



Norwegian University of
Science and Technology

Reliability of Ignition Source Isolation

Tarjei Olsen Kvalø

Master of Science in Engineering Cybernetics

Submission date: July 2010

Supervisor: Tor Engebret Onshus, ITK

Norwegian University of Science and Technology
Department of Engineering Cybernetics

Problem Description

Ignition source isolation is a safety system used in the oil and gas industry to minimize the probability that hydrocarbon leaks from the process are ignited.

In order to determine risk levels across the installation, the expected effectiveness or reliability of this system must be evaluated.

Problem statement for this thesis work is as follows:

1. Construct a model of the process by which a piece of equipment in a hazardous area successfully ignites hydrocarbon gas.
2. Using this model and available data from the industry, develop a set of weighing factors for equipment types commonly found in the process area to account for their relative contribution to the overall ignition probability.
3. Apply the above to a module on an actual oil and gas installation in order to estimate the effectiveness of the isolation system. That is, how much does it reduce the overall ignition probability.

Assignment given: 01. February 2010

Supervisor: Tor Engebret Onshus, ITK

Abstract

This thesis work was a study into how the effectiveness of ignition source isolation can be estimated. This safety system works by isolating electrical equipment from power when flammable gas is detected on oil and gas installations. Improving the understanding of how effective this system actually is at reducing explosion risk in hazardous areas was the main motivation, as this could help operators and authorities form a more accurate risk picture.

The main part of the work is the development and discussion of a model for ignition that was made so that it could be used to estimate this effectiveness. A detailed model is presented first, based on evaluating failure modes of equipment, then suggestions are made for how it could be simplified to be of practical use in risk analysis.

The second part of the project was to gather enough data from industry sources to be able to estimate key parameters in the model relating to the failure probability of Ex barriers and the ignition probability resulting from common types of process equipment. Not enough data was found to support a quantification of these parameters, but results from a major maintenance project on an oil and gas installation in the Norwegian sector was reviewed and discussed.

The method of systematically evaluating failure modes in order to determine risk could be useful in other applications, and the suggested way to proceed with the work in this report is to continue gathering data and analyzing it to build up a credible set of failure probabilities for Ex barriers and common equipment types.

Preface

This Master's thesis represents the final semester's work in the Master of Technology program at the Norwegian University of Science and Technology (NTNU) in Trondheim. It was carried out in cooperation with the Department of Engineering Cybernetics and Scandpower while I was based in Oslo.

While I felt that I succeeded in achieving some of the goals set out in the problem statement and definitely learned a lot about the subject matter, it cannot be denied that I did not get as far as I had set out to do. I had intended for the project to be mainly based on using data analysis to develop weighting factors for ignition sources, and when little data came in I was scrambling for information. Scandpower was working on a project in parallel with mine that had some of the same goals, and they were interested in finding data as well. However due to different timescales on their project compared to mine, they had not been able to gather much useful data either.

I extend thanks to Scandpower for providing me with a desk and computer to work from at their head office at Kjeller. I would also like to thank Øyunn Simonsen and Svein Køhler at Statoil for giving me access to data from their maintenance project. In the same manner I should thank Thore Andersen and Roar Olsen on the Norwegian Electrotechnical Committee (NEK) for giving guidance on Ex protection types. Finally I want to thank my supervisor at the Department of Engineering Cybernetics, Tor Onshus.

Table of contents

1.	Introduction	1
1.1.	General	1
1.2.	Previous work.....	1
1.3.	Scope of work.....	2
1.4.	Structure of this report.....	3
2.	Ignition by electrical equipment	3
2.1.	General	3
2.2.	Hot wires and surfaces	4
2.3.	Electric sparks	4
3.	Explosion protection.....	6
3.1.	General	6
3.2.	Ex d – flameproof construction	6
3.3.	Ex e – increased safety	6
3.4.	Ex p – pressurization	7
3.5.	Ex i – intrinsic safety.....	7
3.6.	Ex m, Ex q and Ex o – encapsulation and immersion	8
3.7.	Ex n – non-sparking	8
4.	General model for ignition and ignition source isolation	9
4.1.	General	9
4.2.	Modeling discrete ignition.....	10
4.3.	Modeling continuous ignition	12
4.4.	Ignition source isolation	13
4.5.	Worked example.....	15
5.	Model discussion.....	16
5.1.	General	16
5.2.	Model assumptions.....	16
5.3.	Model parameters	19
5.4.	Using the model in risk analysis.....	20
6.	Data review and analysis.....	21
6.1.	General	21

6.2.	Benjaminsen and van Wiechen data.....	22
6.3.	Benjaminsen and van Wiechen data analysis.....	23
6.4.	Data from oil and gas development in the Norwegian sector.....	24
6.5.	Analysis of data from oil and gas development	25
7.	Discussion and conclusion	28
7.1.	General	28
7.2.	Discussion	28
7.3.	Conclusion and further work.....	29
	Appendix A (on CD).....	31

Formula list

1. Equation set governing ignition	4
2. Upper bound for spark energy for a capacitive circuit	5
3. Upper bound for spark energy for an inductive circuit	5
4. Ignition probability for single discrete ignition source	10
5. Probability that single failure mode is active	10
6. Probability of failure in Ex protection for single ignition source	11
7. Probability that a discrete ignition source will spark in a time step	11
8. Ignition probability for single continuous ignition source	12
9. Proportion of time a single continuous ignition source is hot	13
10. Probability of gas cloud ignition for discrete sources before isolation	13
11. Residual ignition probability for single discrete source after isolation	14
12. Probability of gas cloud ignition for discrete sources after isolation	14
13. Probability of gas cloud ignition for continuous sources before isolation	14
14. Probability of gas cloud ignition for continuous sources after isolation	14
15. Effectiveness of ignition source isolation	15
16. Probability of failure for Ex protection by group	23

Table list

1. Parameters for failure modes, discrete sources	10
2. Parameters for worked motor example	15
3. MTBF for failures in Ex protection per Benjaminsen and van Wiechen	22
4. Tests and faults in data from maintenance project	24
5. Known and unknown information about data set from maintenance project	25
6. Confidence interval and computed $P_{EX_FAIL}(i)$ for maintenance project	26

1. Introduction

1.1. General

Ignition source isolation is a safety system in common usage in any industries where explosive atmospheres could form. It aims to reduce explosion risk by electrical isolation of any equipment that could ignite the atmosphere, and is predicated on detection of the explosive atmosphere. The principle is applicable to hydrocarbon gas clouds such as can be formed from process leaks in the oil and gas industry as well as to explosive dust clouds or flammable mists.

The main motivation for studying the reliability of this system comes from risk analysis in the oil and gas industry. The ability to accurately assess the risk levels on platforms and installations is important both to operators in the industry and to the regulatory authorities. With the recent catastrophic loss of life and environmental damage resulting from the accident on the Deepwater Horizon, there is increased attention to risks in this industry from the public as well. That accident and other well-known incidents such as the Piper Alpha catastrophe escalated because leaked gas from the process came into contact with an ignition source and exploded.

While it is clear that ignition source isolation reduces the probability of an explosion, we are not aware of any studies done that have conclusively quantified how much of an effect it has on ignition probabilities. The main goal of this project then is to develop a model that can be used to estimate the effectiveness of ignition source isolation and to find data from industry sources that can be used to quantify the parameters of that model.

In this chapter we reference previous work on the subject, present a more detailed scope of work for the project and outline the structure of this report.

1.2. Previous work

In the Norwegian sector there have been two projects aiming to develop an ignition model for use in risk analysis, JIP-97 and OLF-2004 /4/. OLF-2004 was an update to the major joint industry project JIP-97, aiming to refine the model and ignition probabilities using more up to date data on releases. Both models had in common that the model parameters were estimated by using experienced releases and ignitions. Ignition sources were not individually modeled, rather a generic ignition probability per cubic meter of process equipment was assumed. The

suggested value for the effectiveness P_{ISO} of ignition source isolation was 0.75, which fit well with the accident data but was not based on a study into how the system performs at any level of detail.

In winter 2009, the effectiveness of ignition source isolation was studied by this author, using a module on an FPSO under construction for the Norwegian sector as a case study [7]. In that project much effort was spent on understanding how ignition source isolation was physically and technically carried out. In the end the effectiveness was estimated using a simple method that did not take into account how different ignition sources have varying probability of igniting gas. A more refined method using weighting factors for different categories of ignition sources was suggested, but there was insufficient time in the project to develop credible weighting factors.

1.3. Scope of work

This project consists of three distinct steps:

1. Literature review. In this part of the project we shall survey existing literature on ignition phenomenon and electrical equipment for hazardous areas. The goal is to develop a working understanding of ignition and get familiarized with the various techniques that exist for constructing electrical equipment so that it can be operated safely in hazardous areas.
2. Modeling. First a detailed model of how electrical equipment ends up igniting hydrocarbon gas clouds should be developed. The goal is to set up the model as a series of analytical expressions for ignition from electrical equipment that can be used to evaluate the effectiveness of ignition source isolation. We should then look into ways to simplify the model so that it has an appropriate level of detail for use in risk analysis.
3. Data collection and analysis. In order to be able to establish model parameters, we are dependent on data that could be used to quantify ignition probabilities. The strategy here is to approach operators and other companies in the industry and ask them to contribute failure data for their equipment and other relevant data such as studies on ignition probabilities. We should then analyze the data and discuss how it can be applied to quantify model parameters.

1.4. Structure of this report

- In chapters two and three we review and summarize information on the ignition phenomenon and on explosion prevention techniques respectively.
- In chapter four we develop a model aimed at estimating the effectiveness of ignition source isolation.
- Chapter five is dedicated to the discussion of the model, the assumptions behind it and the parameters used in it.
- In chapter six we review and analyze the data found and discuss how it can be used to set model parameters.
- Chapter seven is the final chapter and contains discussion, concluding remarks and suggestions for further work.

2. Ignition by electrical equipment

2.1. General

This chapter briefly reviews the theory behind ignition of gases and summarizes the two ways in which electrical equipment can provide ignition: by being heated to sufficient temperature, or by releasing a spark with sufficient energy to ignite gas. While the exact temperatures and energy levels required to ignite gas in practice differ widely depending on a range of factors such as gas composition, experimental geometry and laboratory conditions, the fundamental principles at work remain the same.

This section is mainly based on [2]. An in-depth treatment of combustion theory is beyond the scope of this paper, but we will introduce a simplified view of ignition sufficient to consider the relationship between electrical equipment and flammable gases.

Consider a volume V of an explosive gas mixture that is heated by some mechanism to the temperature $T > T_1$, where T_1 is the temperature of the surrounding gas outside of V . We assume the temperature T is uniform across V , and that the temperature drop $T - T_1$ occurs suddenly at the outer limit of V . Consider then that the gas in V starts to react chemically giving off heat, with a reaction rate $G(T)$ measured in Joule/s. This reaction will increase the temperature of V , and due to the temperature difference $T - T_1$, heat will be transported from V to the surrounding gas at a rate of $L(T)$. Now, whether ignition is achieved is determined by whether the rate of heat generation $G(T)$, as T increases, is larger than the rate of heat loss

$L(T)$. When sufficient temperature is reached, the combustion process in V will intensify and ultimately produce enough heat that the heat transfer to the surrounding gas becomes self-sustaining. Therefore, the following conditions must be satisfied at the minimum ignition temperature for a given gas to be ignited:

$$G(T) = L(T)$$

and [1]

$$\frac{dG(T)}{dT} > \frac{dL(T)}{dT}$$

This fundamental equation governs ignition, whether it is caused by a hot surface or an electric spark. It is however difficult in practice to determine $G(T)$, $L(T)$ or the geometry of the ignition zone.

2.2. Hot wires and surfaces

The ignition mechanism of a hot surface is different from a spark ignition in that energy is imparted to the gas over an extended period of time. The autoignition temperature (AIT) for a gas is defined as the minimum temperature required to ignite the gas in air without a spark or flame being present. In theory, material that is heated to this temperature should ignite gas that it is exposed to. However, the AIT for a given explosive gas mixture cannot be regarded as a constant, but is strongly dependent on both the geometry of the ignition source and the dynamic state of the gas [2]. For a hot surface, convection currents around the surface will not allow a particular volume of gas to remain in contact with the surface long enough to reach ignition temperature, unless the surface is of a much higher temperature. The following experiment was cited in [2]:

“When 114-mm-long nickel bars, 1mm thick and 12.5 to 25 mm wide were heated to ignite 11% methane-air, the bar temperatures were 1,079°C for the 25-mm width and 1,114°C for the 12.5-mm-width. This is quite high relative to the ignition temperature of methane, 538°C.”

What can be taken from this is that in most realistic situations, the experienced AIT is likely to be higher than the experimental values cited in literature.

2.3. Electric sparks

Electric sparks occur when the electrical field strength increases above the maximum that the dielectric medium can take, initiating a process known as *breakdown*. This leads to ionization

of the gas between the electrodes, causing the gap to conduct electricity and energy is discharged through the gap as if it were an ohmic resistor. The main difference is that this ohmic resistance is not constant for a given electrode gap and gas, but is reduced as the current in the gap increases /2/. The geometry, material and surface microstructure of the electrodes also influences breakdown voltage.

There are two main modes in which sparks are generated by electric equipment /2/:

- Arcing at closing contacts or between fixed electrodes in a capacitive circuit. Energy stored in the capacitor is released as contacts close or the gap between fixed electrodes breaks down.
- Opening contacts in an inductive circuit. Energy stored in the inductor is released as opening contacts interrupts current in the circuit.

In a similar manner to the way AIT is experimentally determined for different gases, minimum ignition energy (MIE) for a particular gas mixture can be determined using test apparatus. Also similarly to the case for hot surfaces, these referenced values tend to be conservative due to the test conditions – the turbulence and non-optimal electrode spacing found under realistic conditions result in higher spark energies required for ignition /2/. An upper bound for the spark energy E_G when closing a given capacitive circuit can be found by:

$$E_G = \frac{1}{2}CU^2 \quad [2]$$

and equivalently when opening contacts in an inductive circuit:

$$E_G = \frac{1}{2}LI^2 \quad [3]$$

where C is capacitance, U is voltage, L is inductance and I is current. These are derived by assuming that all of the energy in the circuit goes into the spark.

3. Explosion protection

3.1. General

In the context of this paper, explosion protection is a term for a variety of techniques used to prevent electrical equipment from igniting gas. Equipment that has been constructed using these methods is generally referred to as Ex equipment and in this chapter we review the main types of Ex protection. This chapter is mainly drawn from /1/ and /2/.

3.2. Ex d – flameproof construction

Several types of electrical equipment become hot enough or release sparks of sufficient energy to ignite an explosive mixture. A technique for operating these equipment types safely in hazardous areas is to provide an enclosure constructed in such a way that, if ignition does occur, the flame cannot propagate outside the enclosure and spread to the surrounding atmosphere. The enclosure is typically not vapor-tight, and one or several gaps (typically flanges) allow the outside atmosphere to penetrate the enclosure and vice versa. For this type of protection to be effective, three main criteria must be satisfied:

- The enclosure must be able to contain an internal explosion without damage
- An internal explosion must not heat the outside of the enclosure so much that it becomes capable of igniting the outside atmosphere
- An internal explosion must not be able to propagate to the outside atmosphere

Items 1 and 2 above are satisfied through material choice and dimensioning the enclosure properly, while item 3 depends on the correct dimensioning of the gap separating the inside of the enclosure from the outside atmosphere. For a particular explosive gas mixture, the maximum experimental safe gap (MESG) can be determined. When ignition occurs inside the enclosure, the pressure inside increases, expelling a jet of hot gas through the gap(s). The MESG is the minimum gap distance at which quenching effects renders the gas jet unable to ignite the outside atmosphere.

Ex d protection is typically used on control stations, motors, fuses, switchgear, pumps and power electronics /5/ and /6/.

3.3. Ex e – increased safety

Unlike Ex d protection, increased safety devices are not designed to contain an internal explosion if it should occur. Rather it is apparatus that in normal operation is nonsparking,

and has been designed conservatively. When used within its ratings, any failure has an acceptably low probability of producing an ignition capable spark or hot surface. This includes short circuit and overload conditions. Typical requirements for Ex e apparatus include:

- Creepage and clearance distances much larger than required for ordinary equipment
- No part of the device may exceed temperatures corresponding to the marked T code during starting, normal operation or recognized overload
- Increased attention to robustness compared to normal industrial equipment

Ex e protection is normally used on motors, control panels, lights and junction boxes /5/ and /6/.

3.4. Ex p – pressurization

Ex p protection uses a positive overpressure to prevent explosive atmospheres from entering an enclosure. The overpressure is required to be at least 0.5 mbar, and is maintained by continuously pumping in fresh air or an inert gas. When the system is designed correctly, this excludes an outside explosive atmosphere from penetrating the enclosure. Some requirements for pressurized enclosures are:

- Intake of the protective gas supply must be placed in a nonhazardous location
- Enclosure must be robust enough that accidents of foreseeable nature and normal conditions of use will not damage the enclosure such that positive overpressure cannot be maintained

Ex p protection is most often used in cases when other types of protection are not suitable, due to its expense. Examples of use are control rooms, large instrument cabinets or large dc motors /5/ and /6/.

3.5. Ex i – intrinsic safety

In an intrinsically safe system, safety is afforded by the design of the system, not by the subsequent addition of protective measures. The system has been designed such that it is incapable of releasing sufficient electrical energy under normal or abnormal conditions to cause ignition. This is accomplished through strictly limiting the energy available to the circuit. Intrinsic safety is a term applied to systems (equipment and wiring), not to single devices. Key principles of intrinsic safety design include:

- Limiting the electric energy that can be stored in the circuit (capacitance/inductance)
- Putting barriers in place to reduce the likelihood of a voltage higher than the rated voltage appearing at the terminals of the circuit
- Fault tolerant design – the two subtypes of intrinsically safe systems are Ex ia and Ex ib. The former requires continued safe operation in the event of up to two independent faults, while the latter tolerates up to one fault.

Due to energy limitations, intrinsic safety cannot be used for high power equipment. It is mainly used for measurement and control, automation technology, sensors and actuators /5/ and /6/.

3.6. Ex m, Ex q and Ex o – encapsulation and immersion

These three techniques are similar in the way that they prevent any spark-capable or heat-producing parts of the equipment from coming into contact with the outside atmosphere, safety is provided by segregation. The three types are:

Ex m – Encapsulation, also referred to as hermetic sealing. The ignition-capable parts of the equipment are embedded in a solid or semi-solid compound. Used primarily for small apparatus, instrumentation and control gear /5/ and /6/.

Ex q – Powder filling. The electric parts of the equipment are surrounded by quartz sand or other inert powder. Any arc or spark within cannot cause a gas explosion even if some gas has penetrated the sand. Used primarily for capacitors and transformers /5/ and /6/.

Ex o – Oil immersion. Here all ignition-capable components are immersed in oil to sufficient depth that they cannot ignite an explosive atmosphere above the surface of the oil. Used primarily for switchgears, transformers and magnetic contactors /5/ and /6/.

These methods are not used as frequently on oil and gas installations as methods 3.1-3.4, but are included for completeness.

3.7. Ex n – non-sparking

Ex n is equipment designed to not provide an ignition source in normal use, and covers a variety of protection methods. Equipment in this category often uses some of the techniques from 3.1 to 3.5, but fall short of qualifying for classification in those categories. The equipment is safe as long as it is operated within specified operating limits, but fault tolerance

is generally not built in. For that reason it cannot be used in hazardous areas classified as Zone 1 or Zone 0.

4. General model for ignition and ignition source isolation

4.1. General

The goals for setting up a general mathematical model of ignition source isolation in this paper are twofold; to gain an understanding of the processes involved, and to identify the key parameters that have to be estimated in order to study the phenomenon quantitatively. To assist with modeling, we define some assumptions and limitations. They are as follows:

1. We consider a module that has been classified as a hazardous area on an oil and gas installation.
2. The module has a large amount of equipment of different types, and any equipment that draws electrical power is considered an ignition source.
3. Leaked gas is considered to be uniformly at its most easily ignitable concentration.
4. Each ignition source is assumed to have two possible ignition modes: either by releasing an ignition-capable electric spark, or by being sufficiently hot to ignite gas. We label these modes as discrete and continuous ignition respectively.
5. For a given ignition source, we assume that it has a certain probability of igniting gas in discrete mode per time step. Discrete ignition does not happen at the moment when the ignition source is exposed to gas, but is rather defined by certain failure modes in the equipment or randomly.
6. Continuous ignition is assumed to happen immediately in the time step the ignition source is exposed to gas.
7. Only equipment that is being operated is capable of igniting gas.
8. When ignition source isolation is activated for an ignition source, it is turned off completely with no residual probability for igniting gas.

The ignition probabilities of individual ignition sources are the building blocks for a larger model for ignition, so we first develop models for discrete and continuous ignition. Then we use these to model ignition source isolation and its effectiveness, and finally describe a small worked example of how the model could be applied.

4.2. Modeling discrete ignition

First we examine ignition by electric sparks, and consider an individual ignition source. Assuming it has been exposed to flammable gas, two things must happen for it to ignite the gas:

1. The Ex protection must be ineffective. We denote the probability of this occurring for ignition source i as $P_{EX_FAIL}(i)$. Note that $P_{EX_FAIL}(i) = 1$ for unprotected equipment.
2. An ignition-capable spark must be released. The probability of at least one such spark being released in a time step for ignition source i is denoted $P_{SPARK}(i)$. This factor can be thought of as the intensity of the ignition source.

We can then define the ignition probability for a discrete source as follows, per time step of operation:

$$P_{I,D}(i) = P_{EX_FAIL}(i) * P_{SPARK}(i) \quad [4]$$

Let us first consider the first factor on the right-hand side of this equation. For each Ex protected device, we assume there are n distinct, known failure modes that cause the protection system to be ineffective. For each of these failure modes, three key parameters apply:

Table 1: Parameters for failure modes, discrete sources

Parameter	Significance
$MTBF(j)$	The mean time between failures for failure mode j
$t_m(j)$	The mean time before failure mode j is detected, and presumably corrected by maintenance
$S(j)$	The severity of failure mode j , the probability that this failure mode will cause the Ex-protection to fail to prevent an ignition

Statistically, when the device has been in service for $MTBF(j)$ hours, the failure mode j occurs, and remains active for $t_m(j)$ hours. We can see from this that the probability that failure mode j will be active at a given time can be expressed as:

$$P_{ACTIVE}(j) = \frac{t_m(j)}{MTBF(j) + t_m(j)} \quad [5]$$

It is sufficient that one such failure mode is active for the protection system to be ineffective. Therefore we can find $P_{EX_FAIL}(i)$ indirectly by calculating the probability that no such failure mode is active:

$$P_{EX_FAIL}(i) = 1 - \prod_{j=1}^n (1 - P_{ACTIVE}(j) * S(j)) =$$

$$1 - \prod_{j=1}^n \left(1 - \frac{t_m(j)}{MTBF(j) + t_m(j)} * S(j)\right) \quad [6]$$

As a simple example, consider an Ex d protected electric motor. A known failure mode is the gap becoming expanded due to corrosion. Let's say the MTBF for this failure is 7000 hours, and it is typically only discovered during periodic maintenance that occurs every 1000 hours. Therefore we set t_m to 500 hours as an average value. If we further assume that this failure mode reduces the effectiveness of the protection by 50% and is the only possible failure mode, we then have: $P_{EX_FAIL}(i) = 1 - \left(1 - \frac{500}{7000+500} * 0.5\right) = 0.033$.

Now going back to equation [4], we investigate the ignition source intensity, that is the parameter $P_{SPARK}(i)$, for discrete ignition source i . The equipment can be thought of as having a certain probability of generating ignition-capable sparks in normal operation, without any fault conditions present. We refer to this, the probability that the ignition source will release a spark in a time unit of normal operation, as its background intensity: $P_{SPARK_B}(i)$. For normally nonsparking equipment this value will be zero. Then there are a number of faults that could occur that have their own associated probability to produce a spark. These can be characterized by the parameters $MTBF(j)$ and $t_m(j)$ as was the case for failures in Ex-protection. We also need a parameter for the severity of the failure, that is, the resultant probability of spark release per time unit when the failure mode is active. We use $S(j)$ for this, even though the meaning is changed from the definition in table 1. We are then able to use a similar strategy as previously, and can state that:

$$P_{SPARK}(i) = P_{USE}(i)$$

$$* \left(1 - (1 - P_{SPARK_B}(i)) * \left[\prod_{j=1}^n \left(1 - \frac{t_m(j)}{MTBF(j) + t_m(j)} * S(j)\right)\right]\right) \quad [7]$$

Where $P_{USE}(i)$ is the percentage of time the equipment is in use, statistically.

Further developing our example of the Ex d protected motor above, we look at a time step of one second and determine the following: The motor is used to drive a pump and is and has only 0.05 % chance of sparking per second of normal use. It is in use 10% of the time. Additionally, there is a failure mode associated with contamination of grease in the motor compartment. This results in 0.5% probability for a spark in a second. This failure mode is found to occur with a frequency of every 200 hours on average, and is typically detected and corrected within 12 hours. Ignoring any other failure modes, we get:

$$P_{SPARK}(i) = 0.1 * (1 - (1 - 0.05) * \left(1 - \frac{12}{200 + 12} * 0.5\right)) = 0.0077$$

Equation [4] models the ignition probability for a single discrete ignition source per time unit of use, and for our electric motor example we would get: $P_{I,D}(i) = P_{EX_FAIL}(i) * P_{SPARK}(i) = 0.033 * 0.0077 = 2.5 * 10^{-4}$.

4.3. Modeling continuous ignition

The main difference in modeling terms between discrete and continuous modes of ignition are that while the former is described by a certain probability of sparking in a time unit, continuous ignition is assumed to be instantaneous. We can however develop an expression for it in a similar way as was done in the previous chapter. For equipment to ignite gas via a hot surface, two things must happen:

1. The Ex protection must fail. This is the exact same $P_{EX_FAIL}(i)$ as was used in equation [4].
2. A sufficiently hot surface must develop. We can define the percentage of time any part of the equipment is hot enough to ignite gas as $P_{HOT}(i)$. As previously, this can be termed the intensity of the ignition source.

We then have the probability that a continuous ignition source i will ignite gas it is exposed to:

$$P_{I,C}(i) = P_{EX_FAIL}(i) * P_{HOT}(i) \quad [8]$$

$P_{EX_FAIL}(i)$ can be calculated as in equation [6]. An expression for $P_{HOT}(i)$ can be found using the same technique as was used to find $P_{SPARK}(i)$ in the previous chapter. First we

consider the percentage of time the equipment gets hot enough to ignite gas in normal operation, this is the background intensity $P_{HOT_B}(i)$. Then any faults that could occur that have their own probability $S(j)$ of producing a hot enough surface must be taken into account. We then get an expression for $P_{HOT}(i)$ that is analogous to the one for $P_{SPARK}(i)$:

$$P_{HOT}(i) = P_{USE}(i) * \left(1 - (1 - P_{HOT_B}(i)) * \left[\prod_{j=1}^n \left(1 - \frac{t_m(j)}{MTBF(j) + t_m(j)} * S(j) \right) \right] \right) \quad [9]$$

4.4. Ignition source isolation

In order to derive an expression for the reliability or effectiveness of ignition source isolation, we evaluate discrete and continuous ignition sources separately then combine the two. We assume that a hydrocarbon gas cloud is present in the module. The cloud has a volume V and is growing at a constant rate, exposing a new volume V_{NEW} in every time step. Our strategy will be to find the probability of the gas cloud igniting for two cases:

1. Base ignition probability: no isolation of ignition sources
2. Ignition probability after ignition sources have been isolated

The effectiveness E_{ISO} of isolation can be derived by comparing the two.

Let us define $P_{I_D_TOT_PRE}$ as the probability that the gas cloud will be ignited by a discrete source in a time step before isolation. We assume there are n discrete ignition sources in the volume V . It is sufficient that one of them releases an ignition-capable spark for the gas cloud to be ignited in a time step. We can therefore calculate $P_{I_D_TOT_PRE}$ by using the same ideas as previously, and get:

$$P_{I_D_TOT_PRE} = 1 - \prod_{i=1}^n (1 - P_{I_D}(i)) \quad [10]$$

Then we look at $P_{I_D_TOT_POST}$, the probability that a discrete source ignites the cloud in a time step after isolation. There are three main component groups that must function correctly before an ignition source can be isolated in the event of a gas leakage. These are:

1. Gas detectors. The gas must be detected, typically by at least 2 detectors, before there can be any ignition source isolation. We designate the reliability of gas detection as E_{DET} .

2. The emergency shutdown system. This covers all control system logic that takes a signal from the gas detectors as input, and sends out signals to shut down all equipment affected by isolation. We designate the reliability of the ESD system as E_{ESD} .
3. The specific isolation mechanism, including relays, circuit breakers and any other components that must function for the ignition source to be isolated from power. The reliability of the isolation mechanism for a given ignition source i is designated $E_{ISO}(i)$.

Reliability in this context means the probability of correct functioning. We can use these factors to express the residual ignition probability for an ignition source i that has been subject to ignition isolation per time step:

$$P_{I_D_RES}(i) = (1 - E_{DET} * E_{ESD} * E_{ISO}(i)) * P_{I_D}(i) \quad [11]$$

Then out of the n discrete ignition sources in V , k are subject to ignition source isolation. We include the discrete ignition sources in V_{NEW} as well, but reduce their intensity by half to account for them only being exposed half of the time step, statistically. We assume these known through examination of ESD logic diagrams. We order them such that the first k ignition sources in n are affected by isolation, so that ignition sources $1..k$ are subject to isolation and ignition sources $k + 1..n$ are not. We then get, by calculating the probability of no ignition happening in the time step and using the same principles as previously:

$$P_{I_D_TOT_POST} = 1 - \prod_{i=1}^k (1 - P_{I_D_RES}(i)) \prod_{i=k+1}^n (1 - P_{I_D}(i)) \quad [12]$$

Due to continuous sources being assumed to ignite gas instantaneously upon being exposed to gas, this ignition probability is related only to the new ignition sources exposed to the gas cloud in a time step. The expressions become identical to the ones for discrete ignition, but here n and k only relate to the ignition sources in V_{NEW} :

$$P_{I_C_TOT_PRE} = 1 - \prod_{i=1}^n (1 - P_{I_C}(i)) \quad [13]$$

$$P_{I_C_TOT_POST} = 1 - \prod_{i=1}^k (1 - P_{I_C_RES}(i)) \prod_{i=k+1}^n (1 - P_{I_C}(i)) \quad [14]$$

The effectiveness of ignition source isolation can then be expressed as the ratio of cloud ignition probability post- and pre-isolation as follows:

$$E_{ISO} = \frac{1 - (1 - P_{I_D_TOT_POST}) * (1 - P_{I_C_TOT_POST})}{1 - (1 - P_{I_D_TOT_PRE}) * (1 - P_{I_C_TOT_PRE})} \quad [15]$$

4.5. Worked example

We illustrate the usage of the model with a worked example from a small gas cloud. Assume we have a gas leak that in the first time step exposes the electric motor from chapter 4.2, 10 light fixtures of the same model and 5 pressure transmitters of the same model. In this example $V = V_{NEW}$, so we reduce the discrete ignition probabilities by 50%. Again using a time step of 1 second, we have the following adjusted parameters:

Table 2: Parameters for worked motor example

Equipment	$P_{EX_FAIL}(i)$	$P_{SPARK}(i)$	$P_{HOT}(i)$	$P_{I_D}(i)$	$P_{I_C}(i)$
Motor	0.033	0.0038	0.013	$1.3 * 10^{-4}$	$4.3 * 10^{-4}$
Light fixture	$1.7 * 10^{-3}$	$1.3 * 10^{-4}$	$6.3 * 10^{-4}$	$2.2 * 10^{-7}$	$1.1 * 10^{-6}$
Pressure transmitter	$3.9 * 10^{-3}$	$3.7 * 10^{-5}$	0	$1.4 * 10^{-7}$	0

The pressure transmitter is not found to be capable of continuous ignition. We can now calculate, for this time step:

$$\begin{aligned} P_{I_D_TOT_PRE} &= 1 - (1 - 1.3 * 10^{-4}) * (1 - 2.2 * 10^{-7})^{10} * (1 - 1.4 * 10^{-7})^5 \\ &= 1.33 * 10^{-4} \end{aligned}$$

$$P_{I_C_TOT_PRE} = 1 - (1 - 4.3 * 10^{-4}) * (1 - 1.1 * 10^{-6})^{10} = 4.4 * 10^{-4}$$

The ESD diagrams for the installation shows that only the motor out of this group is affected by ignition source isolation. We now assume that E_{DET} , E_{ESD} and $E_{ISO}(i)$ for the motor all satisfy SIL 3 and thus are assumed equal to $1 - 10^{-3}$, which gives us $P_{I_D_RES}(i) =$

$(1 - 10^{-3})^3 * 1.3 * 10^{-4} = 1.296 * 10^{-4}$ and $P_{I_C_RES}(i) = (1 - 10^{-3})^3 * 4.3 * 10^{-4} = 4.287 * 10^{-4}$ for the motor. We can then derive:

$$P_{I_D_TOT_POST} = 1 - (1 - 1.296 * 10^{-4}) * (1 - 2.2 * 10^{-7})^{10} * (1 - 1.4 * 10^{-7})^5 \\ = 1.325 * 10^{-4}$$

$$P_{I_C_TOT_POST} = 1 - (1 - 4.287 * 10^{-4}) * (1 - 1.1 * 10^{-6})^{10} = 4,394 * 10^{-4}$$

This allows us to calculate the effectiveness of ignition source isolation in this example as per equation [15]:

$$E_{ISO} = \frac{1 - (1 - 1.325 * 10^{-4}) * (1 - 4,394 * 10^{-4})}{1 - (1 - 1.33 * 10^{-4}) * (1 - 4,4 * 10^{-4})} = 99.7\%$$

5. Model discussion

5.1. General

Now that the model has been described, we discuss its various features and limitations. Our simple worked example aside, using computer simulation is a practical necessity if using it in more realistic scenarios where hundreds or thousands of ignition sources must be considered. If we know the necessary parameters for all ignition sources in the module and their coordinates, along with the layout and geometry of the module itself, we could run simulations with various leakage rates, leakage sources and weather conditions to establish values for the effectiveness of ignition source isolation.

This chapter examines the assumptions that form the framework for the model and gives some suggestions on how the different parameters needed could be established. As mentioned in the introduction however, our main interest in developing this model was for use in risk analysis. We therefore discuss how it could be simplified so that it could be of practical use in the context of a quantitative risk assessment.

5.2. Model assumptions

Now we examine and discuss the assumptions behind the model, to be able to evaluate its realism and applicability. Some assumptions are explicitly stated, but there are other underlying ones that are requirements for our model to be valid. We will go through these as well and consider how the model would look if they were removed.

In the model we consider electric sparks and hot surfaces as the only two ways by which the gas cloud can be ignited. For the purpose of evaluating ignition source isolation, which ultimately only applies to electric equipment, it was considered sufficient to include these two ignition modes. In reality there are several other possible ignition modes, ranging from the credible (friction sparks) to the more esoteric (adiabatic compression) /1/. The calculated ignition probabilities can therefore not be considered general, but only apply to ignition by electric sparks and hot surfaces. It would however be a simple task to extend the model to include friction sparks or other ignition phenomenon by using the same principle of failure mode evaluation as was extensively used in chapter 4.

Assumption 3 in chapter 4.1. states that gas is uniformly considered to be at its most easily ignited concentration. This is a typical convention in risk analysis, as it is the worst case scenario in terms of ignition probability and therefore yields conservative estimates. A real gas cloud will be more highly concentrated close to the source of the leak and less so on its outer edges, and will also depend on leak rate and turbulence in the module.

Assumption 6 in chapter 4.1. states that continuous ignition occurs instantaneously when the equipment is exposed to gas. A more accurate description of hot-surface ignition would be that there is a certain induction time before ignition occurs, depending on the temperature and geometry of the hot area, and the turbulence in the surrounding area. For extremely high temperatures, the induction time will be so low that instantaneous ignition is a reasonable approximation. It is perhaps more likely though that a hot surface will have a temperature somewhere between the stated autoignition temperature from literature and the temperature required for instantaneous ignition. The results from experiments on autoignition temperatures and induction times vary significantly with experimental setup and lab conditions, and no way has been to analytically relate the different contributing factors /2/. Convection currents work against delayed ignition from hot surfaces, which is why this author thinks instantaneous ignition is a reasonable approximation for the model.

Related to this is the assumption that a continuous ignition source has no residual ignition probability after it is turned off via ignition source isolation. The hot surface might take some time to cool after the equipment is isolated, depending on the hot material, its geometry and area conditions. As stated above, delayed ignition from hot surfaces is judged to be a small risk, especially so if it is cooling. If we wanted to include this effect in the model we could use an exponential decay function to model cooling of continuous ignition sources, halving

their individual ignition probabilities after a certain amount of time. Rather than just looking at V_{NEW} , we could go back a certain number of time steps and include the adjusted ignition probabilities for continuous sources that were exposed to the gas cloud in the past.

The model assumes that only equipment that is being operated can be considered an ignition source. There may however be failure modes that make the equipment capable of sparking or becoming hot even if that is not the case. This is not necessarily a problem for the model, such failure modes must be carefully evaluated along with any others, but their ignition probabilities should be divided by $P_{USE}(i)$ for equation [7] to give accurate results.

An underlying assumption behind the model is that the failures in the Ex protection of an ignition source can be considered independently from failures leading to sparks or hot surfaces. This may be the case for the Ex protection categories that can be thought of as barriers that are separate from the potential ignition sources inside and works by segregating them from the potentially explosive atmosphere outside. Recall from chapter 2 that this is not the case for Ex protection categories e and i. Ex e is protection by conservative design and high safety factors, while Ex i is protection by energy limitation in the design. We can incorporate this in the model by considering $P_{EX_FAIL}(i)$ as a failure probability for the physical barrier between the equipment and an explosive atmosphere, and thereby set $P_{EX_FAIL}(i) = 1$ for equipment protected by either of these two Ex categories. Then any failure modes that could result in ignition can be included in $P_{SPARK}(i)$ and/or $P_{HOT}(i)$ as normal.

Another assumption that is not explicitly stated is that the various failure modes in the equipment can be considered independent. We state that each failure mode for a single ignition source has its own independent probability of occurring and results in its own probability for creating a spark or hot surface. The reality on a physical installation is that there are a high number of interdependencies, and something that causes a fault in one ignition source may also cause a fault in or affect the ignition probability for others. A local power spike for instance could affect all the equipment powered from the same source. As accounting for all such potential interactions would be a huge task, we consider this assumption of independence as an acceptable simplification for modeling purposes.

5.3. Model parameters

We now go through the parameters used in the model, and discuss methods that can be used for establishing them. These parameters are not physical constants that can be measured with instruments, and estimating them depends on engineering judgment and access to maintenance records. The basis for this model is having a lot of data on each individual ignition source in the gas cloud, and doing a thorough study to find all the potential failure modes that could cause it to become ignition-capable. A technique like FMECA (failure mode, effects and criticality analysis) /8/ could be used. For each of these failure modes, $MTBF(j)$, $t_m(j)$ and $S(j)$ must be estimated.

$MTBF(j)$: Available reliability data from databases such as OREDA /9/ could be helpful in estimating this. Otherwise detailed maintenance records from the installation or expert opinion can be used. Note that the age of the equipment will likely influence this variable as well.

$t_m(j)$: Knowledge of the maintenance regime on the installation is necessary. Three main factors will go into it: the probability that the failure mode will be discovered outside of periodic maintenance, how often the equipment is subject to periodic maintenance, and the probability of detecting the failure mode during periodic maintenance. If the failure mode is not considered to be detectable, $t_m(j)$ can be set equal to the expected remaining life of the equipment or remaining life of the installation, whichever is shorter. Personnel with operational experience from the installation will be a good source for much of this information.

$S(j)$: This is perhaps the most difficult to evaluate of the three parameters that define a failure mode. The method by which this failure mode increases the likelihood of an ignition must be examined in detail. In cases where such data is not available, it would be safest to set $S(j) = 1$.

When all parameters for the various failure modes have been established for a particular ignition source, $P_{USE}(i)$ and $E_{ISO}(i)$ for that equipment must be estimated.

$P_{USE}(i)$: This will typically be easily determined from operational records. One must keep in mind though the specific scenario we are evaluating. Take the example of a firewater pump for instance. Going by the percentage of time the equipment has been used in the history of

the installation is not wise in this case, because firewater pumps are typically turned on as soon as gas is detected. Therefore its $P_{USE}(i)$ is likely to be close to 100% for our purposes.

$E_{ISO}(i)$: Determining this will depend on how the ignition source isolation is implemented electrically. It is likely to be a series of electrical components such as circuit breakers or relays that all must work for isolation to take place. Using reliability data for these components, $E_{ISO}(i)$ can be calculated.

Finally we have E_{DET} and E_{ESD} :

E_{DET} : The two main things to consider are the probability of gas detector malfunction, and the probability of the gas cloud reaching at least two gas detectors. Reliability for a single gas detector can be easily found from datasheets, but whether the gas cloud exposes enough detectors is scenario dependent. For a large or medium release it may be safe to assume that enough detectors were exposed, but for smaller releases we would most likely have to perform simulations to properly establish this.

E_{ESD} : There will generally be a large degree of robustness and redundancy built into the design of this system, so probability of failure is most likely not significant. The system will SIL rated, which can be used to put a value to this reliability.

5.4. Using the model in risk analysis

While using a detailed model such as described here might be necessary to assess the reliability of ignition source isolation with a high degree of accuracy, estimating all the required parameters for an entire module of process equipment is an undertaking that is far beyond the scope of a quantitative risk assessment. A model to be used for such a purpose must use a comparable level of detail in order to be of practical value. We therefore examine in this section how the model we have developed can be simplified to provide useful input to risk analysis.

The most obvious way to do this is to move away from calculating all the parameters for each specific ignition source, but rather to find results applicable to broader categories. In our model in chapter 4, we calculate $P_{EX_FAIL}(i)$ for an individual ignition source. If we assume that the different types of Ex protection have similar failure modes with similar attributes according to their Ex type, then we only need to find $P_{EX_FAIL}(i)$ for each of the Ex categories

once. A detailed study could be done into common failure modes for each Ex category, and once this is in place, we have usable estimates for $P_{EX_FAIL}(i)$ for all protected equipment.

Similarly, we could evaluate $P_{SPARK}(i)$ and $P_{HOT}(i)$ by groups according to equipment type rather than for individual ignition sources. For instance, we could analyze the common failure modes that could result in high-voltage electrical motors in general becoming ignition-capable, and use these calculated values for $P_{SPARK}(i)$ and $P_{HOT}(i)$ for all such electrical motors. If categorization is performed in this way, the task at hand becomes a much simpler one. Provided that care is taken not to use overly broad categories, the results should still be reasonably accurate.

6. Data review and analysis

6.1. General

An important part of this project was to attempt to obtain quantitative data that could be used to establish parameters in our model. In this chapter we present the results of this data search. Four main data sources were considered:

1. Literature on technical safety and explosion protection.
2. Manufacturers of Ex equipment. It was considered that these companies could be good sources for failure data on Ex barriers as well as on specific equipment used in the industry.
3. Technical safety consultants. These were thought to have knowledge of any previous studies and existing data dossiers that could be used.
4. Oil and gas operators. These companies should have maintenance records from their installations that could be used to analyze failures in Ex equipment.

Most of what was found would fall into the category of qualitative statements, which cannot be used directly for setting parameters. Examples include:

- A manufacturer of Ex lighting says that they do not receive much failure data from their customers on their products, but that a typical failure mode for their Ex d and Ex e light fixtures is water ingress into the equipment. They further state that the most likely cause of this is poor or inadequate maintenance procedures.
- A chairman for a technical committee for standardization of Ex equipment says that he is unaware of any quantitative data related to ignition from Ex protected equipment.

However he states that the greatest risks are associated with equipment that is not installed or operated in accordance with manufacturer specifications or not maintained properly.

- Another member of this committee who works with inspection of Ex equipment states that the most common failures they find for Ex e equipment is improper termination and damage from moisture.

While information of this type is useful for developing an understanding of what failures can occur and what the main risk factors are, we want to focus on quantitative data that can be applied on our model. The only data of this nature that was found was from two sources. The first was found during a literature study, and is applicable to the failure probabilities of different Ex types. The second is a large data set from a maintenance project on an oil and gas development in the Norwegian sector. In this chapter we first review and discuss the applications of the data from first source, then do the same for the data set from the maintenance project.

6.2. Benjaminsen and van Wiechen data

[2] is a reference book on electrical instruments in hazardous location. In a chapter outlining possible quantitative approaches to safety, work by Benjaminsen and van Wiechen is referenced. They published a series of papers between 1967 and 1969 attacking safety problems using probability theory. One of their goals was to be able to do a quantitative comparison of different protective techniques commonly used. While this author has been unable to find their original papers, some of the results are presented in [2]. They quantified the MTBF for electrical equipment by protection type, and specified MTBF as a mean time between failures that make the equipment ignition-capable rather than failures that cause loss of function. The relevant values they used are reproduced here:

Table 3: MTBF for failures in Ex protection per Benjaminsen and van Wiechen

Protection type	MTBF (hours)
Flameproof (Ex d) with flanged joints, windows or direct entry of cables	10^6
Flameproof (Ex d) with threaded joints or indirect cable entry	10^7
Flameproof (Ex d) with housings of very small volume which are not repairable	10^8
Nonincendive (Ex n)	10^4
Pressurized (Ex p)	10^6

Increased safety (Ex e)	10 ⁷
-------------------------	-----------------

They also suggested some values for t_m for nonsparking apparatus:

$t_m = 1000$ hours for failures that are difficult to detect, such as loose rotor bars in squirrel cage motors, loose connections, broken outer bulb of high pressure mercury lamp.

$t_m = 0.1$ hour for failures that will be removed by overload protection

$t_m = 0.01$ hour for failures that will be removed by short circuit or earth fault protection

6.3. Benjaminsen and van Wiechen data analysis

The MTBF values used by Benjaminsen and van Wiechen apply directly to the probability of a failure occurring that causes the Ex protection to be ineffective. The exact failure modes are not specified, but we do not need that in order to use the data. We must then assume that this MTBF value for a particular Ex type represents all possible failure modes that cause loss of protection. In terms of our model, we get for an ignition source i :

$$P_{EX_FAIL}(i) = P_{ACTIVE}(j) = \frac{t_m(j)}{MTBF(j) + t_m(j)} \quad [16]$$

Let us use the example of an Ex d protected ignition source that has flanged joints and direct cable entry, and that its failure is non-obvious. Using their suggested values of $MTBF(j) = 10^6$ hours and $t_m(j) = 10^3$ hours, we get: $P_{EX_FAIL}(i) = \frac{10^3}{10^6+10^3} = 9.9 * 10^{-4}$.

Whether using common failure probabilities for all equipment protected by the same type of Ex barrier is a good idea is a separate discussion from whether Benjaminsen and van Wiechens proposed MTBF and t_m values should be accepted. Leaving the former aside, we consider the validity of their proposed values.

The main questions are around how these values were derived. As we do not have their research available, we are not in a position to review their methodology directly. However their research is over 40 years old at this time, and it seems likely that reliability in safety technology has progressed since then. Assuming their MTBF values were reasonably accurate average values at the time, this makes them conservative today, which is usually regarded as beneficial in risk analysis.

Typical values for t_m are not likely to have changed in the same way, and their proposed t_m of 1000 hours for non-obvious failures seems low. Assuming the Ex failure does not impair the functioning of the equipment, the fault may not be discovered at all or only when the equipment is opened up and inspected internally. This could be performed as rarely as every other year. Therefore it seems prudent to use knowledge of the specific maintenance regime to establish t_m values to be used across the whole installation.

6.4. Data from oil and gas development in the Norwegian sector

While most operators in the Norwegian sector either had no suitable data for this project or declined to contribute any, one of the larger operators shared data from a project they ran on one of their installations that was aimed at discovering failures that could cause Ex protection to be ineffective.

This was a project that ran from four years from July 2005 and covered several platforms on the same oil and gas field. It was a series of planned maintenance operations that specifically targeted Ex equipment and evaluated whether the Ex protection was effective. In order for maintenance personnel to be able to make these judgments consistently, a technical document was prepared that listed inspection criteria for each of the Ex types. The inspection was largely visual in nature.

Across the platforms on this oil and gas development, there were about 25000 tags or single pieces of equipment that were Ex protected and subject to inspection as part of this project, and throughout its lifetime 53911 individual inspections were recorded. This means that some equipment was inspected more than once. Equipment either passed or failed inspection, partial or impaired protection was not considered.

Attached to this report is both the raw data from the inspections extracted from SAP and the technical document containing inspection criteria, appendices A.2 and A.3. Ignoring the categories that have 10 tests or less, we have:

Table 4: Tests and faults in data from maintenance project

Equipment type	Number of tests	Faults found	Fault percentage
Lighting	10743	115	1,07 %
Junction boxes	10449	70	0,67 %
Unspecified	9840	41	0,42 %
Heating	5866	75	1,28 %
Fire and gas	2975	17	0,57 %
Instruments	2207	26	1,18 %

Low voltage motors	1947	38	1,95 %
Loudspeakers	1898	3	0,16 %
Emergency stops	1781	29	1,63 %
Electrical sockets	1472	9	0,61 %
Switches	1160	12	1,03 %
Field telephone	807	26	3,22 %
Motor starter	631	17	2,69 %
Valves	430	2	0,47 %
Actuators	329	0	0,00 %
Misc. Electric	268	4	1,49 %
Control panels	230	0	0,00 %
CCTV	178	2	1,12 %
Manual switch	166	0	0,00 %
High voltage motors	139	1	0,72 %
Distribution board	114	5	4,39 %
Control system	93	1	1,08 %
Measurement station	78	1	1,28 %
Pedestal crane	29	0	0,00 %
Fog horn	16	1	6,25 %
Sum total	53846	495	0,92 %

6.5. Analysis of data from oil and gas development

First let us review what is known and unknown about the data set from this project:

Table 5: Known and unknown information about data set from maintenance project

Known	Unknown
<ul style="list-style-type: none"> • The total number of individual tags / equipment pieces that were subject to inspection (25000) • How many inspections were made on each equipment group and how many of each group passed or failed inspection • For some of the failures, there is a brief description of the nature of the failure. • The criteria the equipment was 	<ul style="list-style-type: none"> • The distribution of the equipment into equipment groups. That is, how many junction boxes, low-voltage motors etc. were there. • The Ex type of inspected equipment • The type or severity of most of the faults that were discovered

measured up against (see attachment)	
<ul style="list-style-type: none"> • How long the program ran (4 years) 	

Recall from chapter 4 that $P_{EX_FAIL}(i)$ can be considered to express the probability that the Ex barrier will be ineffective when tested for a given ignition source. Thus if a sufficiently large number of tests of the Ex barrier was performed, it stands to reason that the ratio of the number of failures to the number of tests would approximate $P_{EX_FAIL}(i)$. The data we have here is in the form of tests and failures, so is at first glance suitable for use in this way. The first question that needs to be answered is then: what is a sufficiently large number of tests?

This question is statistical in nature. Ideally we would want to categorize the equipment by Ex type, as the failure probability should be related to the type of Ex protection. This is unknown however, so we must rather categorize by equipment type and assume that all equipment of the same type has a similar probability of Ex protection failure. If we want to use basic statistical theory from /3/ to analyze the data, we must make a couple of assumptions:

- Failures are independent, random events.
- All inspections of an equipment type can be considered instances of the same event, that is, all junction boxes for instance are inspected the same way.

Then we can present the data from table 4, removing the entries that had no experienced failures and ones of unspecified type and including the margin of error (ME). We also include an estimate of $P_{EX_FAIL}(i)$ assuming that a reported failure means that the Ex protection is completely ineffective:

Table 6: Confidence interval and computed $P_{EX_FAIL}(i)$ for maintenance project

Equipment type	# of tests	# of failures	Fault %	95% conf. ME (+-)	$P_{EX_FAIL}(i)$
Lighting	10743	115	1,07 %	0,20 %	1,27 %
Junction boxes	10449	70	0,67 %	0,16 %	0,83 %
Heating	5866	75	1,28 %	0,29 %	1,57 %
Fire and gas	2975	17	0,57 %	0,28 %	0,85 %
Instruments	2207	26	1,18 %	0,46 %	1,64 %
Low voltage motors	1947	38	1,95 %	0,63 %	2,58 %
Loudspeakers	1898	3	0,16 %	0,18 %	0,34 %
Emergency stops	1781	29	1,63 %	0,60 %	2,23 %
Electrical sockets	1472	9	0,61 %	0,41 %	1,02 %
Switches	1160	12	1,03 %	0,59 %	1,63 %
Field telephone	807	26	3,22 %	1,24 %	4,46 %

Motor starter	631	17	2,69 %	1,29 %	3,98 %
Valves	430	2	0,47 %	0,66 %	1,12 %
Misc. Electric	268	4	1,49 %	1,48 %	2,97 %
CCTV	178	2	1,12 %	1,58 %	2,70 %
High voltage motors	139	1	0,72 %	1,43 %	2,15 %
Distribution board	114	5	4,39 %	3,84 %	8,22 %
Control system	93	1	1,08 %	2,14 %	3,21 %
Measurement station	78	1	1,28 %	2,55 %	3,83 %
Fog horn	16	1	6,25 %	12,10 %	18,35 %

This table should be read as follows: For lighting for instance, this implies that we can be 95% certain that the actual fault percentage is within the interval 1.07 ± 0.20 %. The last column is a conservative estimate for $P_{EX_FAIL}(i)$ for that equipment type taken by adding the experienced fault percentage to the margin of error – we can be 95% confident that $P_{EX_FAIL}(i)$ is this value or lower. The above estimates of $P_{EX_FAIL}(i)$ illustrate the difficulty of using statistical methods to make inferences with a high degree of accuracy on smaller data sets. It is clear that the high margins of error relative to the experienced failure probabilities limit the usefulness of some of these estimates.

Another important question about this data set is what a reported failure constitutes exactly. Clearly it failed inspection, but we have to review the failure data or inspection criteria to be able to determine whether this necessarily represents a completely ineffective Ex barrier or just an increased risk that it will fail. A cursory review of the failures where the nature of the failure was detailed reveals the following examples:

- Three low-voltage motors failed due to water entry into the housing, two others failed due to large amounts of rust found on the motor.
- Two junction boxes failed due to missing the screw and bracket for the lid.
- Several magnetic instrument valves failed due to being rusted shut and impossible to open.
- Two field telephones failed because their loudspeakers did not work.

These examples show that the failures reported in this data set do not necessarily mean missing or significantly impaired Ex protection. It seems that in many cases an item failed inspection if its Ex protection required maintenance. Using a $P_{EX_FAIL}(i)$ calculated on the basis that an inspection failure means ineffective Ex protection, as was done above, is not likely to give realistic ignition probabilities for this installation. It should also be noted that

equipment classified as Ex i was not subject to inspection as part of this project as per appendix A.3. This explains the relatively low number of instruments inspected across the installations, as most of these are likely classified as intrinsically safe.

7. Discussion and conclusion

7.1. General

This chapter aims to tie together the discussion from previous chapters, and contrasts the results from the different data sources. Finally some concluding remarks are presented along with suggestions for further work.

7.2. Discussion

The model developed in chapter 4 has a level of detail and requires a level of effort when calculating parameters that it is not practical to use every time one wants to estimate the effectiveness of ignition source isolation in a module on an oil and gas installation. That is not its intended use. Rather what could be done is to use the described method of failure mode analysis to find representative values of $P_{EX_FAIL}(i)$ for the protection techniques used in the industry. The same method can be used to compute $P_{HOT}(i)$ and $P_{SPARK}(i)$ for a range of typical equipment types found in process areas.

If we have a database populated with typical values such as this, estimating the effectiveness of ignition source isolation becomes a much easier process from case to case. Granted, simulation will still be required in a module with thousands of individual equipment pieces, but one would not have to go through the exercise of estimating every single parameter.

There are some risks associated with foregoing individual analysis, but if the database is large enough one should be able to find equipment there that is equivalent or close enough in terms of ignition probability. Some of the data required for the model cannot be sourced from a database though, we still need the following:

- An overview of the different ESD levels and shutdown logic for the installation in question, so that we know which equipment is affected by ignition source isolation.
- Material detailing how ignition source isolation is physically carried out. This is most likely done in a similar way for all ignition sources, so we can set $E_{ISO}(i) = E_{ISO}$ across the installation.

The second major part of this project was to search for data that could be used to populate such a database of ignition probabilities as was described above. Unfortunately this effort was only partially successful, but we go through the data it to highlight its potential use.

The data cited by Benjaminsen and van Wiechen does apply directly to $P_{EX_FAIL}(i)$. The values they use seem reasonable, but without seeing how it was derived we would hesitate to recommend using it except as comparison data to check computed values of $P_{EX_FAIL}(i)$.

The data from the oil and gas development is interesting, but the fact that it is not organized according to Ex type makes it difficult to apply to general use. One way to relate it to Ex types would be to make a series of assumptions about the Ex type of each of the equipment categories, such as assuming for instance that all junction boxes are of type Ex d. We would hesitate to recommend this approach, as it is bound to dilute the information value of the material. Another way to use it would be to organize our database of $P_{EX_FAIL}(i)$ values by equipment type rather by Ex type. In that case the data would fit right in, but as the values of $P_{EX_FAIL}(i)$ are likely to depend far more on the Ex type than on the equipment it is used on this cannot be recommended.

Another aspect of this material is that the reported failure rates are quite high compared to the assumptions of Benjaminsen and van Wiechen. A possible explanation for this is that the MTBF values used by Benjaminsen and van Wiechen are supposed to represent mean time between loss of safety function, while the failures reported in the maintenance project do not necessarily represent loss of function for the Ex barrier.

No data was found to support any quantification of $P_{HOT}(i)$ and $P_{SPARK}(i)$ for common equipment types. We do not think there is any easy way to get data such as this, there is probably no way around having to performing the analysis work and going through the failure modes of the equipment.

7.3. Conclusion and further work

The three objectives stated when the original problem statement was written were unfortunately not achieved. The first part, developing the model, was performed successfully. However due to the limited availability of data, it was not possible to set up a database of weighting factors as was envisioned without doing a lot of guesswork. And again, not having enough material for this database precluded performing the last part in the problem statement; doing a practical test of the model applied to an actual module on an oil and gas installation.

We had intended to use the same module from the Skarv FPSO that was subject to analysis in the Fall 2009 project, as this was the only dataset available. Still the project should not be considered a failure. Important groundwork was done in establishing a model that can be used to calculate the effectiveness of ignition source isolation, and further work can be done based on this foundation.

The obvious way to go forward is to populate the database described in the previous section. By organizing a broad-participation industry project and getting experts familiar with design of Ex equipment involved as well as personnel with experience from maintenance, one should be able to perform credible analysis of the failure modes leading to ignition for the most common types of process equipment.

Another way to populate the database would be to design a maintenance project similar to the 2005-2009 project detailed in this report. If the maintenance personnel were specifically trained in what to look for and suitable equipment tests devised, we could get failure data keyed to both Ex types and equipment categories. For a statistically significant number of tests to be performed the project would most likely have to run for a long time and across several installations.

Appendix A (on CD)

- A.1. Programs.txt, programs and version numbers used in project
- A.2. Excel spreadsheet: "Oseberg sss23 530"
- A.3. Word document: "Ex-utstyr, tennkildekontroll"
- A.4. Word document "Project report", this report
- A.5. PDF document, this report in PDF format

Bibliography

- /1/ Eckhoff, R. K. (1996):Elektrisk utstyr for eksplosjonsfarlige områder (in Norwegian). Tapir, Norway
- /2/ Magison, E. (1998):Electrical instruments in hazardous locations. ISA, NC.
- /3/ Freedman et al (2007): Statistics, 4th edition. W.W. Norton & Co, New York.
- /4/ Scandpower Risk Management (2006): Ignition modeling in risk analysis. Written for OLF, not published.
- /5/ Scandpower Risk Management (1997): Modeling of ignition sources and quantification of ignition probabilities. Written as part of JIP-97, not published
- /6/ Bartec, ATEX flyer.
<http://ie.jrc.ec.europa.eu/fctestnet/Workshop%20Fuel%20cell%20testing%20aspects/VITO%20JRC-IE%2029nov05%20Bartec%20ATEX%20flyer.pdf> (10. April 2010)
- /7/ Kvalø, Tarjei (2009): Reliability of ignition sources. Project work, not published.
- /8/ US Department of Defense (1949): Procedures for Performing a Failure Mode, Effects and Criticality Analysis. MIL-P-1629.
- /9/ SINTEF (2009): OREDA 2009 handbook. DNV, Høvik,