often also smoke are generated. For the combustion phenomenon to occur, all the fundamental requirements for combustion must be present simultaneously: combustible material, oxygen, and sufficient temperature. If one of the elements is absent, combustion will not occur. (Hyttinen, 2003, pp. 8-9) These fundamental requirements are often presented as a “fire triangle” illustrated in figure 14.

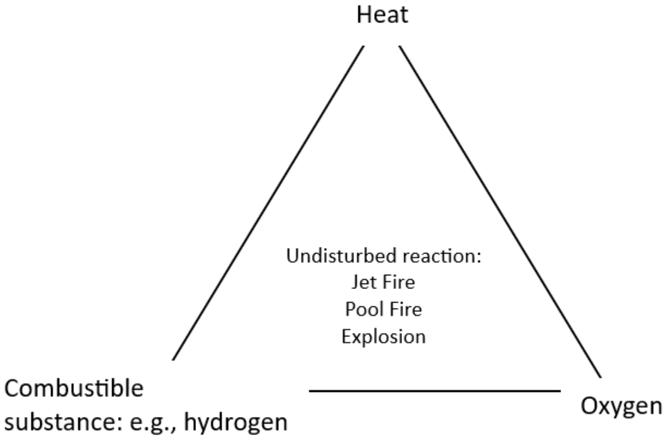


Figure 14. The fire triangle presents the requirements for combustion.

A building or structure fire starts with the ignition phase where a heat source, fuel, and oxygen combine to initiate the combustion reaction. At this point the fire is local, and the fire gases it creates is not hot enough to ignite the surroundings, and thus, the fire only spreads through flame contact. At this stage it is relatively easy to extinguish the fire. The ignition stage is followed by a growth stage, that ends with a flashover resulting in a fully developed fire. Previous the flashover, a phenomenon called backdraft often occur, where a sudden reintroduction of oxygen into an oxygen-depleted confined space ignites the built-up flammable gases. In the fully developed stage, the fire reaches maximum intensity and temperature. The fire consumes all available fuel until it is depleted, and the fire gradually subsides. The fully developed face is followed by a decay or cooling phase, where the fire smoulders or extinguishes. (Hyttinen, 2003, pp. 54-56)

The time it takes for a fire to reach the fully developed stage depends on several factors, such oxygen accessibility and fuel. Studies shows that it in general takes approximately seven minutes for a standard fire (also referred to as a cellulosic fire) to reach the fully developed phase under normal circumstances. (Hyttinen, 2003, pp. 54-56) A standard or cellulosic fire is a fire involving materials such as rags, paper, wood, and other surface materials. The normal stages and the temperature development of a freely evolving standard fire can be seen in figure 15. The fire grows by heat transfer (convection, conduction, and radiation) and flame spread, until all flammable material has burned. (SFS-EN ISO 13702:2015) There are of course many factors that affect how a fire progresses, and especially in an industrial environment there can be various substances that substantially affect the progression.

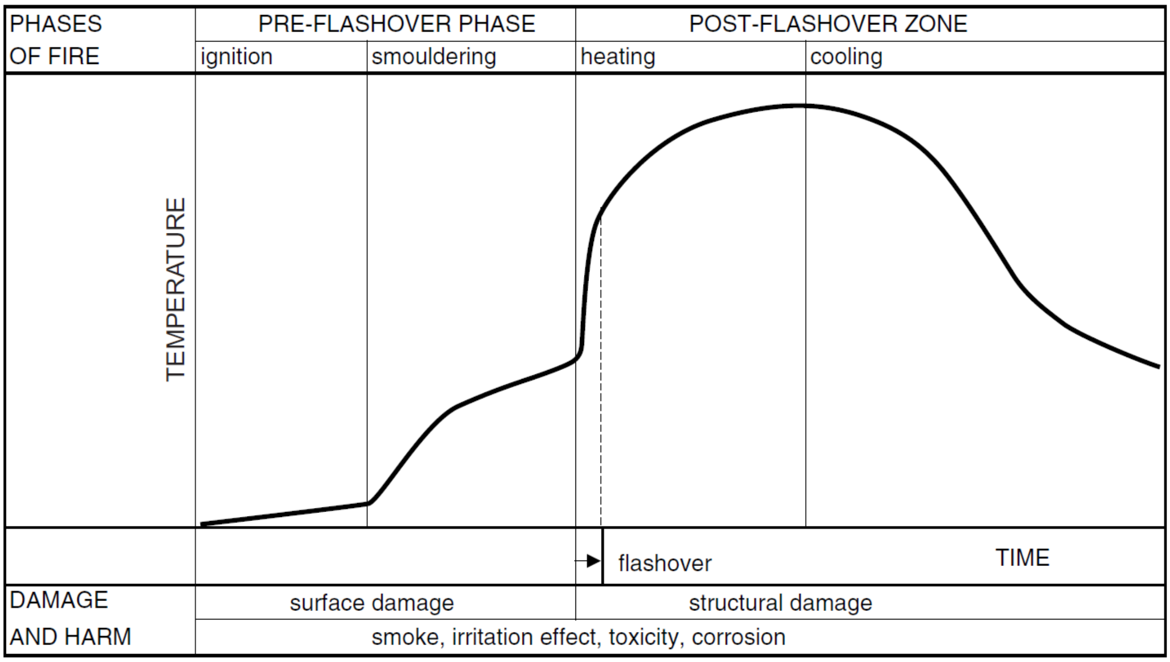


Figure 15. Standard fire progression in a cellulosic fire. (Ongelin & Valkonen, 2016, p. 340)

Different standardized fire curves have been developed to simulate temperature progression during a fire in confined spaces as a function of time. A simple fire progression modelling can be done according to the ISO 834 standard fire curve (figure 16), also referred to as the cellulosic fire curve:

$$\theta_g = 20 + 345\ log\ (8t + 1) \qquad (14)$$

where θ_g is the gas temperate in the fire compartment [˚C]

t is the time [min]

(ISO 834-1:1999, p. 12)

However, in an industrial environment where the fire load, and thus the temperature, often differ from the standard fire curve, the hydrocarbon fire curve (figure 16) presented in SFS-EN-1363-2 is more frequently used:

$$\theta_g = 1080\ (1 - 0{,}325e^{-0{,}167t} - 0{,}675e^{-2{,}5t}) + 20) \qquad (15)$$

where θ_g is the gas temperate in the fire compartment [˚C]

t is the time [min]

(SFS-EN 1363-2:1999, p. 6)

The hydrocarbon fire curve considers a much faster rise in temperature as well as higher temperature compared to the cellulosic fire curve. (SFS 3353:2019, 2019, p. 39)

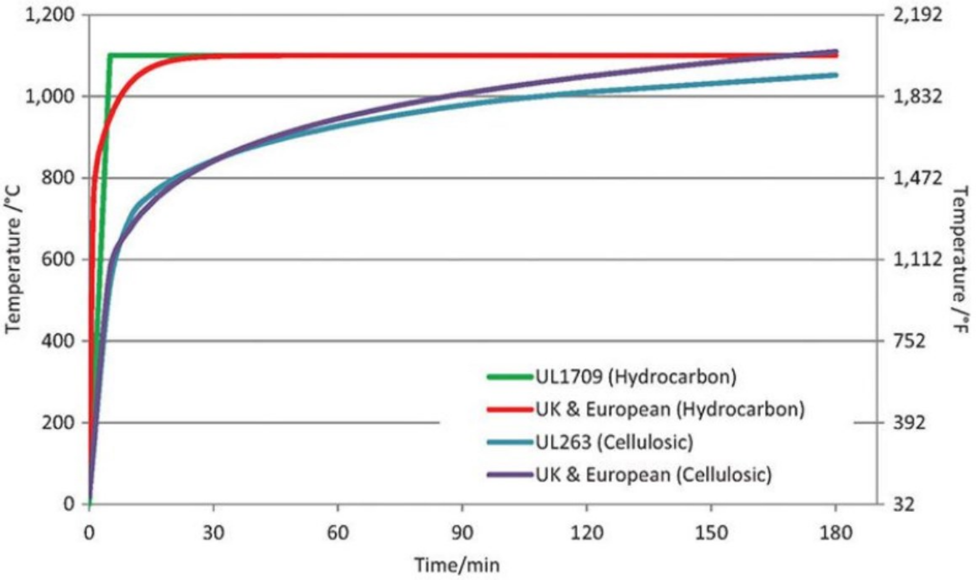


Figure 16. The cellulosic, hydrocarbon and UL 1709 fire curve. (Williams, 2013)

The UL 1709 fire curve (figure 16) considers an even more rapid rise in temperature than the standard hydrocarbon fire curve, and is recommended for jet fire scenarios:

$$T = 1093 \pm 56 \qquad \text{after t = 5} \qquad (16)$$

where T is the gas temperate in the fire compartment [˚C]

t is the time [min]

(ISO 20902-1, 2018, p. 25)

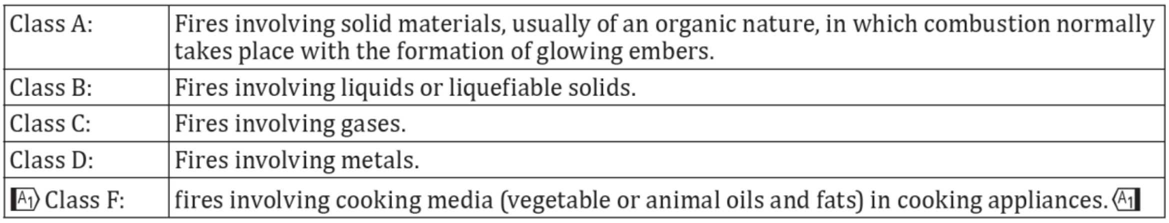
For more complex fire scenarios, functional fire design (performance-based fire design) based on assumed fire development (P0) is more frequently used. Functional fire design takes into account building specific features and allows to predict fire behaviour, smoke movement, and the effectiveness of fire safety measures under various conditions; hence, allowing a more dynamic and sometimes more realistic approach, that allows functional and economic benefits without compromising safety. However, this method usually requires more expertise and is often more time consuming. (Teräsrakenneyhdistys, 2020, pp. 3-4)

Nonetheless, for each distinct case a separate risk assessment must be made where all potential hazards are assessed, and the fire modelling must be done according to each scenario depending on the hazards present. Hence, generally the hydrocarbon fire curve is applied in case of pool fire hazard and general industrial environments, whereas the fire curve UL 1709 is recommended for jet fire situations. (SFS 3350:2016, 2016, p. 48) Load bearing structures must be dimensioned according to the worst-case scenario. Fire type, time under fire and critical temperature for the structure must be assessed for each case. (SFS 3353:2019, 2019, p. 39)

Naturally, different fire exposure also requires different approach for extinguishing purposes, that must be considered when designing a facility and its fire suppression system. For instance, a cellulosic fire is often easily extinguished with water, whereas in a hydrocarbon pool fire situation, water might escalate the fire.

Fires can generally be classified based on the fuel involved according to the classification in SFS-EN 2:1993 + A1:2004 presented in table 1. However, chapter 4.1 will describe some typical fire scenarios in industrial environments, based on the fuel involved or the underlying mechanism of the fire.

Table 1. Fire classification according SFS-EN 2:1993.



Class A:	Fires involving solid materials, usually of an organic nature, in which combustion normally takes place with the formation of glowing embers.
Class B:	Fires involving liquids or liquefiable solids.
Class C:	Fires involving gases.
Class D:	Fires involving metals.
[A1⟩ Class F:	fires involving cooking media (vegetable or animal oils and fats) in cooking appliances. ⟨A1]

(SFS-EN 2:1993 + A1:2004: classification of fires, 1993)

4.1 Fire scenarios in Industrial Environments

In an industrial setting there are in addition to the normal structure fire hazards, additional risks in terms of fire that involves a wide range of substances that can pose various hazards. In addition to the different substances handled, such as hydrogen, an industrial environment often also involves processes and equipment that can malfunction or produce immense amount of heat, and thus can cause a fire.

According to Suomen Kaasuyhdistys ry (Suomen Kaasuyhdistys ry, 2023, p. 8) various ruptures and leaks, external fires and operational errors are the main causes for accidents involving fire in facilities that handles flammable gases and liquids. The main causes for fires in industrial environments generally, are chemical reactions, mechanical sparks, lighting, various flames, static electricity, electrical sparks and arcs as well as hot surfaces and processes. (SFS-EN ISO 13702:2015, 2015, pp. 26-28)

According to the Emergency Services Academy in Finland (Pelastusopisto), there were 610 building fire alarm assignments and 106 emergency tasks related to hazardous substances in industrial facilities in Finland 2022. The majority of the emergency assignments concerning hazardous substances were associated with flammable gases or liquids. In 2022, there were a total of 51 fatalities related to fire in Finland, but there have been no fire-related fatalities in industrial facilities in the last five years. (Loponen & Luikkonen, 2023, pp. 19,28,34)

A **hydrocarbon fire** is a fire where hydrocarbons such as gasoline, diesel, oil, or natural gas burn. Characteristically, a hydrocarbon fire develops much faster than a cellulosic fire and can reach 1100˚C within 5 minutes (SFS 3353:2019, 2019, p. 9). A hydrocarbon fire usually also reaches higher temperatures than a cellulosic fire (SFS-EN ISO 13702:2015, 2015, p.

25). Hydrocarbon fires often produce an immense amount of heat as well as thick black toxic smoke, and therefore poses a great risk to individuals, structures, and vital processes. Figure 17 shows the intensity of a hydrocarbon fire as well as the vast amount of black smoke generated. Hydrocarbon fires are commonly encountered in industrial settings where hydrocarbons are processed but also e.g., transformers containing substantial amounts of oil or incidents involving vehicles used for transportation can cause a hydrocarbon fire. Hydrocarbon fires often require specialized firefighting techniques and equipment, such as foam additives or dry chemical agents, to be extinguished and to mitigate the consequences. (SFS-EN ISO 13702:2015, 2015, p. 24)

Figure 17. A hydrocarbon fire at Deepwater Horizon in the Gulf of Mexico 2010, taken by the U.S. coast guard. (Williams, 2013)

A **jet fire** refers to a type of fire that occurs in a high-pressured stream of combustible gas (or atomized liquid) that burns. A jet fire typically occurs in an industrial setting and arises from a leak in a vessel containing some form of pressurized flammable gas or liquid. As jet fires are a risk associated with flammable gas stored under high pressure, jet fires are thus a significant and severe hazard in hydrogen processing facilities. Characteristically, a jet fire has a long flame and high heat. It is destructive to anything in its vicinity. The heat transfer from a jet fire can be 200kW/m^2, which is much higher than e.g., a pool fire. A jet fire burns closely to its source and will often burn until the release is stopped. (Nolan, 2010, pp. 55-

56) The flame temperature can be very high and can within seconds rise to almost 1400˚C as seen in figure 18 (R. Stølen, 2018, p. 3). Active fire suppression systems usually has little effect on a jet fire, but such systems can be used to protect other structures and equipment from the heat transfer as well as prevent the fire from spreading (SFS-EN ISO 13702:2015, 2015, p. 24).

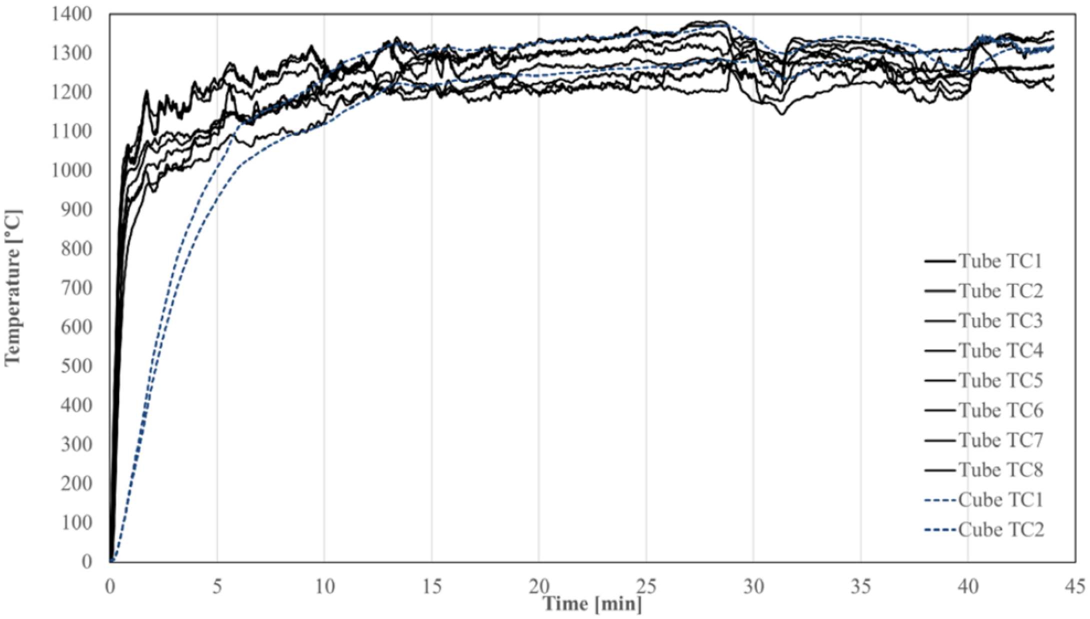


Figure 18. Characteristically, the temperature in jet fire rises instantly. (R. Stølen, 2018, p. 3)

A **pool fire** is a fire where a liquid or material form a pool that produces vaporized fuel which ignites above the pool. Pool fires are generally based on a liquid, although gas and solid materials can cause a pool fire. (Chakrabarty, Mannan, & Cagin, 2015, p. 12) A pool fire is a diffusive fire where gas vapors from the pool that rapidly ignite, leading to the transfer of more heat to the liquid, causing further vaporization of gas. This loop will make the fire area to grow rapidly in size. Heat transfers by convection and radiation, and the heat transfer rate can reach 30-50kW/m^2. (Nolan, 2010, p. 56) A pool fire is necessarily not static, as it can move as the liquid moves. Foam fire extinguishers can be very effective against pool fires, especially hydrocarbon pool fires. The foam will form a protective layer on top of the liquid, and thus, suppress the air flow to the fire which reduces the fire. The extinguish-foam solution used must be selected to be suitable for the specific liquid or material that is burning. (SFS-EN ISO 13702:2015, 2015, p. 24)

Flash fires occurs when fire spreads suddenly and rapidly across a diffuse fuel mixture, such as a gas or vapor, typically lasting for a short duration (Nolan, 2010, p. 57). It usually occurs when a fuel mixture above the upper flammability limit attains oxygen enough to ignite. It travels from the ignition source towards its release point. Though it is unlikely that is causes immediate fatalities, it can cause damage to structures and individuals. Large flash fires can also ignite other flammable sources inside a large area. A flash fire is not an explosion, although, it can develop into an explosion in confined spaces. (Chakrabarty, Mannan, & Cagin, 2015, p. 19)

A **dust explosion** is also a common type of fire or explosion in industrial environments. In a dust explosion a cloud consisting of small combustible particles such as dust or powder ignite, usually causing a type of flash fire. (Hyttinen, 2003, p. 35) As dust explosion is not that relevant in the context of hydrogen processing facilities, dust explosions will not be further discussed.

4.2 Explosion

An explosion is a rapid release of energy. The damaged an explosion causes are dependent on energy dissipation mechanisms, such as a pressure wave, projectiles, thermal radiation, and acoustic energy (Chakrabarty, Mannan, & Cagin, 2015, p. 21). An explosion always involves a pressure wave, but it can also involve fragments, projectiles, vibration, and noise. The shockwave often poses a risk of structural collapse, but for instance, also the vibrations caused by an explosion can damage structures. Projectiles normally has an initial velocity of up to 1000 m/s, and it is difficult to assess their launch angle and flight path. An explosion also produces heat and hot gases, which can ignite the surroundings. (TOKEVA, 2012, pp. 2-4)

An explosion can be chemical, mechanical, or nuclear (Chakrabarty, Mannan, & Cagin, 2015, p. 22). As nuclear explosions are rare and not relevant to the topic, nuclear explosions will not be discussed. Chemical explosions are usually an exothermic oxidation reaction, and most of the energy is carried by the shockwave which is uniformly distributed in all directions. (HySafe: international association of hydrogen safety, 2017) The energy comes from thermal heating and the number of changed moles in the reaction, as a result from the changed chemical composition. (Chakrabarty, Mannan, & Cagin, 2015, p. 22). The type of pressure it creates depends on the combustion process (HySafe: international association of hydrogen safety, 2017).

A mechanical explosion, also called physical explosion, typically originates from a pressurized gas (Chakrabarty, Mannan, & Cagin, 2015, p. 24). It is a result of various physical phenomena (Hyttinen, 2003, p. 20). Characteristically, a mechanical explosion is caused by a rapid expansion of a pressurized gas combined with structural failure. The most common mechanical explosion is a Boiling Liquid Expanding Vapor Explosion, also called BLEVE, which will be separately discussed in chapter 4.2.1. Another form of mechanical explosion is a rapid phase transition (RPT), where a vapor explosion results in a phase change of fluid in contact with hotter or colder liquid. The energy release is often smaller than in a chemical explosion, although RPT still can cause a shockwave and fragmentation. (HySafe: international association of hydrogen safety, 2017)

There are two kinds of explosions that derives from flammable gases: detonation and deflagration. As briefly discussed in chapter 3.1, the difference between a detonation and deflagration is the speed the flame front travels. In a detonation the reaction moves faster than sound (supersonic), whereas in a deflagration the reaction moves slower than the speed of sound (subsonic). In a detonation the reaction propels the shockwave ahead of it. The slower speed of the reaction in a deflagration, conversely, result in the pressure front moving away from the reaction at the speed of sound. Hence, a detonation causes much more damage. The phenomena are explained in figure 19. A typical detonation pressure in a free space is around 1,6 MPa but can increase to 15-35 MPa in a pressure vessel. (Hyttinen, 2003) Deflagration pressure typically is around 10 kPa for free hydrogen, but it can be significantly higher in a confined space (Kotchourko & Jordan, 2022, p. 14). Generally, a detonation requires a more stoichiometric[7] fuel mixture and greater ignition energy compared to a deflagration (ISO/TR 15916:2015, 2015, p. 21). Table 2 shows the physical effects of detonation pressure. Figure 20 compares the pressure spikes of deflagration and detonation pressure.

---

[7] Stoichiometric refers to the ideal ratio of fuel and oxygen required for complete combustion.

Table 2. Physical effects of explosion pressure. (Note, modified from original table)

Effect	Pressure [kPa]
Windows break	3,5 - 7
Pressure knocks person over	7
Eardrum ruptures	34
Lung injury	100
Risk of death	240
50% risk of death	345
99% risk of death	450

(Hyttinen, 2003, p. 23)

As acknowledged in chapter 3.1, a deflagration can turn into a detonation, called deflagration to detonation transition (DDT). DDT is a complex phenomenon, which is not fully solved in theoretical combustion theory. (Chakrabarty, Mannan, & Cagin, 2015, p. 21)

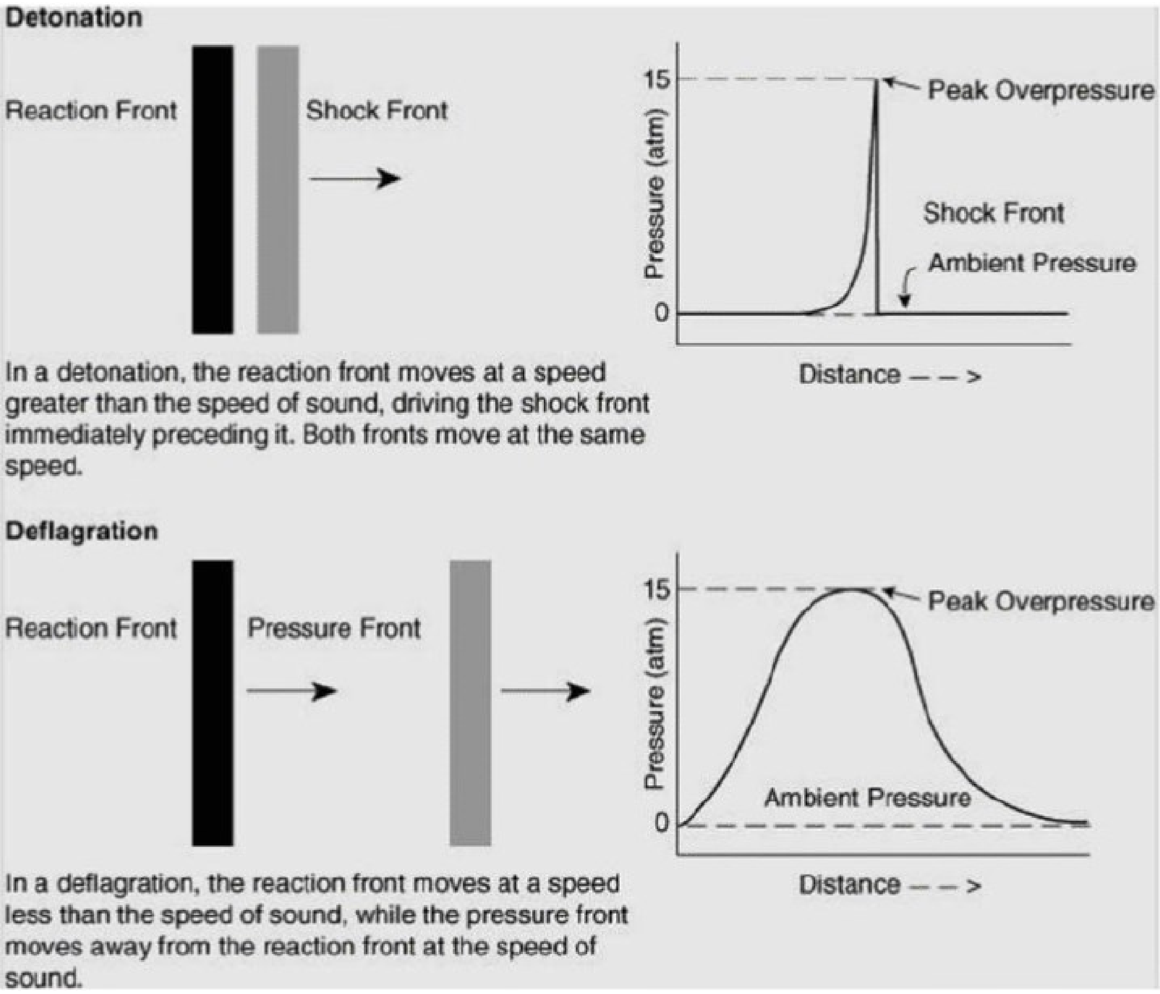


Figure 19. The difference between detonation and deflagration is the speed the reaction front travels. (Chakrabarty, Mannan, & Cagin, 2015, p. 22)

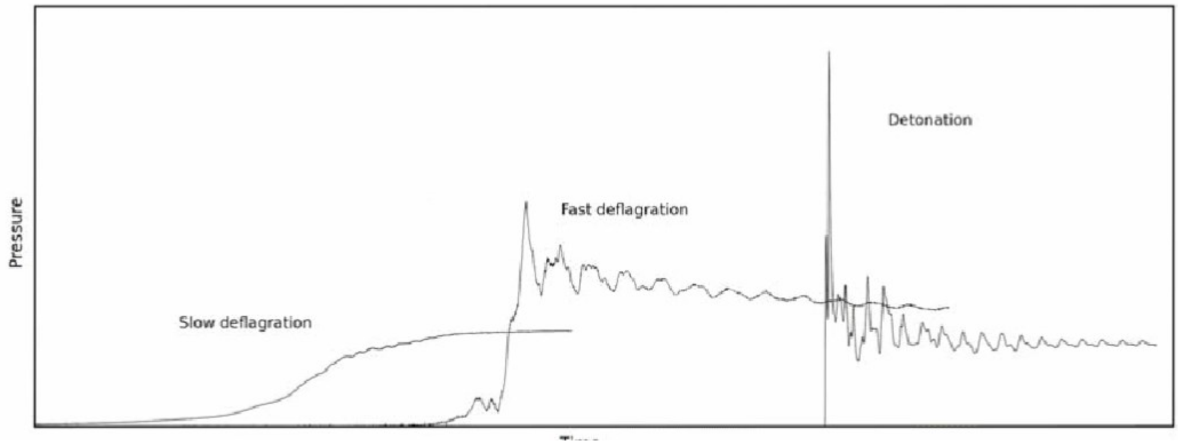


Figure 20. The pressure spike is much higher in a detonation compared to deflagration. (Kotchourko & Jordan, 2022, p. 156)

4.2.1 Boiling Liquid Expanding Vapor Explosion

Boiling Liquid Expanding Vapor Explosion, also called BLEVE, is a mechanical explosion, where a pressurized vessel containing a liquified gas ruptures and explodes, due pressure loss that consequently drops the liquids boiling point. The temperature of a liquified gas inside a vessel rapidly rises (a), until the vessel ruptures (b), which vaporizes the liquified gas that expands and ultimately starts to boil (c), thus resulting in the vessel exploding (d). The process is illustrated in figure 21. (Chakrabarty, Mannan, & Cagin, 2015, p. 27)

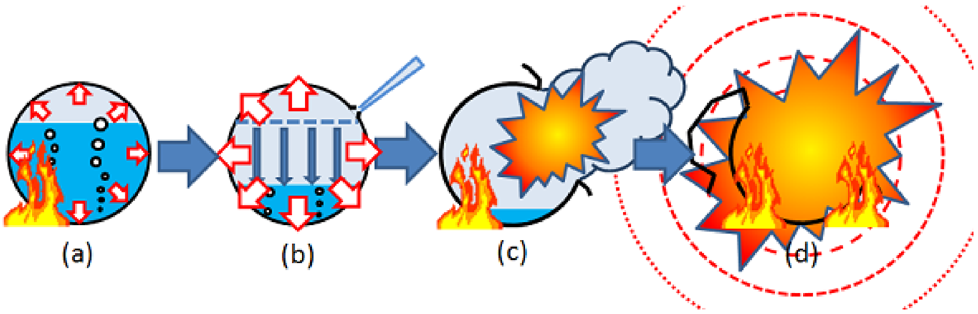


Figure 21. Course of events in a BLEVE. (Sonkar, 2020)

The phenomena result in a fire ball (if the gas is flammable), a shockwave and fragment projection. Major causes for a BLEVE are fire and mechanical damage. (Chakrabarty, Mannan, & Cagin, 2015, p. 27) The destructive force is dependent of the density of the liquid; a higher density leads to a more destructive force (HySafe: international association of hydrogen safety, 2017). It is recommended that pressure relief valves as well as a deluge system are installed in equipment and objects where an elevated risk of BLEVE exists, as this significantly reduces the risk of BLEVE. (SFS 3353:2019, 2019, p. 27).

5 Relevant Regulation and The Legal Framework in Finland

This chapter presents the key aspects of the legislation in Finland that governs fire safety in industrial facilities and facilities that handles flammable chemicals. The basic principles regarding fire safety in buildings are stated in *The decree of the Ministry of the Environment on fire safety in buildings*[8] *(*848/2017). In addition, there are regulations for industrial facilities that handle flammable chemicals, with the most significant being:

- 856/2012, *Government Decree on the Safety Requirements for the Industrial Handling and Storage of Hazardous Chemicals.*[9]
- 390/2005, *Act on the Safety of Handling Hazardous Chemicals and Explosives.*[10]

The following act and decrees will be mentioned since they also govern certain aspects of the fire safety in facilities that handle flammable chemicals, however, they will not be discussed in detail in this thesis:

- 685/2015, *Government Decree on the Supervision of Handling and Storage of Hazardous Chemicals.*[11]
- 576/2003, *Government Decree on the Prevention of Hazards posed by Explosive Atmospheres to Workers.*[12]
- 917/1996, *Government Decree on Equipment and Protective Systems Intended for Use in Explosive Atmospheres.*[13]
- 1439/2016, *Government Decree on the Compliance of Equipment and Protective Systems Intended for Use in Explosive Atmospheres.*[14]
- 132/1999, Land Use and Building Act[15]

---

[8] Ympäristöministeriön asetus rakennusten paloturvallisuudesta

[9] Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista

[10] Laki vaarallisten kemikaalien ja räjähteiden käsittelyn turvallisuudesta

[11] Valtioneuvoston asetus vaarallisten kemikaalien käsittelyn ja varastoinnin valvonnasta

[12] Valtioneuvoston asetus räjähdyskelpoisten ilmaseosten työntekijöille aiheuttaman vaaran torjunnasta

[13] Räjähdysvaarallisiin ilmaseoksiin tarkoitetuista laitteista ja suojausjärjestelmistä annetun asetuksen

[14] Valtioneuvoston asetusräjähdysvaarallisissa tiloissa käytettäväksi tarkoitettujen laitteiden ja suojausjärjestelmien vaatimustenmukaisuudesta

[15] Maankäyttö- ja rakennuslaki

Worth noting that the legislation can be considered as bare minimum requirements regarding safety, that must be complied with; hence, providing a legal framework for safety aspects. Explosive atmospheres (ATEX) will be discussed in more detail in chapter 6.3.

5.1 Decree of the Ministry of the Environment on Fire Safety in Buildings

The "*Decree of the Ministry of the Environment on fire safety in buildings*" (848/2017) states the general principles regarding fire safety in buildings. This regulation applies to the construction of new buildings as well as the expansion of existing buildings or the addition of surface area within a building. (Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, §1)

5.1.1 General Principles

A fire design classification must be applied for every building according to the following categories: P0, P1, P2, and P3. The fire design classifications P1, P2, and P3 are used when the building is designed according to the classes and numerical values specified in the decree. The fire design class P0 is used when the building is designed predominantly or entirely using a method based on assumed fire development. Also, different parts of a building can belong to different fire design class, provided that the spread of fire from one part to another is prevented by firewalls. (Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, 2017, §4)

A building or its fire compartments must be categorized based on the main intended use. For production and storage facilities, also a fire hazard class must be determined. There are two fire hazard classes: fire hazard class 1 and 2. The fire hazard class is determined based on fire hazard, chemicals handled (fire load) and risk of explosion. More detailed information on how to determine the fire hazard class can be found in the *Decree of the Ministry of the Environment on fire safety in buildings: Explanatory memorandum*[16]. (Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, §5)

---

[16] Ympäristöministeriön asetus rakennusten paloturvallisuudesta: perustelumuistio

The fire load must be determined when fire design class P0 or P1 is used. The fire load for a fire design class P1 building can normally be determined according to fire load classes in §7 (848/2017) based on the buildings intended use, but in the case of production facilities and storages a separate assessment must be made for each distinct case. This is also the case when designing the building according to fire design class P0. (Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, §6)

The number of levels is restricted in P2 and P3 production facilities. A P3 production facility is restricted to one level and a maximum height of 14 meters. A P2 production facility is restricted to one level in both fire hazard classes. An exception is made for both P2 and P3 facilities for a second floor of maximum 200m^2 as a separate fire compartment or 50m^2 in the same fire compartment. If a P2 facility has two levels, the maximum number of persons is restricted to 50 (with an appropriate automatic fire suppression system 100 persons is allowed). In a P3 facility individuals are not allowed on the second level. For fire design class P0, a separate assessment for the maximal number of persons allowed must be made for each case. (Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, §8-9)

The Decree also regulates the requirements regarding emergency evacuation such as maximum distance to the nearest exit and the number of exits, along with arrangement for firefighting and rescue tasks. However, as these requirements are dependent on various factors, these requirements will not be discussed in detail here.

5.1.2 Building Components and Fire Compartments

The structural fire-resistance capacity for load bearing structures in production facilities are specified in fire design class P1 and P2. The general case for a P2 facility with one level is R30[17]. If the facility is equipped with an appropriate automatic fire suppression system or surface materials at least class A2[18], R15 is allowed. For a P1 facility in one level, the general

---

[17] R30 refers to structural load bearing requirement (withstand collapse) in a standard fire case, where R stands for load bearing capacity and 30 for 30 minutes. (Ympäristöministerion asetus rakennusten paloturvallisuudesta: perustelumuistio, 2017, p. 6)

[18] A2 refers to the fire classification of surface materials, where A2 means the materials involvement in fire is highly restricted. See annex 5 (Ympäristöministerion asetus rakennusten paloturvallisuudesta: perustelumuistio, 2017, p. 7)

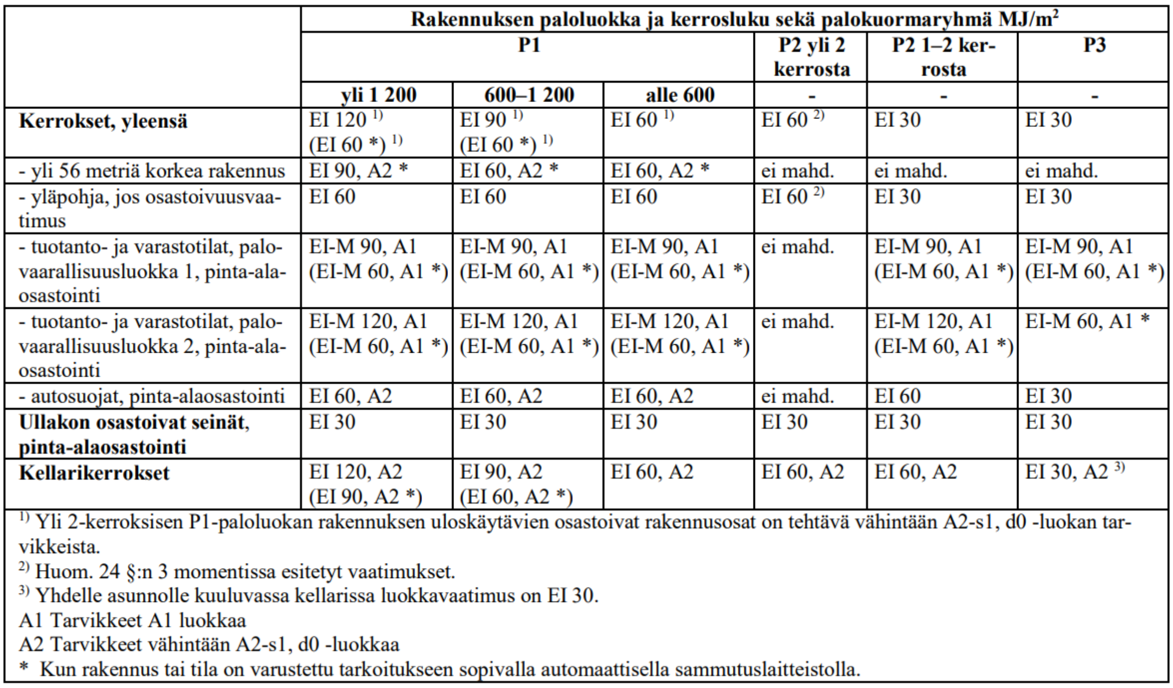
requirement is R60. If the facility is equipped with an appropriate automatic fire suppression system, the requirement is R30. In addition, if the surface materials are at least class A2, the requirement is R15. In fire design class P3 there are no requirements specified. For multilevel P1 production facilities, there are different requirements depending on the numbers of levels, fire load and building height, in accordance with §12 table 3 (annex 6). If the building is designed according to fire design class P0, a separate assessment must be made for each case according to assumed fire development. (Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, §11-13)

Depending on the floor area, number of levels and intended use, a building must be divided into fire compartments (fire zones) to restrict the spreading of fire and smoke, as well as to ensure safe evacuation and to facilitate rescue and firefighting operations. Different levels in a P1 and P2 facility must be different fire compartments. Spaces that significantly differ in terms of fire load and intended use, must be different fire compartments. (Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, §14-15)

The size of the fire compartments is restricted. A production facility in one level, fire design class P1 and fire hazards class 1 is generally restricted to 6000m^2. In the case of two levels the size is restricted to 4000m^2 and over two levels 3000m^2. In a P2 building the size of a fire compartment is restricted to 4000m^2. In a fire design class P1 and fire hazard class 2 facility, the size is of a fire compartment is generally restricted to 2000m^2 in one level and 1000m^2 if the facility has multiple levels. Fire design class P3 is restricted to 2000m^2 (must be equipped with an appropriate automatic fire suppression system). In some cases, the surface area of the fire compartment can be increased by up to 50 percent if the space is equipped with a fire alarm connected to the local emergency response center and effective firefighting can be initiated at an early stage. It is also possible to increase the size of the fire compartment if the facility is equipped with an appropriate automatic fire suppression system. (Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, §14-15)

The decree also specifies requirements for the compartmentalizing building components in fire compartments. The requirements in production facilities are dependent on fire design class, fire hazard class, number of levels and fire load. The requirements are presented in table 3. Generally, doors, small openings and windows can be half of the requirement of the compartmentalizing component. Penetrations are not allowed to significantly compromise the compartmentalizing structure. (Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, §16-18)

Table 3. Requirements for different fire compartmentalizing components.



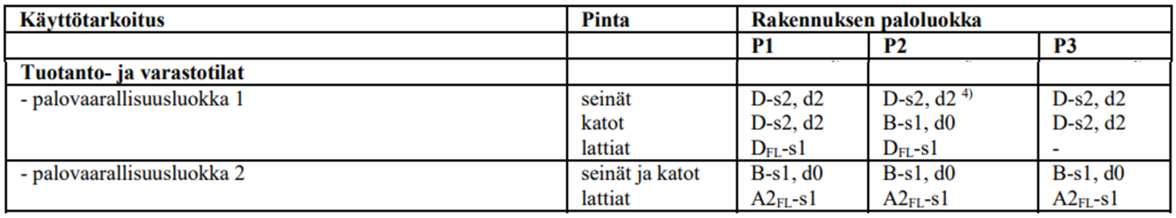
	Rakennuksen paloluokka ja kerrosluku sekä palokuormaryhmä MJ/m^2					
	P1			**P2 yli 2 kerrosta**	**P2 1–2 kerrosta**	**P3**
	yli 1 200	**600–1 200**	**alle 600**	-	-	-
Kerrokset, yleensä	EI 120 1) (EI 60 *) 1)	EI 90 1) (EI 60 *) 1)	EI 60 1)	EI 60 2)	EI 30	EI 30
- yli 56 metriä korkea rakennus	EI 90, A2 *	EI 60, A2 *	EI 60, A2 *	ei mahd.	ei mahd.	ei mahd.
- yläpohja, jos osastoivuusvaatimus	EI 60	EI 60	EI 60	EI 60 2)	EI 30	EI 30
- tuotanto- ja varastotilat, palovaarallisuusluokka 1, pinta-alaosastointi	EI-M 90, A1 (EI-M 60, A1 *)	EI-M 90, A1 (EI-M 60, A1 *)	EI-M 90, A1 (EI-M 60, A1 *)	ei mahd.	EI-M 90, A1 (EI-M 60, A1 *)	EI-M 90, A1 (EI-M 60, A1 *)
- tuotanto- ja varastotilat, palovaarallisuusluokka 2, pinta-alaosastointi	EI-M 120, A1 (EI-M 60, A1 *)	EI-M 120, A1 (EI-M 60, A1 *)	EI-M 120, A1 (EI-M 60, A1 *)	ei mahd.	EI-M 120, A1 (EI-M 60, A1 *)	EI-M 60, A1 *
- autosuojat, pinta-alaosastointi	EI 60, A2	EI 60, A2	EI 60, A2	ei mahd.	EI 60	EI 30
Ullakon osastoivat seinät, pinta-alaosastointi	EI 30	EI 30	EI 30	EI 30	EI 30	EI 30
Kellarikerrokset	EI 120, A2 (EI 90, A2 *)	EI 90, A2 (EI 60, A2 *)	EI 60, A2	EI 60, A2	EI 60, A2	EI 30, A2 3)

1) Yli 2-kerroksisen P1-paloluokan rakennuksen uloskäytävien osastoivat rakennusosat on tehtävä vähintään A2-s1, d0 -luokan tarvikkeista.
2) Huom. 24 §:n 3 momentissa esitetyt vaatimukset.
3) Yhdelle asunnolle kuuluvassa kellarissa luokkavaatimus on EI 30.
A1 Tarvikkeet A1 luokkaa
A2 Tarvikkeet vähintään A2-s1, d0 -luokkaa
* Kun rakennus tai tila on varustettu tarkoitukseen sopivalla automaattisella sammutuslaitteistolla.

(Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, §16, table 6)

The general requirement for construction materials used in a production facility is that they must not contribute to the development of fire in a hazardous manner. General requirements for interior surfaces (table 4) in production facilities depends on the fire design class and the fire hazards class.

Table 4. Requirements for interior surfaces in production facilities (Note, only a part of the original table).



Käyttötarkoitus	**Pinta**	**Rakennuksen paloluokka**		
		P1	**P2**	**P3**
Tuotanto- ja varastotilat				
- palovaarallisuusluokka 1	seinät katot lattiat	D-s2, d2 D-s2, d2 D_{FL}-s1	D-s2, d2 4) B-s1, d0 D_{FL}-s1	D-s2, d2 D-s2, d2 -
- palovaarallisuusluokka 2	seinät ja katot lattiat	B-s1, d0 $A2_{FL}$-s1	B-s1, d0 $A2_{FL}$-s1	B-s1, d0 $A2_{FL}$-s1

(Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, §23, table 7)

5.2 Act on the Safety of Handling Hazardous Chemicals and Explosives

The *Act on the Safety of Handling Hazardous Chemicals and Explosives* (390/2005) governs the general safety principles regarding facilities that handles dangerous chemicals and explosives. The act generally defines the principles of safety measures, the general placement of the facilities, building structures, equipment, and the layout of the production facility area. More detailed regulation is provided in the *Government Decree on the Safety Requirements for the Industrial Handling and Storage of Hazardous Chemicals* (856/2012). (Laki vaarallisten kemikaalien ja räjähteiden käsittelyn turvallisuudesta 2005/390)

The act also states that the risk in terms of explosive atmospheres and the risks associated with explosion hazard must assessed. Appropriate measures must be taken to prevent the formation of explosive atmospheres, the ignition of explosive atmospheres and to minimize the harmful effects of a potential explosion. The premises where explosive atmospheres may occur must be classified based on the frequency and duration of the presence of explosive atmospheres. More detailed regulation is provided in the *Government Decree on the Safety Requirements for the Industrial Handling and Storage of Hazardous Chemicals* (856/2012). (Laki vaarallisten kemikaalien ja räjähteiden käsittelyn turvallisuudesta 2005/390, §41-45)

5.3 Requirements for Industrial Handling and Storage of Hazardous Chemicals

The Government Decree on the Safety requirements for the Industrial Handling and Storage of Hazardous Chemicals (856/2012) specifies the principles in the *Act on the Safety of Handling Hazardous Chemicals and Explosives* (390/2005). The decree complies to all facilities that handles and produces dangerous chemicals or explosives (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §1-2). The decree also regulates some aspects of Explosive atmospheres (ATEX). However, ATEX will be separately discussed in chapter 6.3.

5.3.1 Placement of the Production Facility

The decree states that the effect of an accident, the ability for individuals to protect themselves or to evacuate the area in case of an accident must be assessed. Also, factors influencing the spread and progression of an accident must be evaluated, to prevent and mitigate accidents along with the consequences. Technical factors such as equipment, devices, and methods must also be assessed. The following must be considered when siting a production facility:

1. A fire situation on or outside of the premises
2. An explosion on or outside of the premises
3. The escape of chemicals to the outside area

(Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §4-5)

A production facility must be placed so that in the event of an accident, heat radiation won't cause other buildings, equipment, structures, or other objects to ignite, or prevent individuals from protecting and evacuating themselves. Also, damage to people outdoors in locations where evacuation can be slow in emergency situations, e.g., healthcare facilities, must be considered. A potential shockwave in the event of an explosion must also be considered, so that the pressure load won't cause damaged to the structures of other buildings, facilities, and equipment to such extent that the accident escalates and cause harm to individuals in these buildings. Projectiles and hazard from collapsed or damaged structures must also be assessed. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §6-7)

The production facility must be sited so that an accident won't cause damage to the essential activities for the functioning of communities such as main roads and energy supply systems. In addition, the effects on culturally significant buildings and structures must be assessed. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §11)

Storages and tanks related to the facility must be placed so that the requirements mentioned above is fulfilled. Also, a storage or a tank must be at least five meters from the property boundary. Protective distances for storages and tanks are calculated based on thermal radiation generated by fire and a potential shockwave caused by an explosion. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §13)

The safety distances for process equipment containing hazardous chemicals in relation to external activities are determined considering all potential accidents and consequences related to the chemicals and the process. When determining safety distances, the same rules as with tanks and storages can be applied, unless the process involves specific hazards, such as high heat or pressure, in which case separate risk assessment must be made. Above-ground pipelines must be placed so that the risk of accidents in the event of leakage is minimized. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §18-20)

5.3.2 Placement Within the Production Facility Area

When considering the placement of equipment, buildings, and structures inside the facility area, all effects of a potential accident must be assessed. The following basic principles must be followed:

1. Equipment, buildings, and structures must be located so that: (1) the risk of ignition of unrelated buildings, structures or similar is mitigated, (2) the spread of fire from the production facility, storage areas or process areas to other facilities, storage and process areas, or similar objects is mitigated.
2. Personnel shall not be exposed to thermal radiation, pressure effects, or health hazards to such an extent that it prevents a controlled shutdown of the facility or the evacuation of personnel from the site.
3. Structural failure of buildings and structures or damage to equipment, storage facilities, or other structures to an extent that could result in the escalation of the accident or prevent the controlled shutdown of the facility must be mitigated.

(Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §21)

In addition, the following principles must also be considered:

1. Storages and process areas are separated from each other.
2. Ignition sources not essential for operations are kept separate from flammable chemicals.
3. Incompatible chemicals are kept separate from each other.
4. Processes involving specific explosion hazard are segregated from other activities.
5. Production facilities should only have hazardous chemicals in quantities that are justified from the perspective of operations and safety.
6. Production facilities and storages do not contain unnecessary fire load.
7. In the event of an accident, the spread of chemicals can be limited to the smallest possible area.
8. Tanks and pipelines are placed above ground unless it is necessary for operational or safety requirements to be located underground.

(Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §22-23)

A tank group is allowed to contain a maximum of 30,000m^3 of hazardous chemicals. Tanks in a tank group are allowed to be arranged in a maximum of two rows. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, 22-23) Flammable liquids and gas tanks must be placed with sufficient distance between tank groups and other storage facilities or equipment containing chemicals, to prevent fire from spreading to them, and to avoid dangerous heating or pressure increase of the chemicals stored. Also, sufficient distance to nearby buildings or directly related facilities must be assessed, to ensure that the thermal radiation from a fire cannot ignite the structures, other combustible materials, or cause structural collapse. The safety distance is calculated based on heat transfer caused by fire and the effects of a potential pressure load or projectiles from an explosion. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §24-25)

5.3.3 Requirements for Buildings and Structures

In the design of buildings and structures, the following basic principles must be ensured:

1. When selecting materials and structural components, consideration must be given to associated hazards and the resulting requirements such as pressure load resistance and fire resistance.
2. Rescue and emergency response operators must have unrestricted access to all premises.
3. The spreading of an accident from one area to another must be mitigated as effectively as possible.
4. The spread of chemical leaks from one area of the building to another must be prevented.

(Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §35)

Process areas and storage areas must be separate fire compartments. Furthermore, highly hazardous process stages should be separated from the rest of the process as separate fire compartments. Also, areas where flammable liquids, flammable gases, or aerosols are handled should be separated into separate fire compartments. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §36)

If flammable gases or flammable liquids are handled, or if the process otherwise involves an explosion hazard, the pressure generated from an explosion must be relieved, either through lightweight structures or pressure relief devices in a direction that minimizes the risk of personal injury. At least one of the walls must be an exterior wall in areas where explosive chemicals are being handled or stored. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §37)

In a compartment used for handling or storing flammable liquids, flammable gases, or aerosols, the interior surfaces of the compartments walls and ceilings should meet at least the requirement A2-s1, d0[19]. Furthermore, materials should be selected so that the hazardous properties of the chemicals are considered, and if necessary, surfaces should be protected with a coating that can withstand the effects of the chemicals. In areas where flammable or oxidizing chemicals are handled or stored, the flooring should be made of non-combustible material. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §40)

Compartments where flammable chemicals are handled or stored should be equipped with a ventilation system that prevent any risk to health and minimize the risk of ignition of flammable gases, flammable liquid vapor or mist. The ventilation system in compartments where flammable chemicals are handled and stored should be separated from the ventilation systems of other areas. The sufficiency of the ventilation must be monitored. The spread of hazardous gases, vapours and such in indoor environments should be limited using local exhaust systems, flow-restricting barriers, or other technical means. Furthermore, the ventilation capacity in these compartments must be designed so that flammable liquid vapor or flammable gases in the air do not exceed 25 percent of the lower flammable limit. If people are working in the premises, the ventilation must be designed so that it considers the requirements stipulated in the *Occupational Safety and Health Act*[20] (738/2002). (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §40)

The control room and the control systems necessary for process control must be located, constructed, and equipped in such a way that the equipment in the control room and other process control devices remain operational in the event of an accident. Furthermore, the staff must be able to work in the control room for as long as necessary for a safe shutdown of the process. Safe evacuation from the control room must also be possible. Requirements for fire resistance and resistance of explosion pressure must be considered in the design of the control room structures. The sufficient airtightness of the control room structures must be ensured, and the ventilation must be reliable and sufficient during an emergency event.

---

[19] A2-s1, d0 refers to the fire classification of surface materials, where A2 means the materials involvement in fire is highly restricted, s1 means smoke production is minimal and d0 no burning droplets or particles are produced. (see annex 5) (Ympäristöministerion asetus rakennusten paloturvallisuudesta: perustelumuistio, 2017, p. 7)

[20] Työturvallisuuslaki

The ventilation must also be separate from the ventilation of the process and storage areas. If the personnel cannot be quickly evacuated, the facility must have a shelter area where personnel can stay until evacuation is possible. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §41-42)

5.3.4 Emergency Preparedness

If required, the production facility must have a system to detect potentially hazardous conditions and to warn people on the premises without delay. Based on assessment in collaboration with the local fire department, the alarm system must also be linked directly to the emergency response center. Leak detection sensors or other reliable methods is necessary when there is a possibility of significant quantities and concentrations of flammable substances leaking. Furthermore, the production facility must generally also have a fire detection system to detect and locate fires. The alarm systems should be planned in collaboration with the local fire department. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §72)

Water for firefighting, cooling, and other hazard mitigation purposes must be sized to be sufficient for the fixed firefighting and cooling systems, fire hydrants, and the needs of the emergency response within the production facility area. Water quantity for firefighting must be sized to be sufficient for the estimated worst-case fire scenario and must be ensured if necessary. Fire hydrants and water supply stations must be located near firefighting targets to ensure accessibility. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §74)

A suitable automatic fire suppression system must be installed in areas of elevated fire hazard, areas where extinguishing can be challenging due to factors such as compartment height, or areas where rapid extinguishing is particularly important. Areas with significantly higher fire or explosion hazard should be equipped with a fixed fire suppression system. Furthermore, if necessary, the facility must have smoke extraction in areas where flammable chemicals are handled or stored. (Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856, §76,78)

5.4 Standards and Guides

The fundamental principles regarding structural fire design can be found in **Eurocode EN 199(X)-1-2** (depending on structural material) in combination with the national annex. In addition to Eurocodes, there are some specific standards for facilities that processes hydrogen and other flammable gases. This chapter presents the central standards that provide guidelines for the design, along with useful guides that can be applied in the design of a hydrogen facility.

SFS 3353:2019 "Combustible chemicals production plant" addresses the design of facilities that produce flammable chemicals, along with the prevention of accidents within the facility through technical solutions as well as mitigation of the consequences of accidents. (SFS 3353:2019, 2019)

ISO/TR 15916:2015 "Basic considerations for the safety of hydrogen systems" provides hydrogen specific guidelines for the use and storage of hydrogen in its gaseous and liquid forms. It identifies basic safety considerations, risks, and hazards, in addition to providing basic knowledge regarding the properties of hydrogen relevant to safety. (ISO/TR 15916:2015, 2015)

SFS 3350:2016 "Tank storage of flammable and combustible liquids and associated handling facilities" is applicable to the storage of flammable liquid chemicals, where the total quantity of flammable liquids stored is 500 m^3 or more, including tank, container, and drum storage areas, primarily in above-ground tanks. Focus is on the flammability and ignition sensitivity of flammable liquid chemicals, the spread of potential fires, and requirements related to the handling of fire incidents. The formation of vapor clouds has also been taken into consideration in the standard. (SFS 3350:2016, 2016)

SFS 3352:2014 "Service station for flammable liquids" can be applied to the design of distribution stations of liquid fuels. The structural models provided in the standard can be used as a guideline for the design and construction of other similar facilities handling flammable liquids. (SFS 3352:2014, 2014)

Finnish Safety and Chemicals Agency (TUKES) "Tuotantolaitosten sijoittaminen" is a guide that provides recommendations on how to consider the risk of accidents caused by chemicals when siting hazardous chemical handling or storage facilities (i.e., production facilities). The guide advises on the types of accidents that should be considered when deciding the placement of a production facility, as well as it provides necessary data for calculating the consequences of accidents. In addition, the guide provides recommendations for safety distances. (Turvallisuus ja kemikaalivirasto, 2015)

Finnish Safety and Chemicals Agency (TUKES) "Vaarallisten kemikaalien käsittely ja varastointi" provides guidelines for the placement of chemical storage and handling areas within the facility, the construction of equipment and tanks, maintenance, and safety arrangements. (Turvallisuus ja kemikaalivirasto, 2021)

Finnish Safety and Chemicals Agency (TUKES) "ATEX: Räjähdysvaarallisten tilojen turvallisuus" is a guide on the application of ATEX-areas. (Turvallisuus ja kemikaalivirasto, 2015)

ATEX 2014/34/EU "Guidelines" provides guidelines for the application of the European Parliament Directive 2014/34/EU for explosive atmospheres (ATEX). (Cossellu & Mayerhöfer, 2022)

SFS-EN IEC 60079-0:2019 "Explosive atmospheres - Part 0: Equipment - General requirements" establishes general construction, testing, and marking requirements for equipment and ATEX-components used in explosive atmospheres. In addition, **SFS-EN IEC 60079-(X)** specifies complementary requirements for different components and applications used in ATEX-areas. (SFS-EN IEC 60079-0:2019, 2019)

SFS-EN IEC 60079-10-1:2021 "Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres" deals with area classification in facilities where flammable gases or vapors may be present. It can be used as a support for the design, manufacturing, operation, and maintenance of equipment used in explosive atmospheres. (SFS-EN IEC 60079-10-1:2021)

The **SFS-Handbook 59:2022** provides guidelines for the classification of hazardous areas when a mixture of flammable liquid, gas, vapor, or mist occurs under explosive conditions. (Suomen Standardisoimisliitto SFS ry, 2022)

ISO 26142:2010 Hydrogen detection apparatus - Stationary applications specifies the requirements and test methods for hydrogen detection apparatus. (ISO 26142:2010, 2010)

SFS 3357:2017 “Firefighting and fire control equipment for flammable liquid storage” is applicable to fire suppression and fire control systems for flammable liquid storages when the total quantity of stored flammable liquid is above 500m^3 or flammable liquid gas is above 10m^3. (SFS 3357:2017, 2017)

Yellow book - “Methods for the calculation of physical effect” provides guidelines for calculations of the physical effects of the release of hazardous substances. (van den Bosch & Weterings, 2005)

The National Fire Protection Association also provide guidelines for hydrogen generation, installation, storage, piping, use, and handling in its **NFPA 2 “Hydrogen Technologies Code”**. However, the standard is intended for the US market, and its applicability must be ensured with the local building and fire authority. (National Fire Protection Association, 2022)

In addition to the above-mentioned standards, The Finnish Safety and Chemicals Agency (TUKES) maintains a list of standards on its website, which by following TUKES considers meeting the requirements of the legislation regarding combustible chemical facilities.

The need for additional hydrogen related standardization is acknowledged by the industry and legislators, and currently the work for unified hydrogen industry standards is in progress. (European Clean Hydrogen Alliance, 2023, p. 5)

6 Fire Protection, Prevention and Suppression

Fire protection, or prevention, can be divided into active and passive fire protection. Passive fire protection refers to the structural fire protection measures implemented in a building, namely the measures taken to prevent and limit the effects of fire and smoke on structures in the event of fire. Its purpose is not to extinguish the fire, only to protect the building and its structures. Hence, passive fire protection helps to contain and restrict the spread of fire. Active fire protection on the contrary, actively controls or even extinguishes the fire; therefore, it complements the passive fire protection. (Säteilyturvakeskus (STUK))

6.1 Active Fire Protection

Active fire suppression systems can either be automatic, which means they automatically detect a fire and initiate the fire suppression process, or the system can be manual in which case an individual must manually activate the system. The main function of an active fire suppression system is to extinguish or suppress the fire until the fire can be extinguished by other means. An active fire suppression system can also prevent re-ignition for an extended period by maintaining a sufficient concentration of extinguishing agent in the compartment. (Rakennustietosäätiö RTS, 2012, p. 1) There are four main mechanisms for fire suppression or extinguishing: heat dissipation (cooling), suffocation (removal of oxygen), removal of the combustible material, and inhibition (interrupting the combustion reaction). Most suppression techniques use multiple mechanisms simultaneously. (Hyttinen, 2003, p. 69) Table 3 presents commonly used extinguishing agents and their respective fire suppression mechanisms.

Table 3. Extinguishing agents and their respective fire suppression mechanisms.

Agent	Mechanism
Water	Cooling and suffocation
CO_2	Suffocation (and cooling)
Inert gas	Suffocation
Extinguishing powder	Inhibition and cooling
Aerosol extinguishers	Inhibition and cooling
Foam concentrates	Suffocation (and cooling)

(Hyttinen, 2003)

A **sprinkler system** is a water based extinguishing system, which extinguishing effect is primarily based on the cooling of the burning material and combustion gases. The heat a fire generates triggers the nozzle in the system, causing water to be released onto the fire. A water source supplies water to the sprinkler system and ensures a continuous flow of water. Generally, each sprinkler nozzle in the sprinkler system operates independently, so water is only discharged from the nozzle that has been activated. If the nozzle is unable to contain the fire, additional nozzles will activate one by one due to the heat the fire generates, until the fire is under control. Mostly, the activation of a nozzle also triggers a fire alarm. Typically, a nozzle is activated at 70˚C, although the activation temperature can be modified if necessary. The water quantity of the sprinkler system is determined based on the intended use of the protected space and the fire load or stored substance. Sprinkler systems are widely used in industrial environments. (Rakennustietosäätiö RTS, 2012, pp. 3-4)

Water mist fire suppression systems basically works the same way as a sprinkler system. The main difference is in the size of the droplets produced. A water mist fire suppression system produces very small droplets that vaporize and effectively absorbs heat. This cools the fire area and pushes oxygen-rich air out of the fire area along with the generated steam. Water mist fire suppression systems are divided into low-pressure, medium-pressure, and high-pressure systems, which together with the nozzle type affects the droplets size. The main benefit in comparison to a sprinkler system is that usually the same extinguishing effect is achieved with less water. Generally, the water quantity required for the system is determined in the same way as a sprinkler system. However, the suitability of a water mist fire suppression system must be demonstrated through simulated fire tests that simulate the conditions of the protected area. (Rakennustietosäätiö RTS, 2012, pp. 4-5) The general difference between a sprinkler system and a water mist fire suppression system in practice can be seen in figure 22.

Figure 22. The difference between a sprinkler- and water mist system is in the size of the water droplet. Sprinkler system to the left. (Rakennustietosäätiö RTS, 2012, p. 5)

A **water deluge system** or **water spray system** is a system that extinguish or limits a fire in its early stages. Open nozzles direct water towards the fire, creating a water curtain to isolate the burning area or to form a water film on the protected surface. The water cools the fire, while the water curtain absorbs thermal radiation along with the water film that prevents the protected surface from heating. Water spray systems is used for targeted fire protection. It is also possible to further enhance the effectiveness of the system by using various foam/water mixes, especially in the case of flammable liquids. (Rakennustietosäätiö RTS, 2012, p. 6)

Gas suppression systems aims to automatically extinguish an emerging fire in its early stages as well as to maintain a sufficient concentration of fire-suppressant agent to prevent re-ignition. The basic principle of the system is either to reduce the oxygen concentration in the protected space or to interrupt the combustion reaction. Gas suppression systems are effective for suppressing liquid and electrical fires. They can also be used to extinguish flammable solid materials such as wood and textiles, although higher suppressant concentrations and longer retention times are typically required. A benefit is that the systems normally do not cause any additional damage to the protected area. There are safety risks associated with the use of gaseous suppressants, such as reduction of oxygen levels in the space. Hence, the suitability of a gas suppression system must be considered with this aspect in mind. The most used gas suppressants agents are carbon dioxide, halocarbon gas and different inert gases such as argon. (Rakennustietosäätiö RTS, 2012, pp. 7-8)

A **foam fire suppression system** utilizes a foam-solution as the extinguishing agent. It forms a layer of foam on the burning surface, that is lighter than the burning liquid and acts as a barrier that suffocates the fire as well as prevents the release of flammable gas. Foam fire suppression systems are typically used in industrial settings, such as chemical plants and oil refineries, where flammable liquids are present. The selected foam agent must be suitable for the specific flammable liquid targeted. (Rakennustietosäätiö RTS, 2012, p. 10) A foam fire suppression system in action can be seen in figure 23.

Figure 23. A foam fire suppression system in action. (Rakennustietosäätiö RTS, 2012, p. 10)

Powder fire suppression systems uses a powder typically consisting of sodium bicarbonate, potassium sulphate, or potassium bicarbonate. The main extinguishing effect is flame-suppression and surface coverage. The powder forms an inorganic polymer on the surface of the burning material, which coats the surface of the material. The flame-suppression is caused by a chemical effect of the decomposition products that has a cooling effect. Powder is especially effective for liquid and gas fires. The difficult clean-up should always be taken into consideration. (Rakennustietosäätiö RTS, 2012, p. 10)

An **aerosol fire suppression system** uses aerosol particles, typically solid or liquid particles, to suppress or extinguish a fire. These particles are released into the area as a fine mist or aerosol cloud. The fire suppressing effect is based on interrupting the combustion chain reaction. Aerosol fire suppression systems is mostly used in engine compartments in boats, motor vehicles, and heavy machinery. (Rakennustietosäätiö RTS, 2012, p. 11)

In an **oxygen-depleted fire suppression system**, the oxygen concentration is maintained or reduced to a level where ignition and spreading of fire through an open flame is not possible. Mainly used in computer rooms, hazardous material storages and art, book, and film storage facilities. (Rakennustietosäätiö RTS, 2012, p. 12)

Different **smoke ventilation systems** and **fire alarm systems** can also be viewed as active fire protection, although their main function is to improve conditions for safe evacuation or to alarm individuals. Smoke ventilation systems also removes some of the hot fire gases, which affect the fire progression in a suppressing way; hence, it helps to suppress the fire. (CEN/TR 12101-5:fi, 2014, p. 8)

6.2 Passive Fire Protection

The purpose of passive fire protection (PFP) is not to extinguish the fire, but to protect the building and its structures, by preventing or mitigating heat transfer. PFP restricts and contains the fire as well as secures structural integrity; hence, allowing for evacuation and firefighting. (Tremco CPG, 2023) The purpose is also that critical safety systems, such as fire water pumps, cables, emergency-shutdown systems (ESD), and valves maintain their functionality (SFS-EN ISO 13702:2015, 2015, p. 20). Generally, there are three methods to fire protect structures: heat insulation, improvement of heat retention capacity and structural fire protection. Examples of structural fire protection are suspended ceilings, placing columns outside fire compartments or placing columns inside walls. (Ongelin & Valkonen, 2016, p. 372) Fire compartmentation is also a basic PFP method, where the basic idea is to restrict the fire into a smaller compartment. Fire compartmenting will, however, not be further discussed here, as this chapter will discuss some of the main PFP methods for fireproofing (steel)structures in industrial environments.

Fireproof coating or **intumescent paint** is a coating that rapidly expands many times its original thickness when submitted to heat. The coating forms a stable carbonaceous char, that reduces the heat conducted from the fire to the structure; thus, allows the structure withstand fire longer before failing. (Gabriel, 2022)

Fire protection sprays or **fire-retardant sprays** is a widely used method for fire protection, especially in industrial environments. It is a vermiculite-based substance usually mixed with cement or gypsum, that is sprayed directly onto the structure. It is lightweight, cost effective and the amount of material implemented is proportional to the amount of time of fire protection achieved. (Progressive materials, 2023) The disadvantage with fire-retardant sprays is the aesthetic aspect, as seen in figure 24.

Figure 24. Fire-retardant spray on steel structures. (Progressive materials, 2023)

Hollow sections can be **filled with water** that consumes thermal energy; hence, it cools the structure in the event of fire. The water can be circulated to enhance the cooling effect even more. With water filled hollow section no outside protection is necessary required. Water cooling is very effective, and the temperature in a section usually stays around 200 - 250˚C during a fire. Water filled hollow sections are mainly used in columns. (Ongelin & Valkonen, 2016, p. 376)

In the same ways as water filled sections, hollow sections can also be **filled with concrete.** It is a simple but effective way, that does not change the appearance of the structure. The concrete slows the temperature rise in a fire situation, but the concrete also carries most of the load and by using steel reinforcement, the sections load capacity in a fire situation can be significantly improved. (Ongelin & Valkonen, 2016, pp. 375-376)

Fire-resistant panels or boards are also widely used. There are two types of fire-resistant boards, lightweight and heavyweight boards. Lightweight boards are usually used when an aesthetic finish is not needed, whereas heavyweight boards are used when a decorative finish is required. (SteelConstruction.info, 2023)

Different kind of **insulation** can also work as passive fire protection. These often have multiple layers of non-combustible materials such as **cellular glass, mineral wool, ceramic fibre, or endothermic mats**. Insulation is often used on industrial piping, equipment, and steel structures. Hybrid versions of fire protection is also an option; for instance, using fireproof coating and insulation. (Tim & Cusick, 2021)

6.3 Explosive Atmospheres (ATEX)

Explosive atmosphere, also known as ATEX areas or spaces (atmosphèes explosibles), is an area where a combustible or explosive air mixture may occur. Characteristically, explosive atmospheres can be found in industrial environments where flammable gases and liquids are handled. (Turvallisuus- ja kemikaalivirasto, n.d.)

The minimum requirements for ATEX areas are found in the EU directives:

- *Directive 1999/92/EC of the European Parliament and of the Council on “minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres”.*
- *Directive 2014/34/EC of the European Parliament and the Council on “on the harmonisation of the laws of the Member States relating to equipment and protective systems intended for use in potentially explosive atmospheres”*.

The European parliament has also released guidelines for the Directive 2014/34/EC, “Guidelines to Directive 2014/34 EU /(ATEX)”, that provide more detailed instructions.

In addition, ATEX is also regulated by Finnish law:

- 1139/2016, *Act on the Conformity of Equipment and Protection Systems Intended for Use in Potentially Explosive Atmospheres.*[21]
- 576/2003, *Government Decree on the Prevention of Hazards posed by Explosive Atmospheres to Workers.*[22]
- *917/1996, Government decree on Equipment and Protective Systems Intended for Use in Explosive Atmospheres.*[23]

The ATEX-directive states that an employer must assess and consider the probability and duration of explosive atmospheres, the probability of ignition sources being present in workspaces, including electrostatic discharges, and their potential to become active and cause ignition. Also, equipment, substances, processes, and their potential interactions and the extent of anticipated effects must be considered. (EUROPEAN PARLIAMENT, 1999, §3-4)

The fundamental principle of ATEX is to identify potential explosive atmospheres and prevent the possibility of explosive conditions to arise, or if not possible to prevent such conditions, eliminate all ignition sources. The first core strategy of ATEX is to eliminate the possibility of dangerous conditions. As discussed in chapter 3.1, the flammability of hydrogen depends on certain conditions, such as the ignition limit. If these conditions are eliminated, explosive atmospheres will not be present. Elimination of such conditions can, for instance, be achieved through proper ventilation; in the event of a hydrogen leakage, the lower ignition limit will not be exceeded if enough hydrogen is vented out. (Kotchourko & Jordan, 2022, pp. 317-318) Some basic means to avoid explosive conditions in hydrogen facilities are purging of systems with an inert gas, use of leak-free systems, disposal of hydrogen through ventilation if needed, maintaining positive system-pressure when handling liquid hydrogen and proper ventilation in ATEX-areas alongside nearby areas (ISO/TR 15916:2015, 2015, p. 35).

---

[21] Laki räjähdysvaarallisissa tiloissa käytettäväksi tarkoitettujen laitteiden ja suojausjärjestelmien vaatimustenmukaisuudesta

[22] Valtioneuvoston asetus räjähdyskelpoisten ilmaseosten työntekijöille aiheuttaman vaaran torjunnasta

[23] Asetus räjähdysvaarallisiin ilmaseoksiin tarkoitetuista laitteista ja suojausjärjestelmistä

If an explosive atmosphere cannot be eliminated, the second core strategy is to eliminate all ignition sources. This can be achieved for example by using electronical equipment that are classified for use in ATEX-areas (EX-equipment), and thus, suited for explosive atmospheres. It is also important to avoid all kind of oxidizers in ATEX-areas. (Kotchourko & Jordan, 2022, pp. 317-318) Ignition sources can be eliminated by avoiding static electrical charges, electrical short circuits, lightning discharges, mechanical sources such as friction or vibration, and heat sources such as flames and hot surfaces (ISO/TR 15916:2015, 2015, p. 37).

As it often is impossible to implement sufficiently reliable explosion protection measures to completely achieve explosion-free conditions, the harmful effect of a potential explosion must also be mitigated as much as possible. Methods to reduce these effects include using explosion-resistant structures, reducing explosion pressure, damping the explosion, preventing the spread of flames and explosion. (Turvallisuus ja kemikaalivirasto, 2015, p. 10)

In facilities handling flammable gases, all areas where explosive atmospheres may occur must be classified based on the frequency and duration of potential explosive conditions according to the following classes:

1. Class 0: Area where a flammable atmosphere consisting of air and a gas, vapor, or mist of flammable substance is present continuously, long-term, or frequently.
2. Class 1: Area where a flammable atmosphere consisting of air and a gas, vapor, or mist of flammable substance is likely to occur occasionally during normal operation.
3. Class 2: Area where a flammable atmosphere consisting of air and a gas, vapor, or mist of flammable substance is unlikely during normal operation, and if it occurs, it is for a short duration.

   (EUROPEAN PARLIAMENT, 1999, Annex 1)

In these ATEX classified areas the following minimum requirements regarding explosion protection must be ensured:

1. Any leaked and/or released flammable gases that may pose an explosion hazard must be appropriately directed away or transferred to a safe location, or if this is not possible, secured or made safe by other suitable means.
2. If the explosive atmosphere contains multiple types of flammable gases, vapours, mists, the protective measures should be based on the highest potential hazard.
3. When mitigating the risk of ignition, consideration must also be given to static electricity discharges individuals, or the work environment carries or produces.
4. Only equipment, protective systems, and associated switching devices that can safely be used in explosive atmosphere in accordance with the explosion protection document shall be used.
5. All necessary measures must be taken to ensure that the working area, equipment, and associated switching devices are designed, constructed, assembled, installed, maintained, and used in a way that mitigates explosion hazard. If an explosion occurs, the effects and the spread of the explosion must be controlled as much as possible, and appropriate measures must be implemented to mitigate the effects of a potential explosion on employees.
6. If necessary, employees must be warned, by visual and/or audible signals, and removed from the area before dangerous conditions occur.
7. Emergency escape routes must be provided and maintained to enable employees to evacuate hazardous areas quickly and safely in case of an emergency.
8. Before using an area where explosive atmospheres may occur for the first time, a general explosion safety check must be conducted. All safety measures necessary to ensure explosion protection must be kept up to date.
9. If required based on the risk assessment:

- In the event of a power failure and if the power failure could cause an accident to escalate, it must be possible to keep the equipment and protective systems operating.

- When using an emergency shutdown system, the energy accumulated must be dissipated or dealt with so that it poses no excess hazard.

(EUROPEAN PARLIAMENT, 1999, annex 2)

An explosion protection document must be prepared, where all hazards are assessed, the measures taken are explained, and different areas and their classification are demonstrated (EUROPEAN PARLIAMENT, 1999, §8). The area classification document must be prepared in accordance with standard SFS-EN IEC 60079-10-1:2021. Areas where explosive atmospheres may occur must also be indicated with a warning sign (figure 25) (EUROPEAN PARLIAMENT, 1999, annex 2). More details about the classification of ATEX-areas in hydrogen facilities can be found in SFS-EN IEC 60079: Explosive atmospheres. 10-1: Classification of areas. Explosive gas atmospheres.

Figure 25. Warning sign that indicates explosive atmosphere. (Turvallisuus ja kemikaalivirasto, 2015, p. 16)

7 Fire Safety Considerations and Mitigating the Hazards in the Design

As previously discussed, hydrogen possesses some distinct properties that presents some challenges regarding fire safety in hydrogen processing facilities. These risks must be assessed in the design process and addressed in the design. This chapter presents methods to mitigate these risks and the consequences, as well as various other safety aspects that must be considered in the design. The methods and design considerations presented here is based on legislation, codes, standards, and industry best practice. Of course, as not all hydrogen facilities are identical, a separate risk assessment must be made for each case, and all the methods introduced here may not be possible or necessary to implement. In addition to the requirements that derives from regulation, also insurance companies may have requirements for the fire safety in a facility.

7.1 Fire Safety Philosophy

The overall fire safety in a hydrogen processing facility can be viewed as different layers of protection; starting with the process design, followed by control systems, prevention and mitigation measures, facility emergency response, and the fire departments emergency response being the last layer of protection. (SFS 3353:2019, 2019, p. 25) This hazard control hierarchy is illustrated in figure 26.

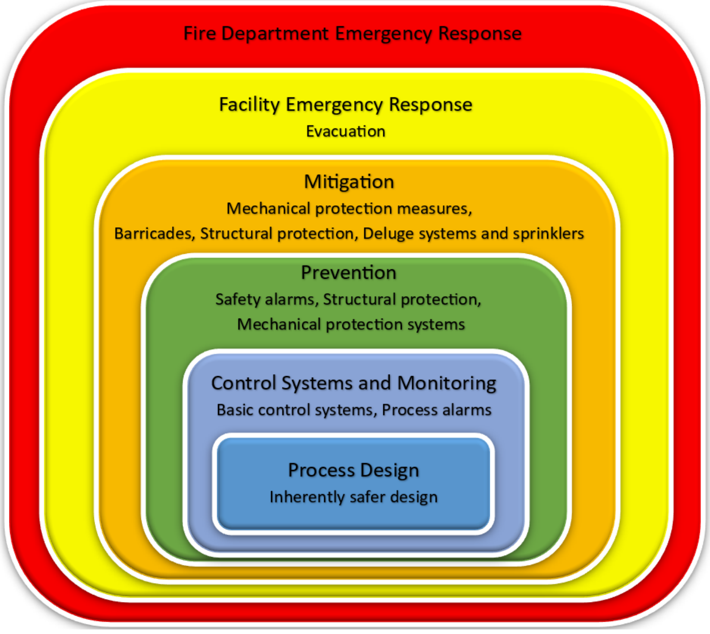


Figure 26. Hazard control hierarchy. (Note, modified from original) (SFS 3353:2019, 2019, p. 25)

The first step in the fire safety design process is to identify potential hazards and their consequences, followed by consideration for the variety of means to address them: eliminate, prevent, avoid, mitigate, or accept. The desired option is always to eliminate the hazard. As this in many cases is not an option, means for preventing or avoiding the hazard must be considered. If the hazard cannot be eliminated, avoided, or prevented, the consequences of a potential accident must be mitigated. Sometimes, if the consequences are insignificant and can be tolerated, the last option is to accept the hazard. This option always requires careful consideration. (ISO/TR 15916:2015, 2015, p. 30). The hierarchy for the safety design principles is presented as a pyramid in figure 27.

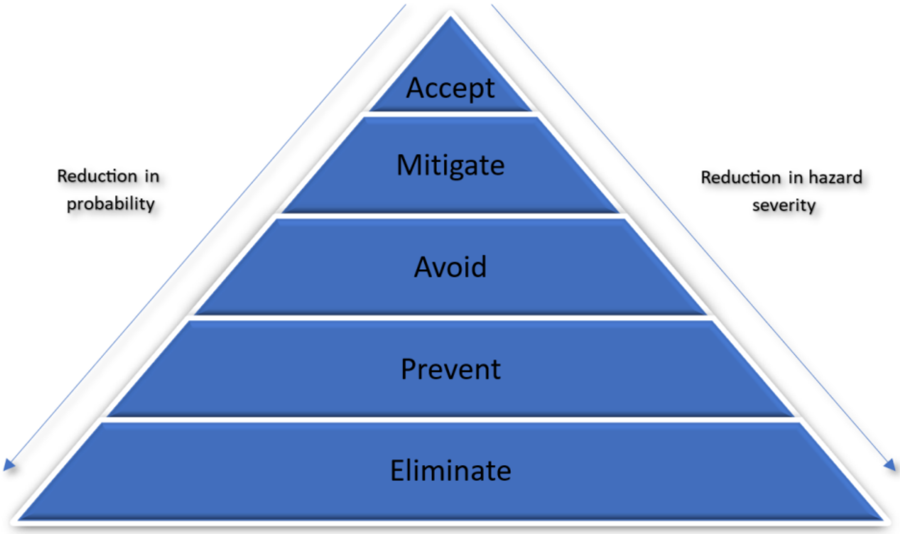


Figure 27. Hierarchy for safety design. (Note, modified from original) (Ramboll internal document)

Figure 28 summarizes the fundamental principles when preventing and mitigating hazards in the design. The methods or measures can roughly be categorized into probability reducing methods such ignition control and different structural solutions, and consequence reducing methods such as active/passive fire protection and warning systems. (Kotchourko & Jordan, 2022, p. 320)

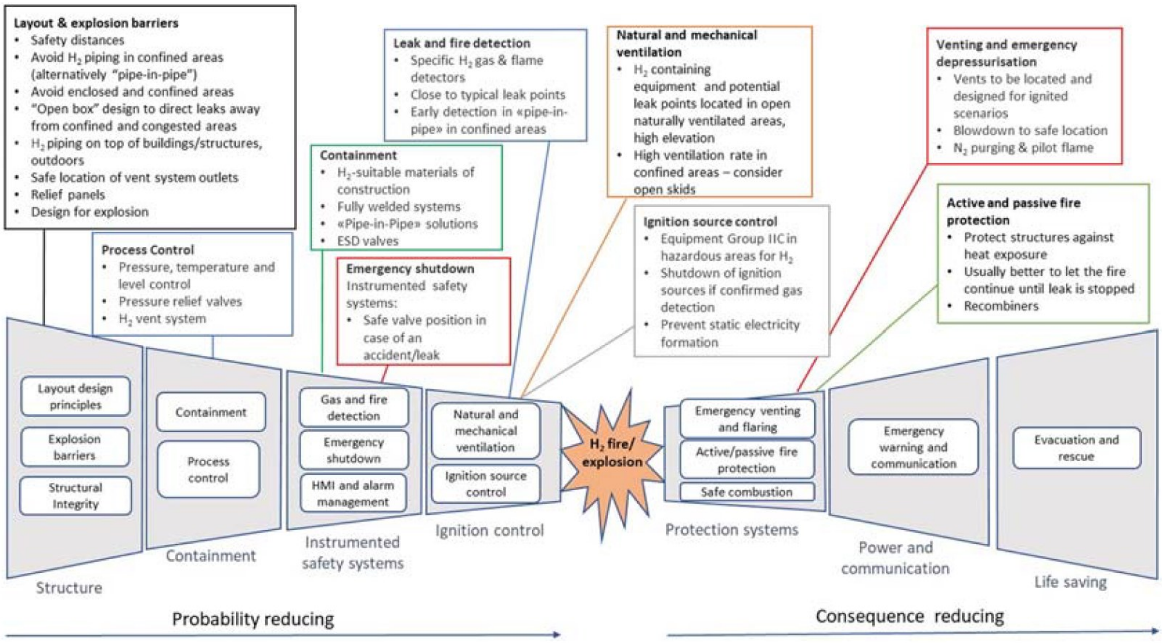


Figure 28. Basic fire and explosion mitigation measures. (Kotchourko & Jordan, 2022, p. 320)

The final fire safety design of the facility can be considered a combination of the requirements originating from legislation (building regulation), based on fire design class, the purpose of use, fire hazard category and fire load, in addition with the requirements originating from process safety, various fire scenarios, and consequence modelling. Figure 29 illustrates the path that originates from these requirements, which govern the final safety design of the facility including active and passive fire protection, structural fireproofing and design, and consequence mitigation.

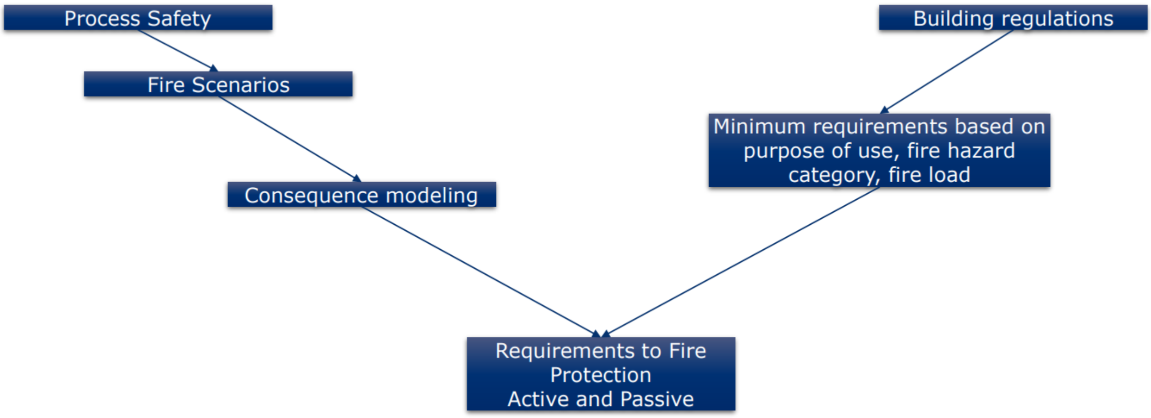


Figure 29. Fire safety philosophy. (Mikko Hakola, presentation, 2023)

7.2 The Design Process

According to Mikko Hakola (Project Director at Ramboll), the design process starts with the conceptual design phase (pre-FEED). After the conceptual design is approved, the basic engineering phase can begin. The preliminary safety design is usually completed in the early stages of the design process. Generally, it is more cost-effective to 'design out' the hazards in the early design phases, rather than applying measures to mitigate the consequences of the hazards at a later design phase. (Personal communication, Mikko Hakola)

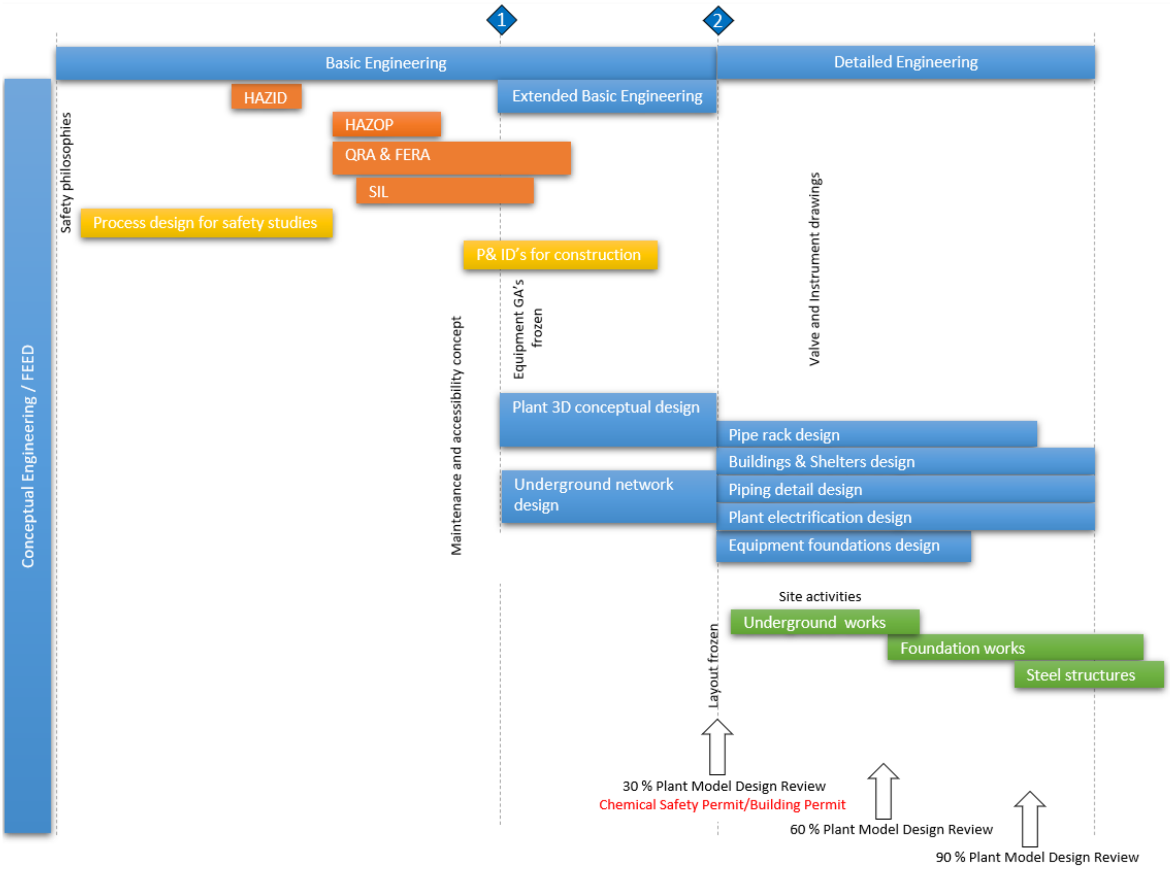
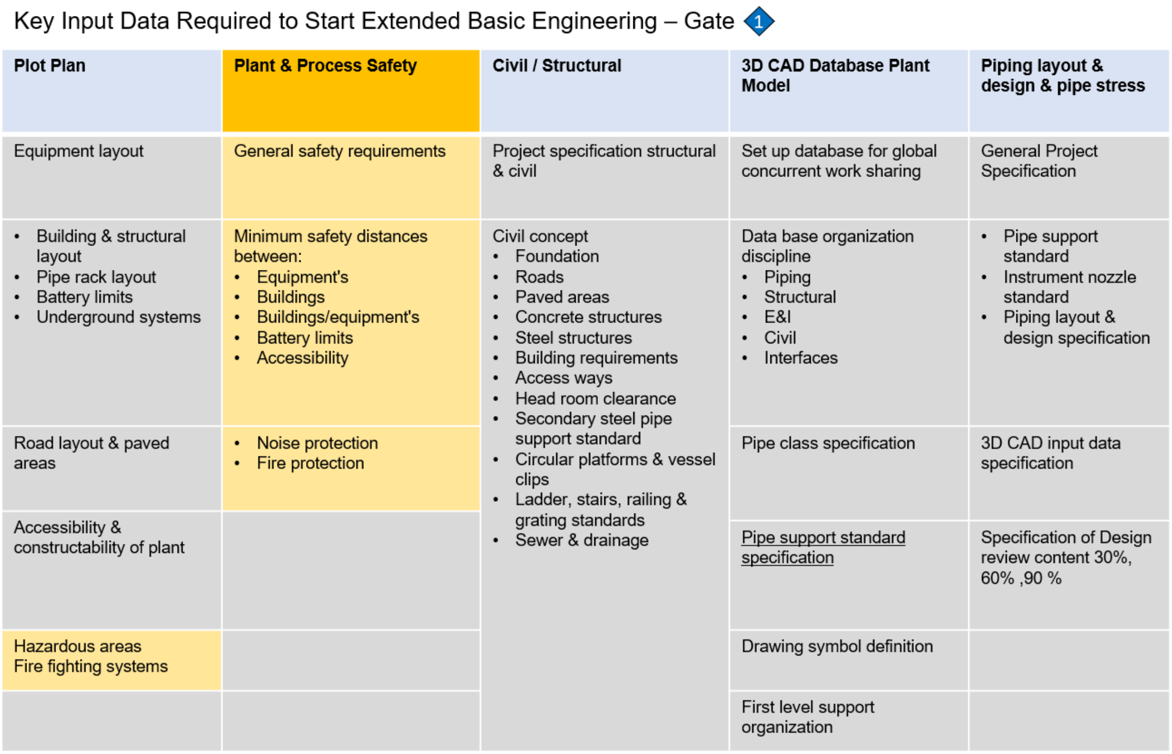


Figure 30. The different stages in the design process. (Note, modified from original) (Hakola, 2023)

Figure 30 gives a generic overview over the design process and its different stages. The safety design starts with establishing the safety design philosophy. After the process design is defined, the next step is to conduct a safety analysis (safety studies). The basic engineering phase is where Hazard Identification (HAZID) and Hazard and Operability (HAZOP) studies are conducted to identify hazards and to assess the risks (Theunissen, 2022). These studies are followed by Fire & Explosion Risk Assessment (FERA), Quantitative Risk Assessment (QRA) and Safety Integrity Level (SIL) studies. These studies function as the basis for the safety design together with regulatory requirements. (Mikko Hakola)

In the basic engineering phase, the basis of design and the plant safety concept are determined. In some cases, the basic engineering phase is further divided into extended basic engineering, which usually includes preliminary 3D-modelling. This typically requires that the layout is fixed. The basic engineering phase provides a material take off (MTO) for the final investment decision (FID). The goal of the basic engineering phase is to have a plant concept model that is approved by the client. This usually means that around 30% of plant model design is completed. At this stage, the building permit is applied for and approved. Prior to the building permit a chemical safety permit must be approved by TUKES, which usually also involves collaboration with the local fire department. A hydrogen production facility also requires an environmental permit. (Personal communication, Mikko Hakola)

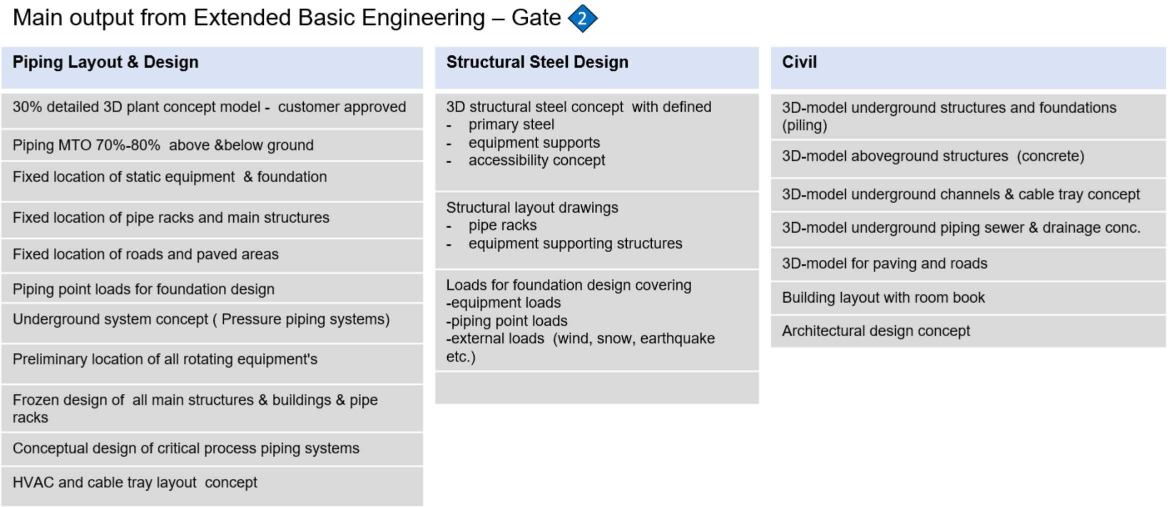
After the client has approved the plant model concept and the building permit is approved, the detail engineering phase can begin. The detail engineering phase is where the final safety design is concluded. Figure 31 illustrates suggested key input data required from the basic engineering phase, to start the extended basic engineering phase. Figure 32 displays suggested key output from the extended engineering phase. Figure 33 displays the main activities in each design phase. (Personal communication, Mikko Hakola)



Key Input Data Required to Start Extended Basic Engineering – Gate 1

Plot Plan	**Plant & Process Safety**	**Civil / Structural**	**3D CAD Database Plant Model**	**Piping layout & design & pipe stress**
Equipment layout	General safety requirements	Project specification structural & civil	Set up database for global concurrent work sharing	General Project Specification
• Building & structural layout • Pipe rack layout • Battery limits • Underground systems	Minimum safety distances between: • Equipment's • Buildings • Buildings/equipment's • Battery limits • Accessibility	Civil concept • Foundation • Roads • Paved areas • Concrete structures • Steel structures • Building requirements • Access ways • Head room clearance • Secondary steel pipe support standard • Circular platforms & vessel clips • Ladder, stairs, railing & grating standards • Sewer & drainage	Data base organization discipline • Piping • Structural • E&I • Civil • Interfaces	• Pipe support standard • Instrument nozzle standard • Piping layout & design specification
Road layout & paved areas	• Noise protection • Fire protection		Pipe class specification	3D CAD input data specification
Accessibility & constructability of plant			Pipe support standard specification	Specification of Design review content 30%, 60% ,90 %
Hazardous areas Fire fighting systems			Drawing symbol definition	
			First level support organization	

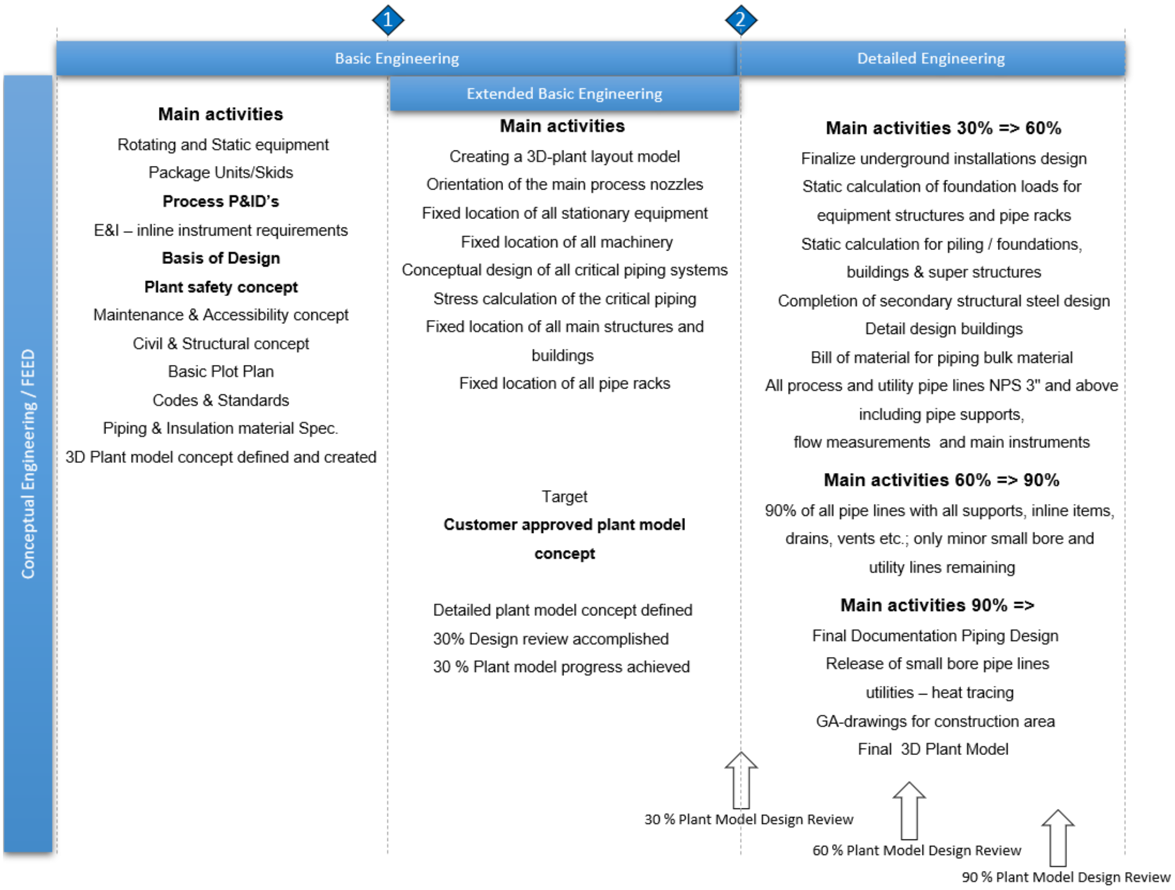
Figure 31. Key input required to start extended basic engineering. (Note, modified from original) (Hakola, 2023)



Main output from Extended Basic Engineering – Gate 2

Piping Layout & Design	**Structural Steel Design**	**Civil**
30% detailed 3D plant concept model - customer approved	3D structural steel concept with defined - primary steel - equipment supports - accessibility concept	3D-model underground structures and foundations (piling)
Piping MTO 70%-80% above &below ground	Structural layout drawings - pipe racks - equipment supporting structures	3D-model aboveground structures (concrete)
Fixed location of static equipment & foundation	Loads for foundation design covering -equipment loads -piping point loads -external loads (wind, snow, earthquake etc.)	3D-model underground channels & cable tray concept
Fixed location of pipe racks and main structures		3D-model underground piping sewer & drainage conc.
Fixed location of roads and paved areas		3D-model for paving and roads
Piping point loads for foundation design		Building layout with room book
Underground system concept (Pressure piping systems)		Architectural design concept
Preliminary location of all rotating equipment's		
Frozen design of all main structures & buildings & pipe racks		
Conceptual design of critical process piping systems		
HVAC and cable tray layout concept		

Figure 32. Main output from the extended basic engineering phase. (Hakola, 2023)



Main activities

Rotating and Static equipment
Package Units/Skids
Process P&ID's
E&I – inline instrument requirements
Basis of Design
Plant safety concept
Maintenance & Accessibility concept
Civil & Structural concept
Basic Plot Plan
Codes & Standards
Piping & Insulation material Spec.
3D Plant model concept defined and created

Main activities

Creating a 3D-plant layout model
Orientation of the main process nozzles
Fixed location of all stationary equipment
Fixed location of all machinery
Conceptual design of all critical piping systems
Stress calculation of the critical piping
Fixed location of all main structures and buildings
Fixed location of all pipe racks

Target
Customer approved plant model concept

Detailed plant model concept defined
30% Design review accomplished
30 % Plant model progress achieved

Main activities 30% => 60%

Finalize underground installations design
Static calculation of foundation loads for equipment structures and pipe racks
Static calculation for piling / foundations, buildings & super structures
Completion of secondary structural steel design
Detail design buildings
Bill of material for piping bulk material
All process and utility pipe lines NPS 3" and above including pipe supports,
flow measurements and main instruments

Main activities 60% => 90%

90% of all pipe lines with all supports, inline items, drains, vents etc.; only minor small bore and utility lines remaining

Main activities 90% =>

Final Documentation Piping Design
Release of small bore pipe lines
utilities – heat tracing
GA-drawings for construction area
Final 3D Plant Model

Figure 33. Main activities for each design phase. (Hakola, 2023)

7.3 Siting

The fundamental principle regarding siting in terms of fire safety is to mitigate the effects and consequences of a potential accident to the surroundings. This is usually achieved by applying sufficient safety distances. A consequence report must be conducted, where different accident scenarios are presented and basis for the selection of the scenarios explained. The basis for the calculations of effects and their suitability must also be demonstrated. When calculating the consequences, it is recommended that the methods presented in the "Yellow book-Methods for the calculation of physical effect" are used. (SFS 3353:2019, 2019, pp. 15-16) Factors that determine safety distances include quantity of hydrogen stored, gas pressure and the condition of the hydrogen (gas, liquid) (ISO/TR 15916:2015, 2015, p. 39).

When calculating safety distances to a third-party object outside the facility, the heat transfer from a fire or explosion must be calculated. When considering the safety distance to a third-party object outside the facility perimeter, a heat transfer value of 8 kW/m^2 shall not be exceeded. In some cases, even values as low as 3kW/m^2 can be required. The physical effects of heat transfer can be seen in figure 34. Furthermore, the effects of a shockwave due to an explosion must also be assessed. It is recommended that a pressure of 10kPa is not exceeded at the boundary of the plot. A pressure load of 5 kPa can lead to minor structural damage, whereas a pressure load of 30kPa can result in load bearing structures collapsing. (SFS 3353:2019, 2019, p. 17) The minimum safety distance for a building with elevated fire hazard is 15 meters from the boundary of the plot and 20 meters to an existing building (Turvallisuus ja kemikaalivirasto, 2015, p. 6).

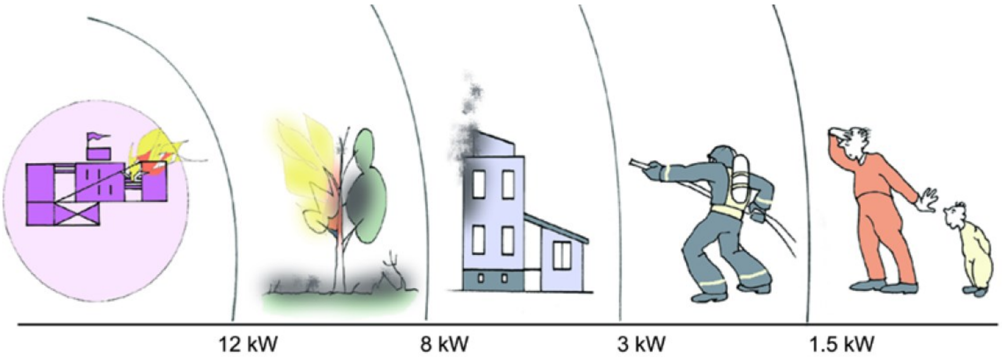


Figure 34. The effects of heat transfer [kW/m^2] (Turvallisuus ja kemikaalivirasto, 2015, p. 16)

Furthermore, safety distance also provide protection for the hydrogen processing facility, and in some cases the safety distance must be determined based on a nearby facility and its hazardous activities that requires a greater safety distance; thus, the hazards from a nearby facility must also be considered. Barricades can also be used for protection, especially against shrapnel and fragments. However, barricades should be used with great care, as they can lead to hydrogen accumulating and premixing, which furthermore can lead to an explosion. A hydrogen processing facility should always have an exclusion area around the facility; that limits access, has approved equipment, and is fenced. (ISO/TR 15916:2015, 2015, pp. 39-40) A sufficient barrier or fence is regarded a 2.4 meters high and sturdy fence (SFS 3353:2019, 2019, p. 53).

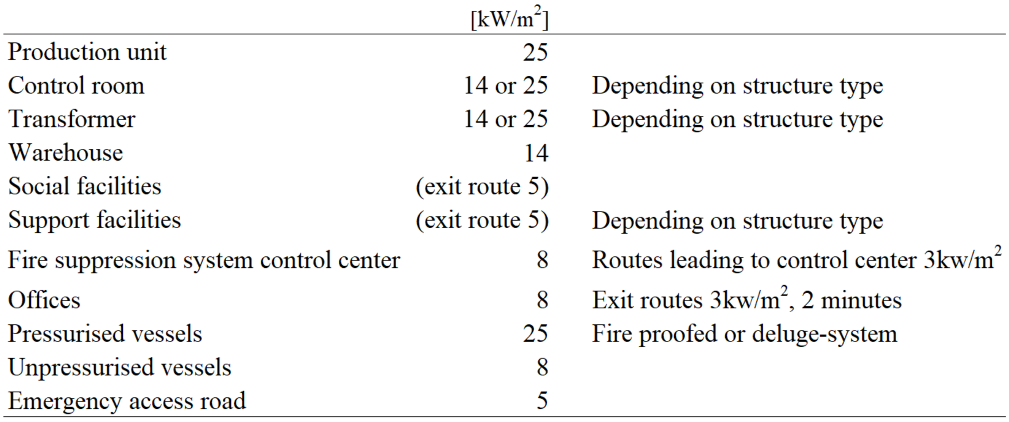
7.4 Facility Area Layout

When designing the layout of the facility the basic principle is that an accident must not escalate. Safety distances are primarily calculated based on heat transfer, but a potential shockwave caused by an explosion must also be considered along with the debris and fragments that follows. Generally, processes and facilities that involve an elevated fire hazard shall be placed, in relation to other objects, at a distance that a potential accident does not propagate or cause flammable substances temperature or pressure to dangerously rise. Heat transfer progression can also be restricted by technical methods such as using a deluge systems or fireproof materials. (SFS 3353:2019, 2019, p. 18)

When determining the safety distance to objects inside the facility processing area, the values presented in annex 7 can be applied. When determining the safety distance to non-production facilities such as offices, the same principles as with objects outside the facility area can be applied (chapter 7.3). (SFS 3353:2019, 2019, p. 18)

When assessing the impact of heat transfer and determining the safety distance between various functional facilities or objects, the maximum heat transfer values presented in table 5 shall not be exceeded (SFS 3353:2019, 2019, p. 23):

Table 5. Recommended maximum heat transfer values. (Note, modified from original table)



	[kW/m^2]	
Production unit	25	
Control room	14 or 25	Depending on structure type
Transformer	14 or 25	Depending on structure type
Warehouse	14	
Social facilities	(exit route 5)	
Support facilities	(exit route 5)	Depending on structure type
Fire suppression system control center	8	Routes leading to control center 3kw/m^2
Offices	8	Exit routes 3kw/m^2, 2 minutes
Pressurised vessels	25	Fire proofed or deluge-system
Unpressurised vessels	8	
Emergency access road	5	

(SFS 3353:2019, 2019, p. 23)

When assessing the impact of the pressure load from a potential explosion and when determining the safety distance between various functional facilities or objects, the maximum values in table 6 shall not be exceeded (SFS 3353:2019, 2019, p. 24):

Table 6. Values for recommended maximum pressure load. (Note, modified from original table)

	[kPa]	
Production unit	20	
Control room	5	Normal structure
Transformer	9	No windows, steel structure
Social facilities	5	Normal structure
Support facilities	5	Normal structure
Fire suppression system control cente	5	
Offices	5	
Unpressurised vessels	20	

(SFS 3353:2019, 2019, p. 24)

Generally, when assessing explosion protection while placing buildings within the facility area, the following factors should be considered:

- buildings should be placed so that short side faces the most probable explosion sources,
- buildings where personnel and other individuals are present in a capacity not required for the actual operation of the process, should be placed as far away as possible from explosion sources,
- buildings should be situated in areas free from congestion and tight spaces, as this adds to the magnitude of an explosion,
- as hydrogen is buoyant, buildings should not be placed uphill from the process facility, and not placed in prevailing downwind direction.

(American Society of Civil Engineers, 2010, p. 9)

Explosion barriers can also be used to protect buildings and other objects inside the facility premises to mitigate the damage from a potential shockwave and flying debris as well as to reduce heat transfer from a fire. As previously discussed, such structures should be considered with great care as they can lead to hydrogen accumulation; hence, increased risk of explosion. (Kotchourko & Jordan, 2022, p. 325)

When considering the locations of filling and emptying stations, sufficient hazard and safety distances must be ensured. The distance of at least five meters from above-ground tanks, buildings, plot boundary, or traffic routes is considered sufficient. Traffic arrangements must also be considered, and generally, filling, and emptying locations must be kept free from other traffic. The driving routes should also be planned in a way that allows the tanker truck to navigate within the facility area without reversing. In addition, sufficient directional guidance must be ensured. (Turvallisuus ja kemikaalivirasto, 2021, pp. 16-17)

If the facility handles different chemicals that are incompatible and might react with each other, these chemicals must be stored separately from each other so that they do not pose an additional danger (Turvallisuus ja kemikaalivirasto, 2021, p. 7). Also, tanks and vessels should have adequate space for condition monitoring and repairs. Generally, at least two meters in all directions is considered sufficient space. (Turvallisuus ja kemikaalivirasto, 2021, p. 19)

7.5 Buildings, Structures, Ventilation and Fireproofing

The *Decree of the Ministry of the Environment on fire safety in buildings* (848/2017), covered in chapter 5.1, regulates the general principles regarding fire safety in buildings. Some fundamental design-principles when designing a hydrogen facility is to use non-combustible materials, avoid spaces where hydrogen can accumulate, minimize ignition sources, have proper ventilation, and use various types of detection technology (ISO/TR 15916:2015, 2015, p. 41). It is also advisable to use hydrogen's properties, such as buoyancy and diffusion, to avoid dangerous conditions that can lead to explosions. For instance, this could mean that the facility processes are installed in open areas or at high elevation to disperse the hydrogen in the event of a leak, in addition to using other means to avoid hydrogen from accumulating. Consideration should also be given to various piping and associated equipment containing hydrogen and their placement. For instance, it is recommended to avoid installing such equipment in confined spaces if possible. If not avoidable, secure connections such as welded connections should be used. (Kotchourko & Jordan, 2022, p. 325)

A production facility can be designed according to regulatory values (fire design class P1, P2 and P3), and usually production facilities such as a hydrogen processing plant are designed as P1 or P2. Alternatively, the facility can be designed based on assumed fire development (P0). Generally, only small facilities can be designed as P3, and such facilities must typically be equipped with an automatic fire suppression system. However, different buildings related to the facility can be of various fire design class. The basic principle when determining the fire design class of a production facility when designing according to regulatory values is illustrated in figure 35. The typical fire hazard classification for a hydrogen facility is generally considered to be fire hazard class 2. However, different areas can be of different fire hazard class, provided that they are separated into different fire compartments or equipped with a suitable target protection system. (SFS 3353:2019, 2019, p. 52) The value of the equipment is also a factor to consider when deciding the building's fire design class. A superior fire design class essentially provides more protection, and usually also more equipment can be salvaged in the event of a fire.

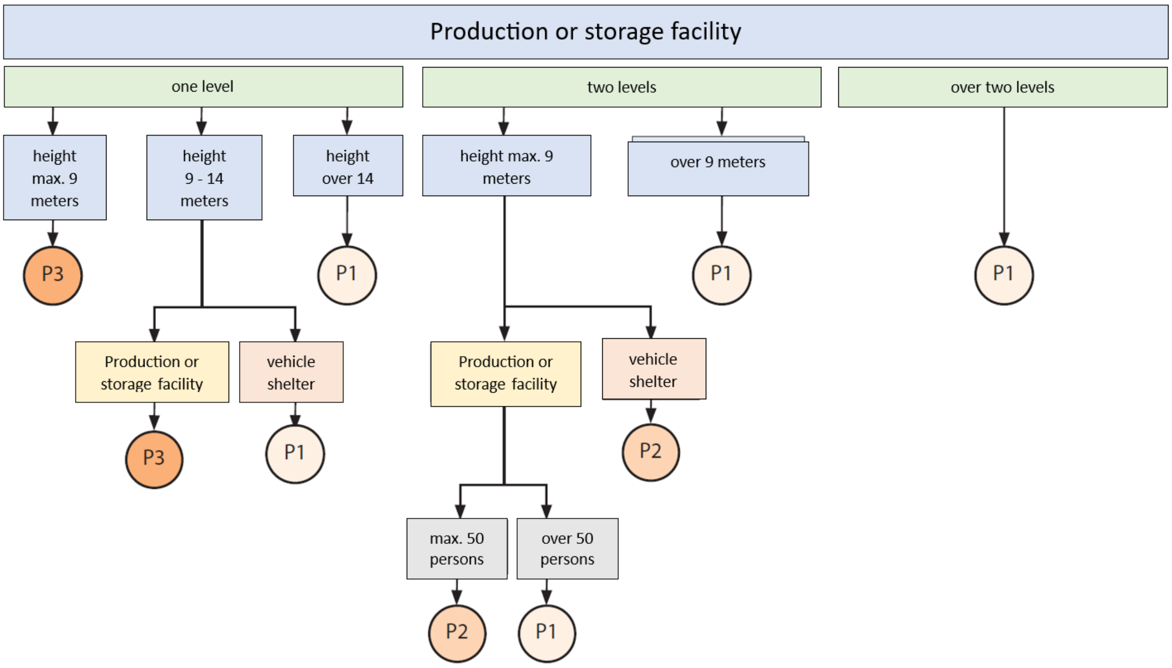


Figure 35. The basic principle when determining the fire design class of a production facility when designing according to regulatory values. (Note, modified from original) (RT 103131, 2019)

When designing according to assumed fire development, the hydrocarbon fire curve (chapter 4, figure 16/equation 15) must be used. The fire load of every fire compartment must always be assessed separately. When designing a hydrogen facility, the risk of jet fire must always be considered; hence, assumed fire development based on the standard UL 1709 fire curve (chapter 4, figure 16/equation 16) is recommended for jet fire situations in addition to the hydrocarbon fire curve. Furthermore, when designing according to assumed fire development, solutions weaker than table values (P1, P2, P3) are not allowed. (SFS 3353:2019, 2019, pp. 51-52)

When designing fire compartments a domino effect related to different processes of the facility must be considered. A domino effect refers to a chain reaction where one event or accident triggers a series of subsequent events that escalates the accident. Process and storage areas as well as exceptionally hazardous processes must always be separate fire compartments with sufficient structural fire protection, which typically means at least EI60[24] (Turvallisuus ja kemikaalivirasto, 2021, p. 6). Process and storage areas must also be separated from electrical distribution boards in a hydrogen-tight (gas-tight) manner. If pressure relief structures are used, the structure must not compromise the integrity of the fire compartmentation. (SFS 3353:2019, 2019, p. 52) Areas with critical safety functions should always be within an own fire compartment or otherwise protected. Walls can also be installed to prevent hydrogen from leaking into a specific area, but the risk of explosion in a confined space should always be considered. (Kotchourko & Jordan, 2022, p. 331) Also, suspended ceilings should generally be avoided or equipped with proper ventilation (ISO/TR 15916:2015, 2015, p. 42).

7.5.1 Fireproofing

Passive fire protection (PFP) should of course be applied to protect load bearing structures so that they at least fulfil regulated requirements, but also various process equipment, pressurized vessels and their load bearings structures should be protected to prevent malfunction or collapse during a fire. Critical piping, electrical wiring and other system-critical equipment should also be protected. As a primary principle, all materials that may be exposed to fire should be non-combustible. Roofs and walls should generally be of class A2-s1, d0. (Kotchourko & Jordan, 2022, p. 331) Load-bearing structures are designed and fireproofed according to the worst-case fire-scenario. Type of fire, the time under fire and critical structural temperature must be defined for each structure. Steel and concrete structures are designed according SFS-EN 199(X)-1-2 together with the national annex. (SFS 3353:2019, 2019, p. 39)

---

[24] EI60 refers to the structural integrity (E) and thermal isolation (I) in fire situations in minutes.

Safety equipment of pressurized processes and vessels, such as safety shut-off and emergency relief valves, must be designed to withstand fire and explosion to be functional in an emergency (SFS 3353:2019, 2019, p. 28). All electrical cables that are associated with safety equipment or required to safely operate and shut down the process must either be fireproofed, placed outside the hazard area or underground. The fireproofing of cables is usually designed to withstand a shorter time under fire than the structures, typically 15 or 30 minutes; basically, the time needed to safely shut down the process. (SFS 3353:2019, 2019, p. 39)

In areas of elevated fire hazard, such as process areas, various piping that is used for transporting hydrogen along with associated load bearing structures must be protected to withstand fire for at least 90 minutes or have sufficient fire resistance according to assumed fire scenario. Piping and other equipment containing hydrogen must also be protected from collision with vehicles. (SFS 3353:2019, 2019, p. 29) Piping associated with fire extinguishing water in addition to other related equipment should primarily be placed outside the hazard area or underground. If not possible, piping and equipment for extinguishing purposes must be fireproofed. (SFS 3353:2019, 2019, pp. 39-40)

When using PFP, it is essential to use materials that has been tested in accordance with relevant standards; resistance to hydrocarbon fires according to the UL 1709 standard and jet fire resistance according to the ISO 22899-1 standard. (SFS 3353:2019, 2019, p. 39)

7.5.2 Explosion Relief

As an explosion always is a potential hazard, and arguably one of the main hazards in a hydrogen facility, the effects of such must be considered. The shockwave pressure initiated by an explosion must always be calculated based on the worst-case scenario. If needed, the duration of the pressure spike and impulse must also be defined when designing the load bearing structures. Such calculations must always be done by qualified and experienced engineers. (SFS 3353:2019, 2019, p. 50)

There are two main methods for handling explosions inside an enclosed construction or compartment. **Explosion relief areas** or **structures** can be installed, which aim to relief some of the shockwave pressure. These can be explosion panels or lightly constructed structures, that in the event of an explosion blows out, and relieves some of the pressure in a way that the load bearings structures avoid damage. The explosion relief area should be as large as possible, and in addition, the panels or other pressure relief structures must not cause flying debris. (Kotchourko & Jordan, 2022, p. 334) It is also important to consider the direction in which the pressure is relieved, so that it does not endanger individuals or other structures (SFS 3353:2019, 2019, p. 51).

The construction can also be **designed against explosion**. This means that the construction is designed to endure high explosive pressure in a way that the construction absorbs the energy from the blast. This will prevent the shockwave from spreading as well as prevent debris from flying to the surroundings. These kinds of structure are often very heavy, typically concrete structures, and can for that reason be impractical. If the facility is located below ground this can be a practical solution. Naturally, it is also possible to use explosion relief structures and explosion absorbing structures simultaneously. (Kotchourko & Jordan, 2022, p. 334)

Generally, at least one wall in a hydrogen production or storage facility must be designed as a lightweight construction, while the other walls pressure resistance must be ensured to prevent collapse of the building. (Turvallisuus ja kemikaalivirasto, 2021, p. 6)

Blast-resistance design and blast-wave calculations are highly complex processes, requiring consideration of various factors, including positive and negative overpressure, impulse, and pressure-time. Additional information regarding blast-wave resistance design can be found in the following guides and standards: *ASCE: Design of Blast-Resistance Buildings in Petrochemical Facilities*, *AISC: Design of Blast Resistant Structure (Steel Design Guide)*, *ASCE 59-22: Blast Protection of Buildings* and the European commission's guides *Calculation for Blast Loads for Applications to Structural* Components and *Advanced design methods for BLAST Loaded steel structures*.

7.5.3 Ventilation

Ventilation is a crucial element when mitigating explosion hazard in a hydrogen facility. The basic principle is to reduce potential flammable mixtures by diluting and removing leaked hydrogen, so that hydrogen/air concentration does not exceed the lower flammability limit. Especially in areas where there is elevated risk of hydrogen accumulation, proper ventilation is crucial. Ventilation can be executed through natural or mechanical ventilation. (Kotchourko & Jordan, 2022, pp. 326-327)

Natural ventilation can be achieved with an open layout and high elevation, using the buoyant properties of hydrogen. Natural ventilation is not sufficient in most cases, especially in enclosed areas, therefore mechanical ventilation is required. Mechanical ventilation should be designed with an inlet at a low level and an outlet at a high level. The outlet must lead to a secure location outside, in a manner that no dangerous accumulation of hydrogen occurs outside. The ventilation system must also be approved for use with flammable gases. (Kotchourko & Jordan, 2022, p. 327) A emergency ventilation system should also be linked to a hydrogen detection system; hence, in the event of increased concentration of hydrogen, the ventilation increases. As a general rule, the release point where hydrogen is disposed should always be above the highest point and not in proximity of electrical lines and equipment or other ignition sources. Hydrogen can easily ignite during an excess pressure relief (blowdown). Therefore, careful consideration must be given to the placement of the blowdown vents and outlets. If large amounts of gaseous hydrogen is disposed, flaring is recommended. (ISO/TR 15916:2015, 2015, pp. 41-42, 32-34)

The ventilation system in a hydrogen facility should not be shut down in an emergency situation, as typically is the normal procedure in buildings during emergencies. It is also recommended that the ventilation is combined with some kind of hydrogen detection system, to enable early detection. The ventilator should also be designed so that in case of mechanical failure, no sparks or other ignition sources occurs. In addition, all other electrical equipment associated with the ventilation must meet the requirements for explosive areas (ATEX). (ISO/TR 15916:2015, 2015, p. 42)

The ventilation must be designed so that concentrations of flammable mixture do not exceed 25% of the lower flammability level. Usually, the ventilation should be 3 – 6 times the room volume per hour in processing areas and one time room volume per hour in storage areas. The airflow must be constantly monitored and shall not be reduced in any circumstance. An emergency ventilation system should also be linked to a hydrogen detection system so that the ventilation increases if a leak is detected (ISO/TR 15916:2015, 2015, p. 42). Areas that have different EX-classification (see chapter 6.3) must have separate ventilation systems. In case of a disruption such as a power outage, the ventilation must be ensured through natural ventilation or otherwise. The possibility of an explosion inside the air ducts must also be considered, and air ducts should generally be equipped with a pressure relief system or otherwise be able withstand the pressure load from an explosion. (SFS 3353:2019, 2019, pp. 49-50).

In areas where hydrogen is produced, handled, or stored, a negative pressure compared to the surrounding areas should be ensured. Intake air must be drawn from the outside or from another safe area. The exhaust air duct from the handling or storing area must be directed straight outside without passing through other areas. Inlet and exhaust openings should be positioned in a way that uniform ventilation is achieved through the flow-through principle. This can be achieved by placing inlet and exhaust openings on opposite walls or roof. (Turvallisuus ja kemikaalivirasto, 2021, p. 10)

7.5.4 Control Room

A control room or area that is required for operating and controlling the process must be constructed and protected in a way, that it remains operational long enough to enable safe shutdown of the process in an emergency. Thus, the construction must withstand the worst-case scenario in terms of fire and explosion; the construction must remain intact and not collapse as well as remain airtight with sufficient ventilation ensured. The outside exterior must be non-combustible and have no windows in the direction of the process. Windows in other directions must withstand a potential explosion. The control room must also be equipped with a fixed extinguishing-system and have positive air-pressure to avoid gases to enter the space. It should also be possible to evacuate the room in multiple directions. (SFS 3353:2019, 2019, pp. 47-48)

7.5.5 Substations

Substations are typically placed near the electrical demand center to avoid transfer losses. It is recommended that the prevailing wind direction is considered, and that substations are not positioned in regions below the prevailing wind direction to minimize the hazards associated with a potential gas leak. Substations should generally also be placed above ground level, to avoid water from pooling. Substations are usually designed with an overpressure, typically 20Pa, to avoid gases and dust to enter the construction. The supply air intake should be equipped with gas detection apparatus, that automatically stops the ventilation upon gas detection. Cables and associated equipment should be protected from potential heat transfer, considering the safe shutdown in an emergency. Substation over 1kV should be designed in accordance with the requirements in standard SFS 6001, PSK 2001 and PSK 2002. (SFS 3353:2019, 2019, p. 46)

Substations must be equipped with an automatic fire alarm system, and if required, also an automatic fire extinguishing system. A CO_2-extinghuishing system is recommended. If the substation is not equipped with an automatic fire extinguishing system, the substation must be equipped with relevant piping and connector for manual CO_2-extinghuising. Transformers in substations usually contains a vast amount of oil, which can cause a hydrocarbon fire. Therefore, transformers must be protected with a concrete bunker, have appropriate collection basins and a dry pipe system for foam fire extinguishing purposes. (SFS 3353:2019, 2019, p. 47)

7.5.6 Office spaces, social facilities, and other occupied buildings

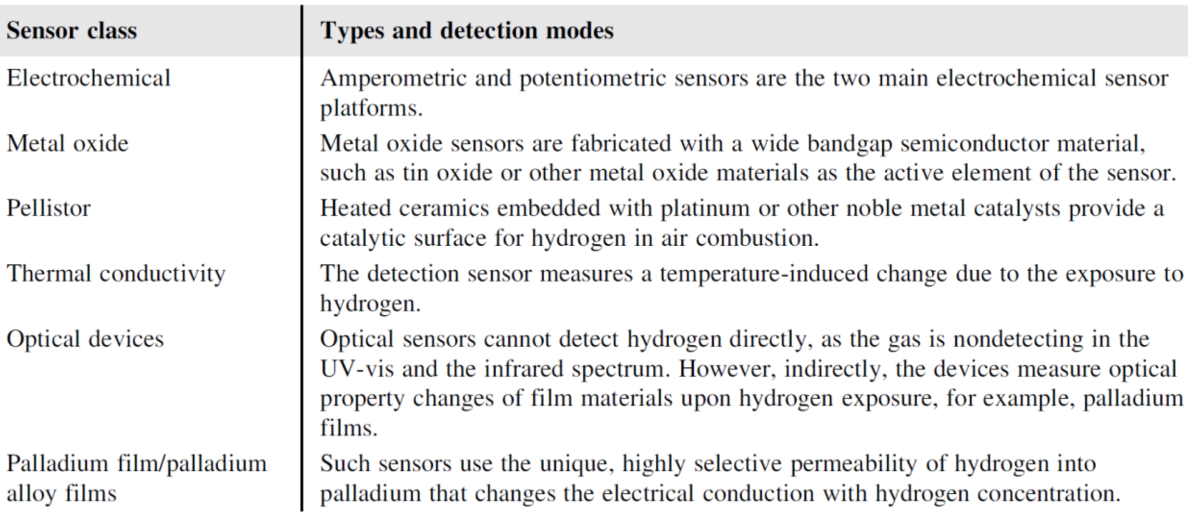
Buildings unrelated to the process should be designed to withstand the effects of a potential emergency incident, in a way that the incident do not harm individuals inside the building. It must also be possible to evacuate the building in multiple directions. If the building is permanently manned, the outer cladding must be fireproof and sufficiently isolated to withstand fire. The structures must be designed to withstand the pressure load from an explosion without collapsing. Windows, doors, and inner structures must not cause a hazard to individuals in case of an explosion. The windows must be safety glass and not placed in the direction of the process if there is a jet fire hazard in the direction of the building. The ventilation should automatically seize if a gas leak is detected. (SFS 3353:2019, 2019, p. 48)

7.6 Fire Detection and Suppression, Smoke Control, and Leak Detection

Leak detection is one of the most important safety measures in a hydrogen processing facility and can be considered as the first line of defence. If a leak is detected early, it is possible through different measures to avoid dangerous conditions to arise. (Kotchourko & Jordan, 2022, p. 323) Hydrogen detection must be present in all areas where hydrogen can be present or accumulate. The leak detection system should warn personnel and, if needed, automatically start safety measures such as ventilation. It can even in some cases be suitable for the leak detection system to be connected directly to the emergency response center. (SFS 3353:2019, 2019, p. 34) It is important to assess and identify potential leak points, natural flow paths e.g., inlets, and places of high elevation where hydrogen can accumulate, and place appropriate leak detection close to these areas. For LH_2 it is also relevant to have gas detection at low points. (Kotchourko & Jordan, 2022, p. 324)

There are various kind of leak detection systems, and various systems should be used simultaneously. Leak detection can be integrated into processes such pressure and valve-position monitoring or be separate hydrogen sensors that constantly monitors concentration in the air. As leak detection sensors uses different kind of technology, it is important to ensure that the technology used is suitable for hydrogen. For instance, two of the most used detection technologies for flammable gases are catalytic and infrared beads, but only catalytic beads are suitable for hydrogen. (Kotchourko & Jordan, 2022, p. 322) Stationary leak detection apparatus should meet the performance requirements in ISO 26142:2010 (ISO 26142:2010, 2010). Table 7 presents various commercially used hydrogen sensor technology.

Table 7. Various hydrogen sensor technology.



Sensor class	Types and detection modes
Electrochemical	Amperometric and potentiometric sensors are the two main electrochemical sensor platforms.
Metal oxide	Metal oxide sensors are fabricated with a wide bandgap semiconductor material, such as tin oxide or other metal oxide materials as the active element of the sensor.
Pellistor	Heated ceramics embedded with platinum or other noble metal catalysts provide a catalytic surface for hydrogen in air combustion.
Thermal conductivity	The detection sensor measures a temperature-induced change due to the exposure to hydrogen.
Optical devices	Optical sensors cannot detect hydrogen directly, as the gas is nondetecting in the UV-vis and the infrared spectrum. However, indirectly, the devices measure optical property changes of film materials upon hydrogen exposure, for example, palladium films.
Palladium film/palladium alloy films	Such sensors use the unique, highly selective permeability of hydrogen into palladium that changes the electrical conduction with hydrogen concentration.

(Kotchourko & Jordan, 2022, p. 322)

Leak detectors are recommended in the following locations: locations where hydrogen leaks or spills are possible, at connections that often are separated, locations where hydrogen could accumulate, air intakes, and exhaust ducts. Usually, alarms are set to be triggered at approximately 25% of the lower ignition limit, which is equivalent to a concentration of 1% hydrogen in air under NTP. Of course, an earlier warning gives more time to respond and implement necessary procedures. (ISO/TR 15916:2015, 2015, p. 38)

Fire detection is another important aspect of safety measures in hydrogen facilities. The fire detection system alarms personnel in case of an incipient fire, allowing for evacuation and other measures. Based on a risk assessment a hydrogen facility should be equipped with an automatic fire detection system, which is directly linked to the local emergency response center. (SFS 3353:2019, 2019, p. 41) A fire detection system naturally must detect a fire as early as possible, which emphasizes the importance of selecting the appropriate technology that is suitable to detect the substance that is burning. Hence, as pure hydrogen burns with minimal amount of smoke, a fire detection system based on smoke detection is less effective. Optical and thermal sensors on the other hand are more suitable for hydrogen fires. (Kotchourko & Jordan, 2022, p. 324) Ultraviolet (UV) detection is often used specifically to detect hydrogen flame, but UV is also sensitive for e.g., sunlight, which can trigger false alarms; hence, careful consideration must be given to the placement of the detectors and the sensor field of view, in addition to the response time and area covered. (ISO/TR 15916:2015, 2015, pp. 16,39). Of course, it is important to remember that there are other fire hazards in a hydrogen facility than a pure hydrogen fire, and thus, a combination of different sensor technology might be a practical solution.

Smoke control is used to ensure safe evacuation, to prevent the fire from spreading and to assist firefighting operations. This can be achieved through smoke exhaust hatches or mechanical smoke extraction fans. A separate risk assessment for the necessity of smoke control must be done for each case, based on intensity of the fire and smoke generation. (SFS 3353:2019, 2019, p. 43)

A **fire suppression system** such as a sprinkler system should be considered. In areas that are especially fire hazardous, or where extinguishing is exceptionally important as well as areas where firefighting is challenging due to height or limited space, an automatic fire suppression system is mandatory. The same applies to spaces and equipment that are critical for the process, or critical during an emergency. Typically, all areas in the facility should be protected by the fire suppression system. In some cases, a targeted protection system such as deluge-system is justified. (SFS 3353:2019, 2019, p. 41) The presence or absence of a fire extinguishing system also affects regulated structural and technical requirements (Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, 2017). Figure 36 and 37 compares the differences in the requirements for P1 and P2 facilities with and without a fire suppression system.

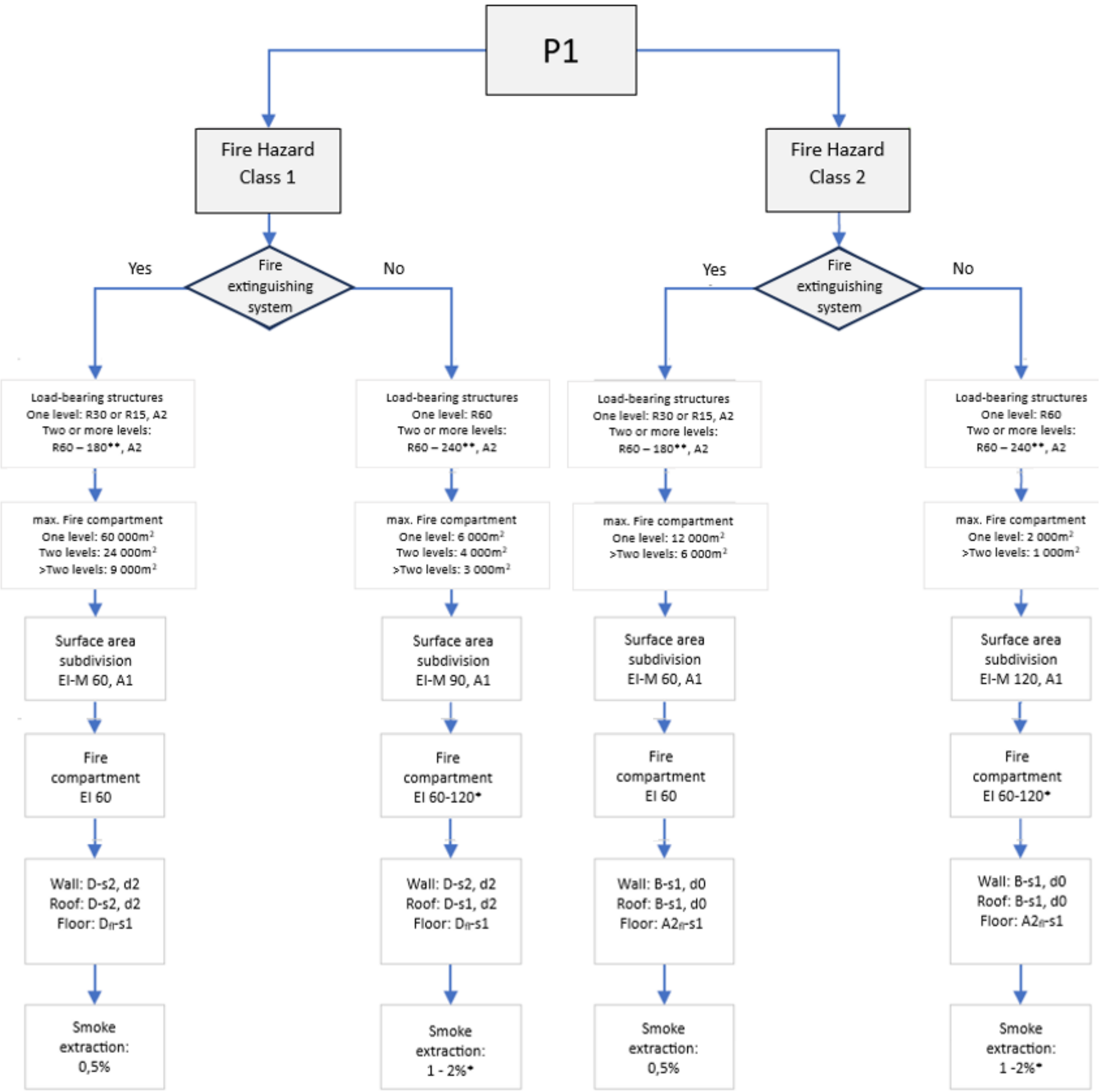


Figure 36. A comparison of the regulated structural and technical requirements with and without a fire extinguishing system in a P1 facility (*depends on the fire load, **depends on the number of levels and the fire load). (Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, 2017)

Figure 37. A comparison of the regulated structural and technical requirements with and without a fire extinguishing system in a P2 facility (*depends on the fire load). (Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, 2017)

As previously mentioned, a hydrogen fire should mainly be handled by letting it burn under controlled conditions until the hydrogen flow is stopped. In some cases, extinguishing a hydrogen fire can lead to the forming of dangerous combustible mixture that might re-ignite, and result in an explosion. For this reason, a fire suppression system should be designed with great care and this aspect in mind. Hence, the most important is to be able to stop the hydrogen flow. Of course, it is always possible that other substances or materials than hydrogen is involved in a fire, and the hydrogen process and other related equipment needs to be protected. In these cases, a fire suppression system can be used to protect and cool down storage systems, system components and tanks, that might explode due temperature and pressure rise, or otherwise be damaged. (Kotchourko & Jordan, 2022, p. 332)

7.7 Considerations for Evacuation and Rescue Services

It must be possible for individuals to evacuate the area safely in an emergency situation. The basic requirements regarding emergency evacuation are presented in the *Decree of the Ministry of the Environment on fire safety in building* (848/2017). In addition, if the facility has process levels that are elevated high above ground level, two separate exits with independent exit routs are mandatory. In high-risk areas, two exits that are at most 15 meters apart is mandatory, or alternatively safe evacuation must be ensured by other means. In some cases, only one emergency exit can be adequate, provided that the risk of fire is minor. (SFS 3353:2019, 2019, p. 32)

The facility must have at least two fire access roads from separate directions, leading to sufficient proximity of the buildings and equipment for rescue services. The fire lanes must have at least six meters of clearance above and the weight of the vehicles must be considered along with enough free space required to operate the vehicles. Buildings and process facilities must have enough sufficient attack routes for rescue services, that can be used in an emergency situation. These should be planned in collaboration with the local fire department. (SFS 3353:2019, 2019, p. 32)

The process facility and other tall buildings must be equipped with dry risers for fire extinguishing water. The necessity and requirements should be planned in collaboration with the local fire department. Fire water stations and fire hydrants must be placed in close proximity to the facility, so that they can easily be accessed during an incident. Facilities with more than 100m^3 of hydrogen stored above ground must have a fixed fire water piping system. Facilities with tanks containing more than 500m^3 of hydrogen must have fireproofing or a fixed fire suppression system. Sufficient amount of water for extinguishing purposes, both for the facilities own fire suppression systems as well as the fire departments need, must be ensured. The amount of water needed must be dimensioned based on the worst-case scenario. (SFS 3353:2019, 2019, p. 33)

8 Conclusion

The aim of the thesis was to present an overview of specific fire safety challenges and design considerations that arise in facilities where hydrogen gas is produced, handled, and stored. Although hydrogen traditionally has been used in various industrial applications, lately, hydrogen has become of accelerating interest for use as an energy source. The literature shows that fire safety is a vital aspect when handling hydrogen, that requires proper design consideration, and therefore, the need for an overview of the topic fire safety is apparent.

This bachelor’s thesis investigated the main phenomena affecting fire safety, highlighting the critical fire safety factors specific to hydrogen facilities. It is clear, that hydrogen possess some characteristics that makes it very challenging in terms of fire safety. First, the wide flammability range in combination with low ignition energy makes hydrogen a very flammable substance. Second, hydrogen also has a tendency to leak, and in respect to other flammable gases hydrogen tends to leak at a higher rate. This, alongside with the buoyant property of hydrogen, easily results in hydrogen accumulation indoors, which furthermore can lead to an explosion. A third vital aspect is material compatibility, as hydrogen can damage certain materials. In addition to these properties, hydrogen typically is stored under high pressure, which further elevates the hazards. However, by understanding these underlying fundamentals it is possible to control and mitigate these hazards through various design and technical solutions.

Industrial environments characteristically present specific types of fire hazard, that must be considered in the design of the layout, structures, and fire suppression systems. Specific to hydrogen, jet fires are a constant hazard as hydrogen is stored under high pressure. In addition to jet fires, also other fire hazards exist; for instance, the risk of hydrocarbon pool fire as transport vehicles containing gasoline or diesel usually operates within the facility area. It is vital that these risks are assessed and understood, so that appropriate measures are implemented, and adequate fire suppression technology is used. Furthermore, the risk of explosion was identified as one of the most significant and severe hazards when handling hydrogen; hence, increased attention must be directed towards identifying explosive atmospheres and to mitigate the hazards associated. Additionally, the thesis discussed the most used methods for both active and passive fire protection in industrial environments today, and it is evident that there are numerous alternative approaches, that exhibits both benefits and disadvantages.

The legislation in Finland gives the legal framework for the design of a hydrogen production facility, and these requirements can be considered as a bare minimum regarding fire safety. In addition, there are some standards along with some helpful guidelines that guides the design. The thesis presented the most central legislation that governs fire safety in facilities that handle flammable chemicals along with the most relevant standards. Nevertheless, the industry and legislators has recognised the need for additional hydrogen specific standardisation and guidelines, and the study finds that there is not much hydrogen specific standards available. However, the work for unified hydrogen industry standards is in progress.

The fire safety philosophy for the design can be viewed as the requirements originating from building regulation in addition to the different fire scenarios that arise from the process itself. When assessing hazards and ways to address them, the first option is always to eliminate the hazard. As this often is not possible, other ways to address the hazards and to mitigate the consequences must be considered. This study identified several vital methods that can effectively prevent and mitigate the hazard in facilities that handles and produces hydrogen. These methods or strategies can further be divided into probability reducing methods and consequence reducing methods. The preliminary safety design is usually completed in the early stages of the design process, and generally, it is more cost-effective to ‘design out’ the hazards in the early design phases, rather than applying measures to mitigate the consequences of the hazards at a later design phase.

Regarding siting and the facility layout, safety distances between various processes, structures and storage tanks is a fundamental approach to prevent accidents such as fires and explosions from escalating. When considering safety distances, it is vital to consider both heat transfer generated by fire along with the blast load from an explosion. When designing the layout, it is also crucial to consider emergency preparedness and to facilitate access for emergency responses and firefighting.

Various structural possibilities to mitigate hazards and the consequences were identified. Fireproofing and the use of non-combustible materials are fundamental principles, and in general, vital process and safety equipment, piping, and similar equipment should be fireproofed or otherwise protected. In addition, different processes involving flammable gases as well as storage and process areas, must be separated as their own fire compartment and separated in a hydrogen-tight (gas-tight) manner. Furthermore, structural explosion relief applications such as lightweight walls, is a vital method to mitigate the consequences and secure structural integrity in the event of an explosion.

Ventilation can be considered a key aspect when avoiding explosive conditions, and together with appropriate leak detection it is the first line of defence. It is vital that the ventilation is designed in coordination with the leak detection, so that the ventilation can be increased if hydrogen is detected. Additionally, it is crucial to identify the critical points where leaks are most expected and to have enhanced leak detection at these locations. Ventilation can be achieved through either natural or mechanical means, and in most situations, a combination of both is necessary.

Active fire protection is also a vital element. Active fire protection is not very effective against hydrogen related jet fires, but it is an effective way to protect other structures, tanks, and systems from jet fires. For instance, deluge systems are a very effective way to protect different storage tanks from fire related heat transfer. In addition, a fire detection system is critical and should be designed to detect hydrogen fires along with other types of fires; hence, the use of correct detection technology is essential.

For further research, it would be most interesting to compare the legislation on fire safety in similar facilities across different countries. Additionally, researching how fire safety can be improved in facilities that produces and handles hydrogen would be of great interest, as well as comparing liquid hydrogen to its gaseous form in terms of fire safety. Likewise, exploring different methods to combat hydrogen fires would also be very intriguing. Also, as an explosion is arguably one of the main hazards in a hydrogen processing facility, researching the various possibilities for explosion relief structures, structural blast-resistance, and their design process would be of most interest.

In conclusion, the information collected and gathered in this thesis can provide an introduction for designers to the topic fire safety and related concerns in facilities that handles and produces hydrogen. In addition, this thesis helps to understand the fundamental principles regarding fire safety related to hydrogen and can serve as a checklist or be used as an aid in the design process.

References

American Society of Civil Engineers. (2010). *Design of Blast-Resistant Buildings in Petrochemical Facilities.* Virginia: ASCE American Society of Civil Engineers.

Andersson, J., & Grönkvist, S. (2019). Large-scale storage of hydrogen. *International journal of hydrogen energy 44*, 11901-11919.

Boudellal, M. (2018). *Power-To-Gas : Renewable Hydrogen Economy for the Energy Transition.* Walter de Gruyter GmbH. Retrieved from https://ebookcentral-proquest-com.ezproxy.novia.fi/lib/novia-ebooks/reader.action?docID=5157882

CEN/TR 12101-5:fi. (2014). *Savunhallintajärjestelmät. Osa 5: Savunpoistolaitteistojen suunnittelu ja mitoitus.* Suomen standarditoimistoliitto SFS.

CEN/TR 17797:2022. (2022). *Gas infrastructure - Consequences of hydrogen in the gas infrastructure and identification of related standardisation need in the scope of CEN/TC 234.* CEN-CENELEC.

Chakrabarty, A., Mannan, S., & Cagin, T. (2015). *Multiscale Modeling for Process Safety Applications.* Elsevier Science & Technology.

Clean Hydrogen Joint Undertaking. (2023). *Clean Hydrogen Joint Undertaking*. (E. comission, Editor) Retrieved 6 15, 2023, from https://wayback.archive-it.org/12090/20220602141654/https://www.clean-hydrogen.europa.eu/index_en

Cossellu, M. G., & Mayerhöfer, J. (2022). ATEX 2014/34/EU "Guidelines" . European Parliament.

European Clean Hydrogen Alliance. (2023). *ROADMAP ON HYDROGEN STANDARDISATION.* European Clean Hydrogen Alliance.

EUROPEAN PARLIAMENT. (1999). DIRECTIVE 1999/92/EC OF THE EUROPEAN PARLIAMENT: minimum requirements for improving the safety and health protection of workers potentially at risk from explosive atmospheres.

Fjellgaard Mikkelsen, R., Meraner, C., Sæter Bøe, A., & Stølen, R. (2020). *Fra bensinstasjon til energistasjon: Endring av brann- og eksplosjonssikkerhet.* RISE Research Institutes of Sweden.

Gabriel, P. (2022). *The different types of Intumescent Coatings & their benefits*. Retrieved from Nullfire: https://www.nullifire.com/en-gb/expert-insights/expert-advice/the-different-types-of-intumescent-coatings-their-benefits/

Gandia, L. M., Arzamedi, G., & Dieguez, P. M. (2013). *Renewable Hydrogen Technologies : Production, Purification, Storage, Applications and Safety.* Elsevier Science & Technology. Retrieved 6 15, 2023, from ProQuest Ebook Central, https://ebookcentral-proquest-com.ezproxy.novia.fi/lib/novia-ebooks/detail.action?docID=1187143.

HySafe: international association of hydrogen safety. (2017). *BRHS: Biennial Report on Hydrogen Safety*. Retrieved 6 18, 2023, from http://www.hysafe.net/wiki/BRHS/BRHS

Hyttinen, V. (2003). *Palofysiikka.* Kuopio: Tammer paino oy.

IEA. (2021). *Global Hydrogen Review 2021.* International Energy Agency.

ISO 20902-1. (2018). *Fire test procedures for divisional elements that are typically used in oil, gas and petrochemical industries-Part 1: General requirements.* International Organization for Standardization.

ISO 26142:2010. (2010). *Hydrogen detection apparatus - Stationary applications.* International Organization for Standardization.

ISO 834-1:1999. (1999). *Fire-resistance tests-Elements of building construction - Part 1: General requirements.* International Organization for Standardization.

ISO/TR 15916:2015. (2015). *Basic considerations for the safety of hydrogen systems.* Danish Standards Foundation. Retrieved 6 26, 2023

Kauranen, P., Solin, J., Törrönen, K., Koivula, J., & Laurikko, J. (2013). *Vetytiekartta-Vetyenergian mahdollisuudet Suomelle.* Tampere/Espoo: Teknologian tutkimuskeskus VTT.

Koponen, J. (2019). ENERGY EFFICIENT HYDROGEN. *Lappeenranta–Lahti University of Technology LUT*. Retrieved from https://lutpub.lut.fi/bitstream/handle/10024/160688/Joonas%20Koponen%20A4.pdf?sequence=1&isAllowed=y

Kotchourko, A., & Jordan, T. (2022). *Hydrogen Safety for Energy Applications: Engineering Design, Risk Assessment, and Codes and Standards.* Butterworth-Heinemann. doi:https://doi.org/10.1016/B978-0-12-820492-4.00007-5

Laki vaarallisten kemikaalien ja räjähteiden käsittelyn turvallisuudesta 2005/390. (2005). Retrieved 9 7, 2023, from https://www.finlex.fi/fi/laki/ajantasa/2005/20050390

Laurikko, J., Jari Ihonen, J. K., Himanen, O., Weiss, R., Saarinen, V., Kärki, J., & Hurskainen, M. (2020). *NATIONAL HYDROGEN ROADMAP for Finland.* (Internet): Business Finland. Retrieved 6 15, 2023, from https://www.businessfinland.fi/4abb35/globalassets/finnish-customers/02-

Lee, A. (2023, 7 14). *Japan opens world's largest green-hydrogen plant near Fukushima disaster site*. Retrieved from Recharge: Global news and intelligence for the energy transition: https://www.rechargenews.com/transition/japan-opens-worlds-largest-green-hydrogen-plant-near-fukushima-disaster-site/2-1-769361

Lee, J. A. (2016). *Hydrogen Embrittlement.* Huntsville: National Aeronautics and Space Administration, NASA.

Loponen, T., & Luikkonen, H. (2023). *Pelastustoimen taksutilasto 2018 - 2022.* Kuopio: Pelastusopisto, TKI.

Motiva. (2023). *Kestävä liikenne ja liikkuminen. Vety.* Retrieved 6 16, 2023, from https://www.motiva.fi/ratkaisut/kestava_liikenne_ja_liikkuminen/valitse_auto_viisaasti/energialahteet/vety

Mäntylä, J.-M. (2023). Suomessa on tapahtumassa kaikessa hiljaisuudessa vetyvallankumous – katso kartalta, yltääkö vihreä siirtymä kotikuntaasi. YLE. Retrieved 7 14, 2023, from https://yle.fi/a/74-20014811

National Fire Protection Association. (2022). *NFPA 2: Hydrogen Technologies Code.*

National Fire Protection Association. (2022). *NFPA 704 - Standard System for the Identfication of the Hazards of Materials for Emergency Response.*

Nolan, D. P. (2010). Handbook of Fire and Explosion Protection Engineering Principles : For Oil, Gas, Chemical and Related Facilities. (E. S. Books, Ed.) Retrieved 6 18, 2023, from https://ebookcentral-proquest-com.ezproxy.novia.fi/lib/novia-ebooks/detail.action?docID=647534

Noordende, H. v., & Ripson, P. (2022). *A One-GigaWatt Green-Hydrogen Plant: Advanced Design and Total Advanced Design and Total.* Hydrohub Innovation Program. Retrieved from https://ispt.eu/media/Public-report-gigawatt-advanced-green-electrolyser-design.pdf

Ongelin, P., & Valkonen, I. (2016). *SSAB, Domex Tube. Hollow sections. EN1993-Handbook.* Keuruu: SSAB Europe Oy.

Pacific Northwest National Laboratory. (2023). *Hydrogen Incidents Database*. Retrieved 7 27, 2023, from H2 Tools: https://h2tools.org/lessons?search_api_fulltext=

Progressive materials. (2023). *A COMPARISON OF THE 2 MAJOR FIRE PROTECTIVE COATINGS FOR STRUCTURAL STEEL AND OTHER MATERIALS*. Retrieved from https://www.progressivematerials.com.au/vermiculite-spray-vs-intumescent-coating/

R. Stølen, R. F. (2018). *Heat flux in jet fires: Unified method for measuring the heat flux levels of jet fires.* Trondheim: Researchgate.

Rakennustietosäätiö RTS. (2012). RT 63-11096 SAMMUTUSLAITTEISTOT. © Rakennustietosäätiö RTS.

Ramboll. (2023). *From idea to reality: Launching your green hydrogen project*. Retrieved 7 14, 2023, from Ramboll.com: https://www.ramboll.com/net-zero-explorers/launching-your-green-hydrogen-projects

Ramboll. (2023). *Ramboll*. Retrieved from Ramboll, about us: https://www.ramboll.com/fi-fi/ramboll-yrityksena

Raunio, T. (2017). Vedyn valmistaminen. Retrieved 6 16, 2023, from https://docplayer.fi/49927752-Vedyn-valmistaminen-tapani-raunio.html

Rivkin, C., Burgess, R., & Buttner, W. (2015). *Hydrogen Technologies Safety Guide.* Oak ridge: NREL: national laboratory of the U.S. Department of Energy. Retrieved from http://www.osti.gov/scitech

RT 103131. (2019). Rakennuksen paloluokan määrittäminen ja keskeiset palotekniset vaatimukset. © Rakennustietosäätiö RTS.

SFS 3350:2016. (2016). *Tank storage of flammable and combustible liquids and associated handling facilities.* Suomen Standardisoimisliitto SFS ry.

SFS 3350:2016. (2016). *Tank storage of flammable and combustible liquids and associated handling facilities.* Finnish petroleum and biofuel association.

SFS 3352:2014. (2014). *Palavien nesteiden jakeluasema.* Suomen Standardisoimisliitto SFS ry .

SFS 3353:2019. (2019). *Palavien kemikaalien tuotantolaitos.* Suomen Standardisoimisliitto SFS ry.

SFS 3357:2017. (2017). *Firefighting and fire control equipment for flammable liquid storage.* Suomen Standardisoimisliitto SFS ry.

SFS-EN 1363-2:1999. (1999). *Fire-resistance tests-part 2: Alternative and additional procedures.* Suomen Standardisoimisliitto SFS.

SFS-EN 2:1993 + A1:2004: classification of fires. (1993). European committee of standardization.

SFS-EN IEC 60079-0:2019. (2019). *Explosive atmospheres - Part 0: Equipment - General requirements.* SESKO ry.

SFS-EN IEC 60079-10-1:2021. (n.d.). *Explosive atmospheres - Part 10-1: Classification of areas - Explosive gas atmospheres.* SESKO ry.

SFS-EN ISO 13702:2015. (2015). *”Petroleum and natural gas industries. Control and mitigation of fires and explosions on offshore production installations. Requirements and guidelines”.* Brussels: European committee for standardization.

SFS-EN ISO 13702:2015. (2015). ”Petroleum and natural gas industries. Control and mitigation of fires and explosions on offshore production installations. Requirements and guidelines”. Brussels: European committee for standardization.

Sivill, L., Bröckl, M., Semkin, N., Ruismäki, A., Pilpola, H., Laukkanen, O., . . . Patronen, J. (2022). *Vetytalous – mahdollisuudet ja rajoitteet.* Helsinki: VALTIONEUVOSTON SELVITYS JA JULKAISUSARJA 2022:21.

Sonkar, R. (2020). *Understanding & Managing Boiling Liquid Expanding Vapor Explosion*. Retrieved 6 20, 2023, from Industrial fire safety review: https://www.isrmag.com/understanding-managing-boiling-liquid-expanding-vapour-explosion/

SteelConstruction.info. (2023). *Fire protecting structural steelwork*. Retrieved from https://www.steelconstruction.info/Fire_protecting_structural_steelwork#Boards

Suomen Kaasuyhdistys ry. (2023, 6 128). LNG-asiakassäiliöt. Retrieved from https://www.kaasuyhdistys.fi/julkaisut/lng-asiakassailiot/

Suomen Standardisoimisliitto SFS ry. (2022). *SFS-Handbook 59:2022 "Räjähdysvaarallisten tilojen luokittelu. Palavat nesteet ja kaasut".* Suomen Standardisoimisliitto SFS.

Säteilyturvakeskus (STUK). (n.d.). *Stuklex*. Retrieved 6 25, 2023, from https://www.stuklex.fi/fi/maaritelmat

Teräsrakenneyhdistys. (2020). *Teräsrakenteiden oletettuun palonkehitykseen perustuva suunnittelu.* Teräsrakenneyhdistys-Tekniset julkaisut. Retrieved from www.terasrakenneyhdistys.fi

Theunissen, S. (2022). *What is the difference between HAZID and HAZOP?* Retrieved from Safeopedia: https://www.safeopedia.com/what-is-the-difference-between-hazid-and-hazop/7/4079

Tim, B., & Cusick, A. (2021). *Passive fire protection in industrial applications*. Retrieved from https://lsc-pagepro.mydigitalpublication.com/publication/frame.php?i=733072&p=&pn=&ver=html5&view=articleBrowser&article_id=4186394

TOKEVA. (2012). *Liite ohje T1. Räjähteet tulipaloissa, lisätietoa.* Retrieved 6 19, 2023, from https://tokeva.fi/assets/attachment-files/Rajahteet_paloissa_lisatietoja2012.pdf

Tremco CPG. (2023). *Mitä on passiivinen palosuojaus?* Retrieved 6 26, 2023, from Nullfire: https://www.nullifire.com/fi_FI/tekninen-alue/tietopankki/mitae-on-passiivinen-palosuojaus/

Turvallisuus ja kemikaalivirasto. (2015). *ATEX Räjähdysvaarallisten tilojen turvallisuus.* Turvallisuus ja kemikaalivirasto TUKES.

Turvallisuus ja kemikaalivirasto. (2015). *Tuotantolaitosten sijoittaminen.* Turvallisuus ja kemikaalivirasto TUKES.

Turvallisuus ja kemikaalivirasto. (2021). *Vaarallisten kemikaalien käsittely ja varastointi.* Turvallisuus ja kemikaalivirasto TUKES.

Turvallisuus- ja kemikaalivirasto. (n.d.). *Räjähdysvaarallisten tilojen laitteet - ATEX*. Retrieved 6 28, 2023, from https://tukes.fi/teollisuus/rajahdysvaaralliset-tilat/rajahdysvaarallisten-tilojen-laitteet-atex#be8e6464

Työterveyslaitos. (2022). *OVA-Ohjeet, lentopetroli*. Retrieved 6 17, 2023, from https://ova.ttl.fi/lentopetroli

Työterveyslaitos. (2022). *OVA-Ohjeet, moottoribensiini*. Retrieved 6 17, 2023, from https://ova.ttl.fi/moottoribensiini

Työterveyslaitos. (2022). *OVA-Ohjeet, nestekaasut*. Retrieved 6 17, 2023, from https://ova.ttl.fi/nestekaasut

Työterveyslaitos. (2022, 7 12). *OVA-Ohjeet, vety*. Retrieved from OVA-ohjeet: https://ova.ttl.fi/vety

Työterveyslaitos. (2023). *OVA-Ohjeet, metaani*. Retrieved 6 17, 2023, from https://ova.ttl.fi/metaani

U.S department of energy. (2023). *Hydrogen Production: Natural Gas Reforming*. Retrieved 6 16, 2023, from https://www.energy.gov/eere/fuelcells/hydrogen-production-natural-gas-reforming

University of Calgary. (n.d.). *Standard conditions for temperature and pressure*. Retrieved 6 24, 2023, from Energy education: https://energyeducation.ca/encyclopedia/Standard_conditions_for_temperature_and_pressure

Valtioneuvoston asetus vaarallisten kemikaalien teollisen käsittelyn ja varastoinnin turvallisuusvaatimuksista 2012/856. (2012). Retrieved 9 7, 2023, from https://www.finlex.fi/fi/laki/ajantasa/2012/20120856

van den Bosch, C., & Weterings, R. (2005). Yellow book-Methods for the calculation of physical effects. Ministeri van Veerker den Waterstaat.

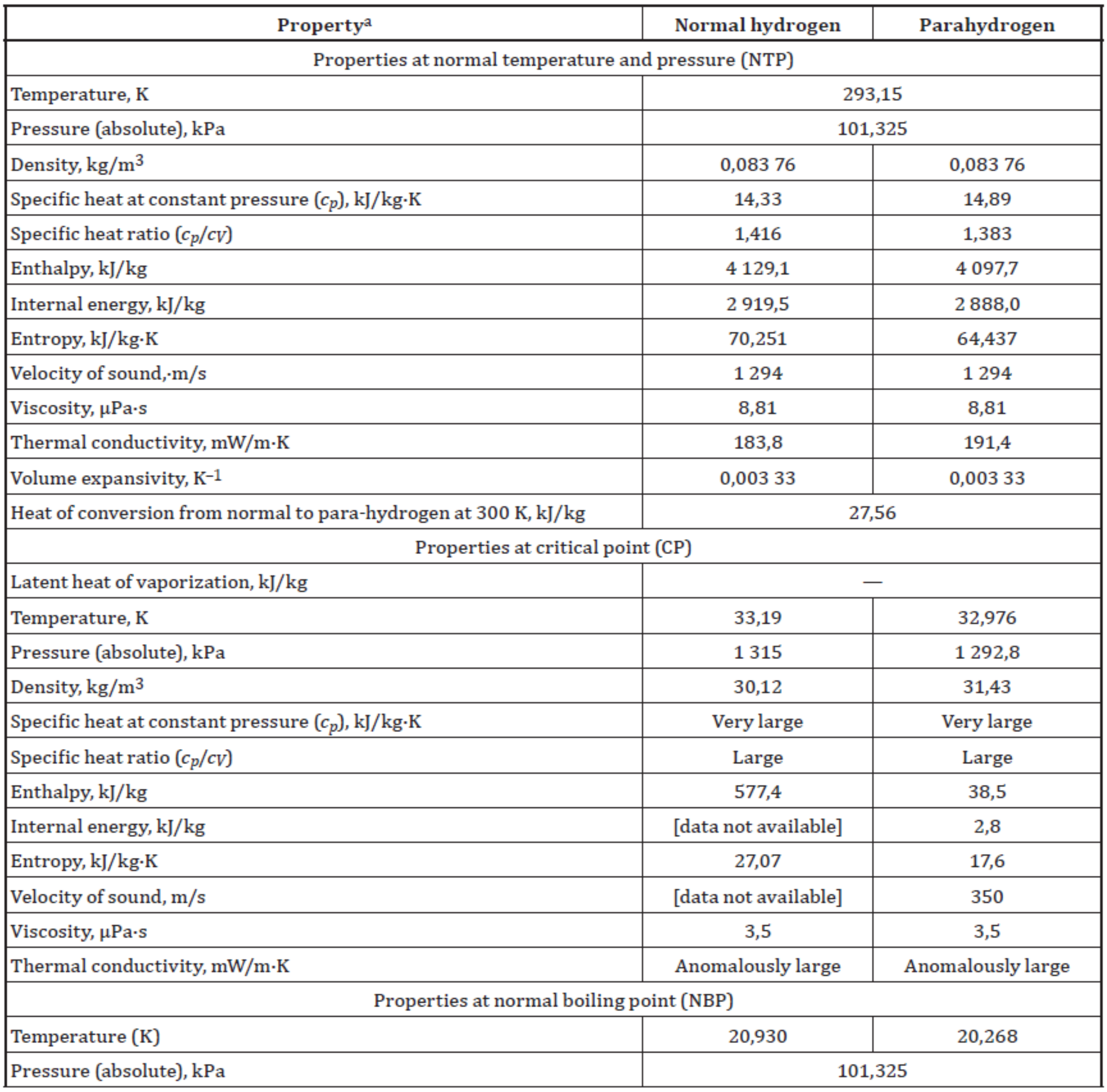
Williams, R. (2013). Rapid Rise Hydrocarbon Fires – An Engineering. *Journal of petroleum technology*. Retrieved 6 19, 2023, from https://jpt.spe.org/rapid-rise-hydrocarbon-fires-engineering-perspective

Ympäristöministerion asetus rakennusten paloturvallisuudesta: perustelumuistio. (2017). Ympäristöministeriö.

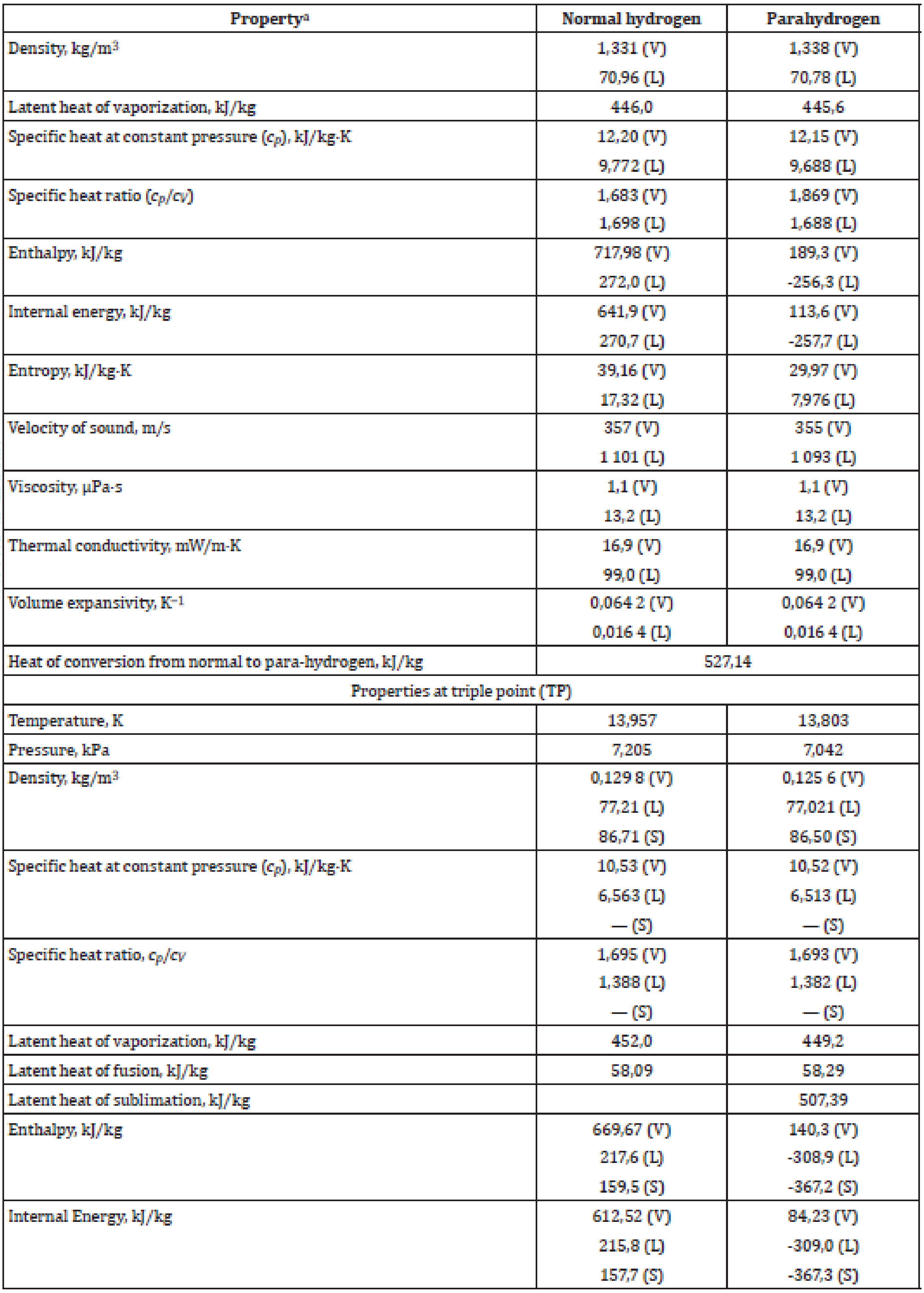
Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017. (2017). Retrieved 9 7, 2023, from https://www.finlex.fi/fi/laki/alkup/2017/20170848

Appendices

Selected safety-related physical and thermophysical properties and combustion properties of normal hydrogen (ISO/TR 15916:2015, 2015, pp. 50-54)



Property[a]	Normal hydrogen	Parahydrogen
Properties at normal temperature and pressure (NTP)		
Temperature, K	293,15	
Pressure (absolute), kPa	101,325	
Density, kg/m^3	0,083 76	0,083 76
Specific heat at constant pressure (c_p), kJ/kg·K	14,33	14,89
Specific heat ratio (c_p/c_V)	1,416	1,383
Enthalpy, kJ/kg	4 129,1	4 097,7
Internal energy, kJ/kg	2 919,5	2 888,0
Entropy, kJ/kg·K	70,251	64,437
Velocity of sound,·m/s	1 294	1 294
Viscosity, µPa·s	8,81	8,81
Thermal conductivity, mW/m·K	183,8	191,4
Volume expansivity, K^{-1}	0,003 33	0,003 33
Heat of conversion from normal to para-hydrogen at 300 K, kJ/kg	27,56	
Properties at critical point (CP)		
Latent heat of vaporization, kJ/kg	—	
Temperature, K	33,19	32,976
Pressure (absolute), kPa	1 315	1 292,8
Density, kg/m^3	30,12	31,43
Specific heat at constant pressure (c_p), kJ/kg·K	Very large	Very large
Specific heat ratio (c_p/c_V)	Large	Large
Enthalpy, kJ/kg	577,4	38,5
Internal energy, kJ/kg	[data not available]	2,8
Entropy, kJ/kg·K	27,07	17,6
Velocity of sound, m/s	[data not available]	350
Viscosity, µPa·s	3,5	3,5
Thermal conductivity, mW/m·K	Anomalously large	Anomalously large
Properties at normal boiling point (NBP)		
Temperature (K)	20,930	20,268
Pressure (absolute), kPa	101,325	



Property[a]	Normal hydrogen	Parahydrogen
Density, kg/m^3	1,331 (V) 70,96 (L)	1,338 (V) 70,78 (L)
Latent heat of vaporization, kJ/kg	446,0	445,6
Specific heat at constant pressure (c_p), kJ/kg·K	12,20 (V) 9,772 (L)	12,15 (V) 9,688 (L)
Specific heat ratio (c_p/c_V)	1,683 (V) 1,698 (L)	1,869 (V) 1,688 (L)
Enthalpy, kJ/kg	717,98 (V) 272,0 (L)	189,3 (V) -256,3 (L)
Internal energy, kJ/kg	641,9 (V) 270,7 (L)	113,6 (V) -257,7 (L)
Entropy, kJ/kg·K	39,16 (V) 17,32 (L)	29,97 (V) 7,976 (L)
Velocity of sound, m/s	357 (V) 1 101 (L)	355 (V) 1 093 (L)
Viscosity, µPa·s	1,1 (V) 13,2 (L)	1,1 (V) 13,2 (L)
Thermal conductivity, mW/m·K	16,9 (V) 99,0 (L)	16,9 (V) 99,0 (L)
Volume expansivity, K^{-1}	0,064 2 (V) 0,016 4 (L)	0,064 2 (V) 0,016 4 (L)
Heat of conversion from normal to para-hydrogen, kJ/kg	527,14	
Properties at triple point (TP)		
Temperature, K	13,957	13,803
Pressure, kPa	7,205	7,042
Density, kg/m^3	0,129 8 (V) 77,21 (L) 86,71 (S)	0,125 6 (V) 77,021 (L) 86,50 (S)
Specific heat at constant pressure (c_p), kJ/kg·K	10,53 (V) 6,563 (L) — (S)	10,52 (V) 6,513 (L) — (S)
Specific heat ratio, c_p/c_V	1,695 (V) 1,388 (L) — (S)	1,693 (V) 1,382 (L) — (S)
Latent heat of vaporization, kJ/kg	452,0	449,2
Latent heat of fusion, kJ/kg	58,09	58,29
Latent heat of sublimation, kJ/kg		507,39
Enthalpy, kJ/kg	669,67 (V) 217,6 (L) 159,5 (S)	140,3 (V) -308,9 (L) -367,2 (S)
Internal Energy, kJ/kg	612,52 (V) 215,8 (L) 157,7 (S)	84,23 (V) -309,0 (L) -367,3 (S)

Property[a]	Normal hydrogen	Parahydrogen
Entropy, kJ/kg·K	46,4 (V) 14,2 (L) 10,1 (S)	37,52 (V) 4,961 (L) 0,739 (S)
Velocity of sound, m/s	307 (V) 1 282 (L) — (S)	305 (V) 1 273 (L) — (S)
Viscosity, µPa·s	0,74 (V) 26,0 (L)	0,74 (V) 26,0 (L)
Thermal conductivity, mW/m·K	12,4 (V) 73,0 (L) 900 (S)	12,4 (V) 73,0 (L) 900 (S)
Volume expansivity, K^{-1}	0,075 2 (V) 0,010 2 (L)	0,075 2 (V) 0,010 2 (L) 0,004 94 (S)
Other properties		
Molecular mass	2,015 94	2,015 94
Equivalent volume gas at NTP/volume liquid NBP	847,1	845,1
Equivalent volume gas at CP/volume liquid NBP	2,357	2,252
Equivalent volume gas at NBP/volume liquid at NBP	53,30	52,91
Equivalent volume gas at TP/volume liquid NBP	546,3	563,8
Equivalent volume liquid at TP/volume liquid NBP	0,919 0	0,919 0
Equivalent volume solid at TP/volume liquid NBP	0,818 4	0,818 1
Pressure required to maintain NBP liquid density in NTP GH_2 (fixed volume, no venting), MPa	172[b]	
Joule-Thomson maximum inversion temperature, K	200	
Diffusion coefficient in NTP air, 10^{-4} m^2/s	0,61	

NOTE 1 (L): Liquid phase.

NOTE 2 (S): Solid phase.

NOTE 3 (V): Vapour phase.

NOTE 4 c_V: Specific heat at constant volume, kJ/kg·K.

NOTE 5 Numbers in parentheses are estimates.

[a] Unless specified otherwise, source of data is Reference [9] in the Bibliography.

[b] Calculated value.

Annex 1

Property	Value[a]
Heating value, kJ/g	119,93 (lower) 141,86 (higher)
Flammability limits, vol fraction, %	3,6 to 76,6 (in NTP air,[5] Method T) 4,2 ... 77,0 (in NTP air,[5] method B) 3,75 ... 75,1 (in NTP air,[6]) 4,1 ... 94 (in NTP oxygen)[c]
Stoichiometric concentration in air, vol fraction, %	29,53
Ignition energy (minimum) for ignition in air, mJ	0,017
Concentration at which the minimum ignition energy is found, vol fraction, %	22 to 26
Auto-ignition temperature, K	858[d]
Ignition temperature (hot air jet), K	943
Stoichiometric Flame temperature in air, K	2 318
Thermal energy radiated from flame to surroundings, %	17 to 25
Maximum laminar burning speed in NTP air, m/s	2,65 to 3,25
Maximum deflagration propagation speed in a stoichiometric NTP H_2/air mixture, m/s	975
Detonation propagation speed in NTP air, m/s	1 480 to 2 150
Maximum experimental safe gap in NTP air, mm	0,08
Quenching gap stoichiometric mixture in NTP air, mm	0,64
Limiting oxygen index, vol fraction, %	5,0
Burning rate of spilled liquid pool, mm/s	0,5 to 1,1

NOTE 1 NTP: normal temperature and pressure (293,15 K and 101,325 kPa).

NOTE 2 NBP: normal boiling point (20,268 K and 101,325 kPa).

NOTE 3 TNT: trinitrotoluene, symmetrical (explosive energy = 4 602 J/g TNT).

[a] Unless specified otherwise, source of data is Reference [9] in the Bibliography.

[b] The values are ones commonly given. It is recommended that they be used only as a guide. These properties are a function of many variables that are to be evaluated to determine their values for a specific application. In particular, they are hardly useful for evaluating a realistic accident situation.

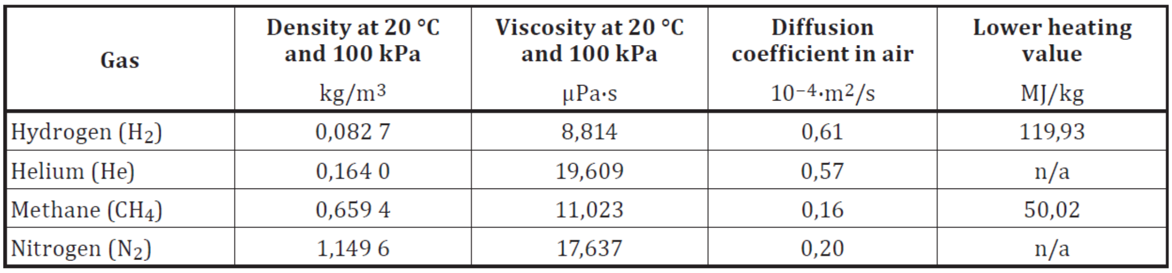
[c] Source of data is Reference [8] in the Bibliography.

[d] Different values have been reported for the auto ignition temperature of hydrogen in air ranging from 773 K to 858 K. This variation may be due to the influence of different materials used to contain hydrogen in test apparatus. See [c] above for the source of data.

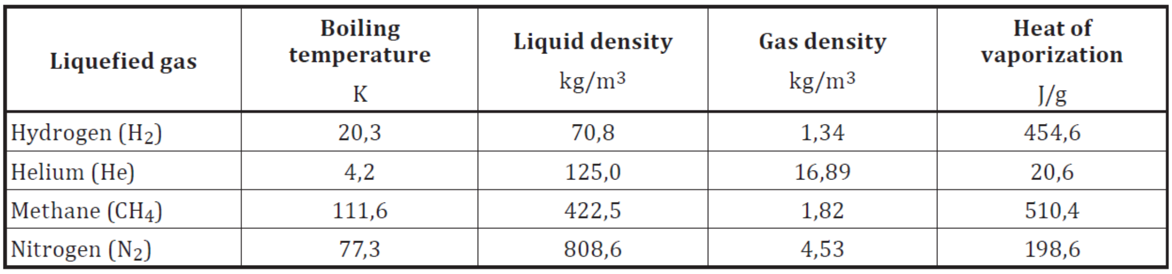
[e] Based on high heat of combustion.

Annex 2

Thermophysical properties of common gases and properties of some cryogenic fluids at their normal boiling point. (ISO/TR 15916:2015, 2015, p. 53)



Gas	Density at 20 °C and 100 kPa kg/m^3	Viscosity at 20 °C and 100 kPa µPa·s	Diffusion coefficient in air 10^{-4}·m^2/s	Lower heating value MJ/kg
Hydrogen (H_2)	0,082 7	8,814	0,61	119,93
Helium (He)	0,164 0	19,609	0,57	n/a
Methane (CH_4)	0,659 4	11,023	0,16	50,02
Nitrogen (N_2)	1,149 6	17,637	0,20	n/a



Liquefied gas	Boiling temperature K	Liquid density kg/m^3	Gas density kg/m^3	Heat of vaporization J/g
Hydrogen (H_2)	20,3	70,8	1,34	454,6
Helium (He)	4,2	125,0	16,89	20,6
Methane (CH_4)	111,6	422,5	1,82	510,4
Nitrogen (N_2)	77,3	808,6	4,53	198,6

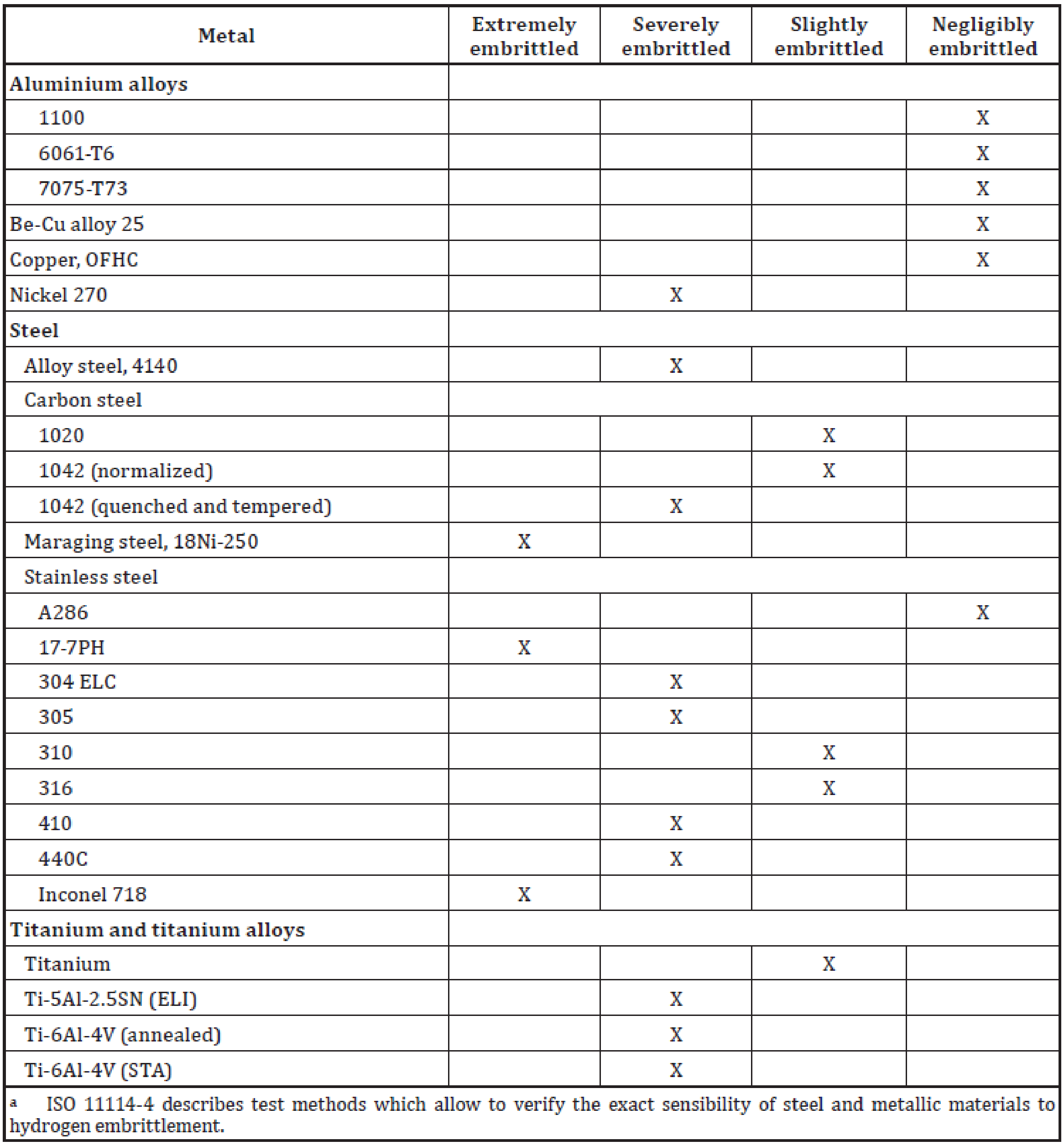
Annex 3

Ignition and combustion properties for air mixtures at 25 °C and 101,3 kPa for several common fuels. (ISO/TR 15916:2015, 2015, p. 56)

Fuel	**Lower flammability limit** % vol. fraction	**Stoichiometric mixture** % vol. fraction	**Upper flammability limit** % vol. fraction	**Minimum ignition energy** mJ	**Auto-ignition temperature** K	**Laminar burning velocity** m/s
Hydrogen (H_2) (see Table B1)	4	29,5	77	0,017	858	2,70
Methanol (CH_3OH)	6,0	12,3	36,5	0,174	658	0,48
Methane (CH_4)	5,3	9,5	17,0	0,274	810	0,37
Propane (C_3H_8)	1,7	4,0	10,9	0,240	723	0,47
Gasoline[a] (C_8H_{18})	1,0	1,9	6,0	0,240	488	0,30

Annex 4

Hydrogen embrittlement and materials compatible with hydrogen. (ISO/TR 15916:2015, 2015, pp. 58,60)



Metal	Extremely embrittled	Severely embrittled	Slightly embrittled	Negligibly embrittled
Aluminium alloys				
1100				X
6061-T6				X
7075-T73				X
Be-Cu alloy 25				X
Copper, OFHC				X
Nickel 270		X		
Steel				
Alloy steel, 4140		X		
Carbon steel				
1020			X	
1042 (normalized)			X	
1042 (quenched and tempered)		X		
Maraging steel, 18Ni-250	X			
Stainless steel				
A286				X
17-7PH	X			
304 ELC		X		
305		X		
310			X	
316			X	
410		X		
440C		X		
Inconel 718	X			
Titanium and titanium alloys				
Titanium			X	
Ti-5Al-2.5SN (ELI)		X		
Ti-6Al-4V (annealed)		X		
Ti-6Al-4V (STA)		X		

[a] ISO 11114-4 describes test methods which allow to verify the exact sensibility of steel and metallic materials to hydrogen embrittlement.

Material	Gaseous hydrogen (GH$_2$) service	Liquid hydrogen (LH$_2$) service[b]	Remarks
METALS			
Aluminium and its alloys	S	S	Negligibly susceptible to hydrogen embrittlement.
Copper and its alloys (such as brass, bronze and copper-nickel)	S	S	Negligibly susceptible to hydrogen embrittlement.
Iron, cast, grey, ductile	NS	NS	Not permitted by relevant regulations and standards.
Nickel and its alloys (such as Inconel and Monel)	E	E	Evaluation needed. Susceptible to hydrogen embrittlement.
Steel, austenitic stainless with > 7 % nickel (such as 304, 304L, 308, 316, 321, 347)	See C.1	See C.1	May make martensitic conversion if stressed above yield point at low temperature.
Steel, carbon (such as 1020 and 1042)	See C.1	NS	Evaluation needed. Susceptible to hydrogen embrittlement. Too brittle for cryogenic service.
Steel, low alloy (such as 4140)	E	NS	Evaluation needed. Susceptible to hydrogen embrittlement. Too brittle for cryogenic service.
Steel, martensitic stainless (such as 410 and 440C)	E	E	Evaluation needed. Susceptible to hydrogen embrittlement.
Steel, nickel (such as 2,25; 3,5; 5 and 9 % Ni)	E	NS	Ductility lost at liquid hydrogen temperature
Titanium and its alloys	E	E	Evaluation needed. Susceptible to hydrogen embrittlement.
NONMETALS			
Asbestos impregnated with Polytetrafluoroethylene (PTFE)[a]	S	S	Avoid use because of carcinogenic hazard.
Chloroprene rubber (Polychloroprene[a])	S	NS	Too brittle for cryogenic service.
Polyester fibre (Dacron)	S	NS	Too brittle for cryogenic service.
Fluorocarbon rubber (Viton[a])	E	NS	Too brittle for cryogenic service.
Polyester film (Mylar)[a]	S	NS	Too brittle for cryogenic service.
Nitrile (Buna-N[a])	S	NS	Too brittle for cryogenic service.
Polyamides (nylon)	S	NS	Too brittle for cryogenic service.
Polychlorotrifluoroethylene (Kel-F[a])	S	S	
Polytetrafluoroethylene [Polytetrafluoroethylene (PTFE)[a]]	S	S	

NOTE 1 S: Suitable for use.

NOTE 2 NS: Not suitable for use.

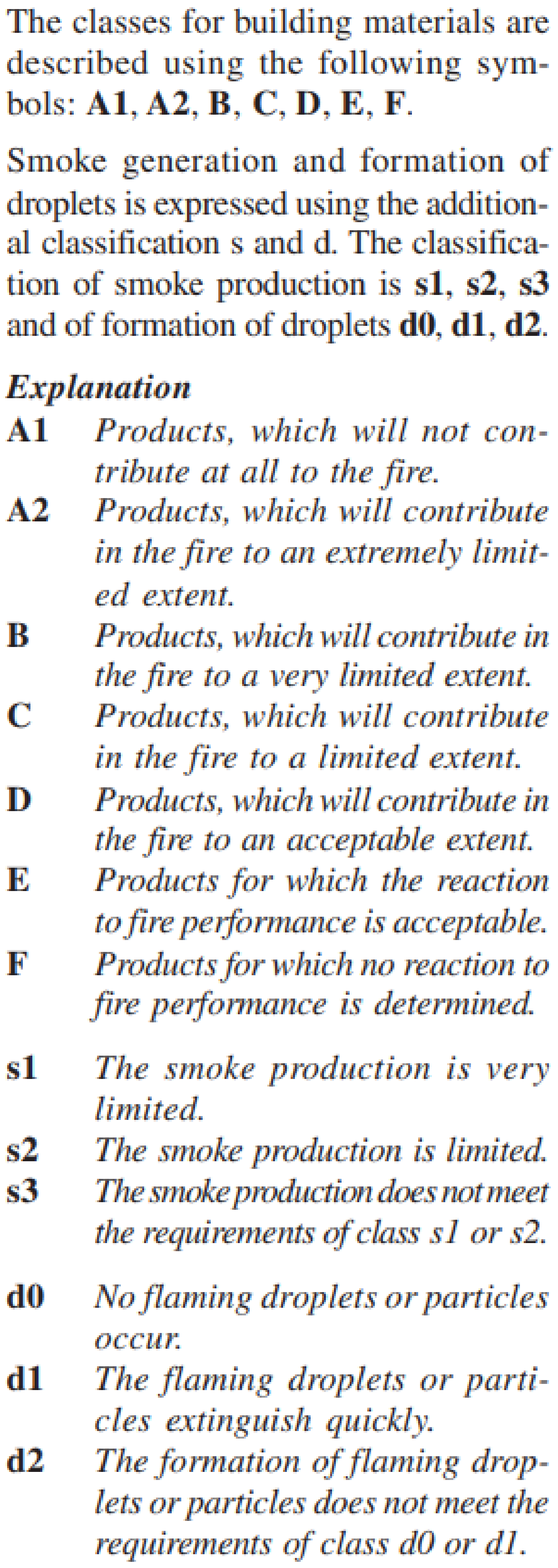
NOTE 3 E: Evaluation needed to determine if the material is suitable for the use conditions.

[a] Polytetrafluoroethylene (PTFE), Polychloroprene, Dacron, Mylar, Viton, Buna-N and Kel-F are examples of suitable products available commercially. This information is given for the convenience of users of this Technical Report and does not constitute an endorsement by ISO of these product(s).

[b] Care should be taken that when the liquid H$_2$ tanks are more or less empty that the upper part could be warm. In this case, the column of GH$_2$ applies instead of LH$_2$.

Annex 5

Fire classification for building materials (Ympäristöministerion asetus rakennusten paloturvallisuudesta: perustelumuistio, 2017)



The classes for building materials are described using the following symbols: **A1**, **A2**, **B**, **C**, **D**, **E**, **F**.

Smoke generation and formation of droplets is expressed using the additional classification s and d. The classification of smoke production is **s1**, **s2**, **s3** and of formation of droplets **d0**, **d1**, **d2**.

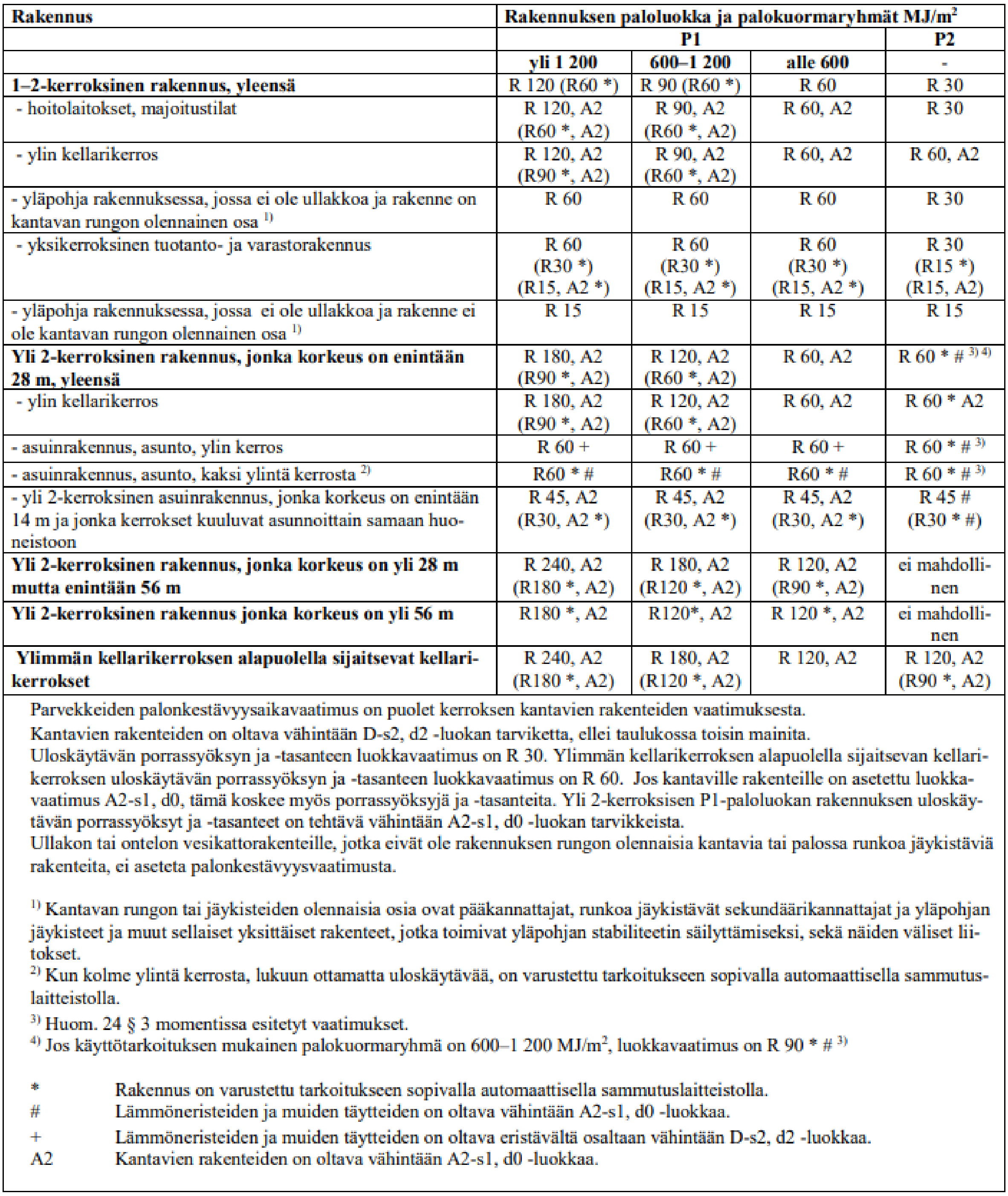
Explanation

A1	*Products, which will not contribute at all to the fire.*
A2	*Products, which will contribute in the fire to an extremely limited extent.*
B	*Products, which will contribute in the fire to a very limited extent.*
C	*Products, which will contribute in the fire to a limited extent.*
D	*Products, which will contribute in the fire to an acceptable extent.*
E	*Products for which the reaction to fire performance is acceptable.*
F	*Products for which no reaction to fire performance is determined.*
s1	*The smoke production is very limited.*
s2	*The smoke production is limited.*
s3	*The smoke production does not meet the requirements of class s1 or s2.*
d0	*No flaming droplets or particles occur.*
d1	*The flaming droplets or particles extinguish quickly.*
d2	*The formation of flaming droplets or particles does not meet the requirements of class d0 or d1.*

Annex 6

Requirements for load bearing structures in fire design class P1 and P2.

(Ympäristöministeriön asetus rakennusten paloturvallisuudesta, 848/2017, §12, table 3)



Rakennus	Rakennuksen paloluokka ja palokuormaryhmät MJ/m^2			
	P1			P2
	yli 1 200	**600–1 200**	**alle 600**	-
1–2-kerroksinen rakennus, yleensä	R 120 (R60 *)	R 90 (R60 *)	R 60	R 30
- hoitolaitokset, majoitustilat	R 120, A2 (R60 *, A2)	R 90, A2 (R60 *, A2)	R 60, A2	R 30
- ylin kellarikerros	R 120, A2 (R90 *, A2)	R 90, A2 (R60 *, A2)	R 60, A2	R 60, A2
- yläpohja rakennuksessa, jossa ei ole ullakkoa ja rakenne on kantavan rungon olennainen osa 1)	R 60	R 60	R 60	R 30
- yksikerroksinen tuotanto- ja varastorakennus	R 60 (R30 *) (R15, A2 *)	R 60 (R30 *) (R15, A2 *)	R 60 (R30 *) (R15, A2 *)	R 30 (R15 *) (R15, A2)
- yläpohja rakennuksessa, jossa ei ole ullakkoa ja rakenne ei ole kantavan rungon olennainen osa 1)	R 15	R 15	R 15	R 15
Yli 2-kerroksinen rakennus, jonka korkeus on enintään 28 m, yleensä	R 180, A2 (R90 *, A2)	R 120, A2 (R60 *, A2)	R 60, A2	R 60 * # 3) 4)
- ylin kellarikerros	R 180, A2 (R90 *, A2)	R 120, A2 (R60 *, A2)	R 60, A2	R 60 * A2
- asuinrakennus, asunto, ylin kerros	R 60 +	R 60 +	R 60 +	R 60 * # 3)
- asuinrakennus, asunto, kaksi ylintä kerrosta 2)	R60 * #	R60 * #	R60 * #	R 60 * # 3)
- yli 2-kerroksinen asuinrakennus, jonka korkeus on enintään 14 m ja jonka kerrokset kuuluvat asunnoittain samaan huoneistoon	R 45, A2 (R30, A2 *)	R 45, A2 (R30, A2 *)	R 45, A2 (R30, A2 *)	R 45 # (R30 * #)
Yli 2-kerroksinen rakennus, jonka korkeus on yli 28 m mutta enintään 56 m	R 240, A2 (R180 *, A2)	R 180, A2 (R120 *, A2)	R 120, A2 (R90 *, A2)	ei mahdollinen
Yli 2-kerroksinen rakennus jonka korkeus on yli 56 m	R180 *, A2	R120*, A2	R 120 *, A2	ei mahdollinen
Ylimmän kellarikerroksen alapuolella sijaitsevat kellarikerrokset	R 240, A2 (R180 *, A2)	R 180, A2 (R120 *, A2)	R 120, A2	R 120, A2 (R90 *, A2)

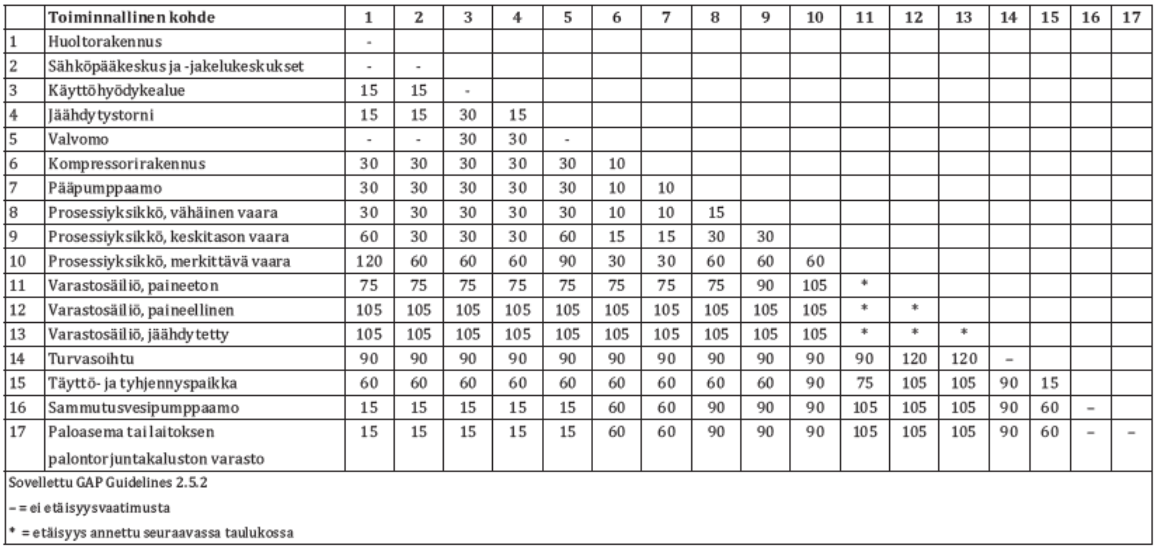
Parvekkeiden palonkestävyysaikavaatimus on puolet kerroksen kantavien rakenteiden vaatimuksesta.
Kantavien rakenteiden on oltava vähintään D-s2, d2 -luokan tarviketta, ellei taulukossa toisin mainita.
Uloskäytävän porrassyöksyn ja -tasanteen luokkavaatimus on R 30. Ylimmän kellarikerroksen alapuolella sijaitsevan kellarikerroksen uloskäytävän porrassyöksyn ja -tasanteen luokkavaatimus on R 60. Jos kantaville rakenteille on asetettu luokkavaatimus A2-s1, d0, tämä koskee myös porrassyöksyjä ja -tasanteita. Yli 2-kerroksisen P1-paloluokan rakennuksen uloskäytävän porrassyöksyt ja -tasanteet on tehtävä vähintään A2-s1, d0 -luokan tarvikkeista.
Ullakon tai ontelon vesikattorakenteille, jotka eivät ole rakennuksen rungon olennaisia kantavia tai palossa runkoa jäykistäviä rakenteita, ei aseteta palonkestävyysvaatimusta.

1) Kantavan rungon tai jäykisteiden olennaisia osia ovat pääkannattajat, runkoa jäykistävät sekundäärikannattajat ja yläpohjan jäykisteet ja muut sellaiset yksittäiset rakenteet, jotka toimivat yläpohjan stabiliteetin säilyttämiseksi, sekä näiden väliset liitokset.
2) Kun kolme ylintä kerrosta, lukuun ottamatta uloskäytävää, on varustettu tarkoitukseen sopivalla automaattisella sammutuslaitteistolla.
3) Huom. 24 § 3 momentissa esitetyt vaatimukset.
4) Jos käyttötarkoituksen mukainen palokuormaryhmä on 600–1 200 MJ/m^2, luokkavaatimus on R 90 * # 3)

*	Rakennus on varustettu tarkoitukseen sopivalla automaattisella sammutuslaitteistolla.
#	Lämmöneristeiden ja muiden täytteiden on oltava vähintään A2-s1, d0 -luokkaa.
+	Lämmöneristeiden ja muiden täytteiden on oltava eristävältä osaltaan vähintään D-s2, d2 -luokkaa.
A2	Kantavien rakenteiden on oltava vähintään A2-s1, d0 -luokkaa.

Annex 7

Safety distances to production relevant facilities and facilities not relevant to production **[m]** (SFS 3353:2019, 2019, pp. 19-20)

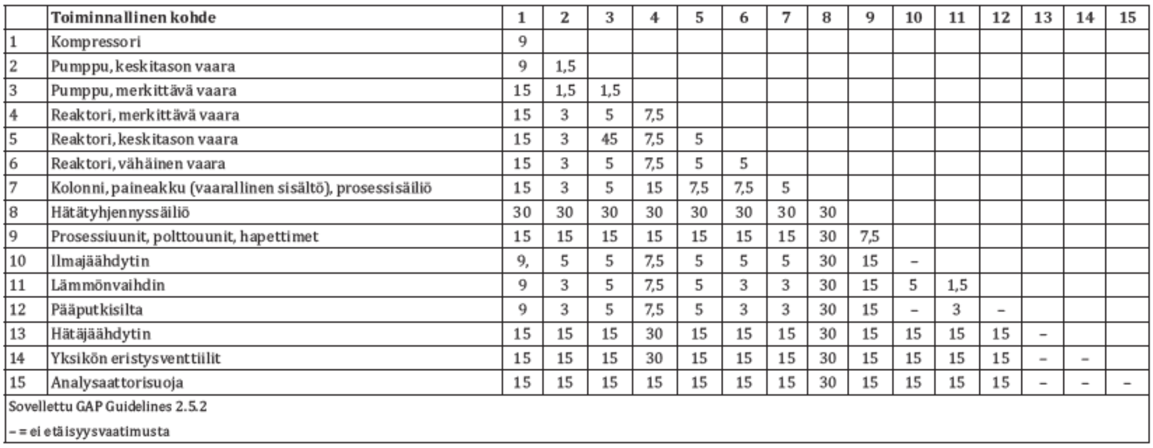


	Toiminnallinen kohde	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**
1	Huoltorakennus	-																
2	Sähköpääkeskus ja -jakelukeskukset	-	-															
3	Käyttöhyödykealue	15	15	-														
4	Jäähdytystorni	15	15	30	15													
5	Valvomo	-	-	30	30	-												
6	Kompressorirakennus	30	30	30	30	30	10											
7	Pääpumppaamo	30	30	30	30	30	10	10										
8	Prosessiyksikkö, vähäinen vaara	30	30	30	30	30	10	10	15									
9	Prosessiyksikkö, keskitason vaara	60	30	30	30	60	15	15	30	30								
10	Prosessiyksikkö, merkittävä vaara	120	60	60	60	90	30	30	60	60	60							
11	Varastosäiliö, paineeton	75	75	75	75	75	75	75	75	90	105	*						
12	Varastosäiliö, paineellinen	105	105	105	105	105	105	105	105	105	105	*	*					
13	Varastosäiliö, jäähdytetty	105	105	105	105	105	105	105	105	105	105	*	*	*				
14	Turvasoihtu	90	90	90	90	90	90	90	90	90	90	90	120	120	–			
15	Täyttö- ja tyhjennyspaikka	60	60	60	60	60	60	60	60	60	90	75	105	105	90	15		
16	Sammutusvesipumppaamo	15	15	15	15	15	60	60	90	90	90	105	105	105	90	60	–	
17	Paloasema tai laitoksen palontorjuntakaluston varasto	15	15	15	15	15	60	60	90	90	90	105	105	105	90	60	–	–

Sovellettu GAP Guidelines 2.5.2

– = ei etäisyysvaatimusta

* = etäisyys annettu seuraavassa taulukossa



	Toiminnallinen kohde	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
1	Kompressori	9														
2	Pumppu, keskitason vaara	9	1,5													
3	Pumppu, merkittävä vaara	15	1,5	1,5												
4	Reaktori, merkittävä vaara	15	3	5	7,5											
5	Reaktori, keskitason vaara	15	3	45	7,5	5										
6	Reaktori, vähäinen vaara	15	3	5	7,5	5	5									
7	Kolonni, paineakku (vaarallinen sisältö), prosessisäiliö	15	3	5	15	7,5	7,5	5								
8	Hätätyhjennyssäiliö	30	30	30	30	30	30	30	30							
9	Prosessiuunit, polttouunit, hapettimet	15	15	15	15	15	15	15	30	7,5						
10	Ilmajäähdytin	9,	5	5	7,5	5	5	5	30	15	–					
11	Lämmönvaihdin	9	3	5	7,5	5	3	3	30	15	5	1,5				
12	Pääputkisilta	9	3	5	7,5	5	3	3	30	15	–	3	–			
13	Hätäjäähdytin	15	15	15	30	15	15	15	30	15	15	15	15	–		
14	Yksikön eristysventtiilit	15	15	15	30	15	15	15	30	15	15	15	15	–	–	
15	Analysaattorisuoja	15	15	15	15	15	15	15	30	15	15	15	15	–	–	–

Sovellettu GAP Guidelines 2.5.2

– = ei etäisyysvaatimusta