Document No.	GP 78-09
Applicability	Group
Date	9 July 2008

GP 78-09

Subsea Safety Instrumented Systems (incl. HIPPS)

Group Practice

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Foreword

This Engineering Technical Practice (ETP) BP Group Practice GP 78–09 is for subsea safety instrumented systems.

Subsea safety instrumented systems (subsea SIS) are a specialised area of subsea equipment which may be used within a subsea production system where economic or environmental conditions rule out the normal situation of a fully rated production system.

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1. Introduction

1.1. Definition of subsea SIS

a. This GP should apply to all subsea production systems (from the wellhead to the Emergency Shutdown Valve (ESDV) at the top of the riser) where one or more parameters of the production environment, normally pressure, cannot be accommodated by the passive design of one or more parts of the system.

b. An active protection system therefore becomes a necessary part of the design.

c. To operate such a system safely, a **risk reduction system** is introduced whereby the critical parameter is monitored so that when it exceeds the allowable level, **autonomous action** is taken to make the system safe.

d. The three principle elements of an SIS are referred to as **sensors, logic solver and final elements**.

2. Scope

a. SIS operate outside the normal subsea system design codes (e.g. API 6A, 17D) and so their design is a specialist activity which encompasses safety engineering, risk based design, reliability engineering and full life-cycle integrity assurance.

b. BP project engineers tasked with incorporating these systems into a subsea project are unlikely to be familiar with this specialised approach to design.

c. This GP therefore provides a detailed introduction to the design of SIS, as it applies to subsea projects. This includes guidance on specialist resources available within BP and externally that are likely to be needed.

d. This GP addresses the design process and key issues to be considered when implementing subsea SIS in subsea production systems.

e. It is intended primarily for design engineers, project engineers and engineering managers with a background in subsea engineering, but with less familiarity of SIS, who are involved in subsea SIS projects.

For example:

- BP facilities engineers undertaking basic design and risk assessment of subsea elements
- Supplier engineers designing Subsea SIS for supply to BP
- Operations engineers responsible for installed subsea SIS facilities

2.1. GP Overview

a. The key parameter in most SIS design applications in addition to functional performance is risk reduction. All SIS require a quantified level of risk reduction to be defined and an associated Safety Integrity Level or SIL rating to be specified and maintained throughout their operational life.

(SIS also require Environmental and Commercial Integrity Levels)

b. The design process should therefore address the full safety life cycle to provide assurance that the required safety integrity is achieved and maintained.

c. Section 4 provides high level general requirements for subsea SIS.

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d. SIS design is an activity undertaken by experienced specialist SIS engineers with a working knowledge of IEC 61511. The GPs identified within Figure 1 are primarily for such engineers use, but Section 5 of this document provides non safety engineers with an understanding of the basic design process and the key requirements that should be met.

e. Section 5 also provides details of the engineering resources which projects can access within BP and externally. The section also provides an awareness of the overall safety and environmental protection legislative framework which may apply in different parts of the world.

f. Section 6 of this GP provides guidance on how the key design decisions and progress deliverables for subsea SIS within a subsea project may be fitted within BP's Major Projects Common Process (MPcp).

g. Sections 7, 8, 9 & 10 address particular issues that are unique to subsea SIS. The issues are arranged in terms of system design (section 7), component design (section 8), testing of subsea SIS (section 9) and operation of installed subsea SIS (section 10).

h. These sections, 6 to 9, identify technical issues that should be addressed and resolved during the subsea SIS design and how different design solutions should be modelled within the risk based design assessment. These sections also include details of current BP and industry best practice and lessons learnt from recent subsea SIS projects.

2.2. Examples of common applications of subsea SIS

a. To date the most common application of a subsea SIS is a subsea high integrity pressure protection system (HIPPS). This is a safety barrier in the form of sensors, logic solver and valves (final elements) which autonomously detect higher than expected pressure and shut in the pressure by closing valves upstream of the non-fully rated pipeline.

b. Other potential Subsea SIS could be:

1. Subsea pump over-pressure protection. The system monitors pressure downstream of a pump and shuts off the pump if pressure rises beyond the safe limit (e.g. due to a downstream blockage).

2. Active cooling spool. The system monitors downstream temperature and shuts in the flow if temperature exceeds the safe limit for the downstream pipework.

c. It should be emphasised that the application of SIS to subsea production systems is a relatively recent development within the subsea industry.

BP have been leaders in the field and have installed subsea HIPPS on Juno and Rhum.

d. A list of installed systems worldwide with the relevant operator is shown in table 1:

Table 1 – Previously Installed HIPPS (as of Nov 2007)

Project	Operator	Installation	Pressure (psi)	Temperature (°F)	Valve I.D. (inch)	SIL Rating	Water Depth (ft)
Kingfisher	Shell	1997	10,000	248	5 ⅛	3	395
Gullfaks	Statoil	2000	10,000	300	7	-	445
Penguin	Shell	2002	8,265	239	5 ⅛	2	460
Juno	BP	2002	5,000	140	7	2	130
Rhum	BP	2005	11,310	300	9	2/3	430
Kristin	Statoil	2005	10,730	347	9	3	1150

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In addition BP is currently, considering subsea HIPPS for Tubular Bells in GOM, Shah Deniz in Azerbaijan and deepwater projects in Egypt.

3. Terms, Definitions and Abbreviations

The following list covers only the most common terms used in this GP. For complete terms, definitions and abbreviations relevant to SIS refer to GP 48-03 or GP 30-75,to be found in the BP ETP Library.

Diagnostic coverage

The ratio of the detected failure rate to the total failure rate of the component or subsystem as detected by diagnostic tests.

Diagnostic coverage does not include any faults detected by proof tests.

Final element

A part of a safety instrumented system which implements the physical action necessary to achieve a safe state.

Functional safety

Ability of SIS, or other means of risk reduction, to perform the actions necessary to achieve or maintain tolerable risk for the process and its associated equipment.

Functional safety applies to all systems and the reduction of all asset risks, including safety, environment, and commercial.

Functional safety assessment

Investigation, based on evidence, to judge the functional safety achieved by one or more protection layers.

Inherently safe design

A facility design that achieves tolerable risk without the need for safety instrumented functions or other hazard prevention or mitigation measures

Logic function

A function which performs the transformations between input information (provided by one or more input functions) and output information (used by one or more output functions).

Logic solver

That portion of the SIS that performs one or more logic functions

Layer of Protection Analysis (LOPA)

A method for undertaking risk based analysis of a system.

Markov model

A computational model based on the Markov chain, or a sequence of random variables in which the distribution of each random variable depends only on its present state and not on how it arrived at its present state. Used frequently in fault tree analysis.

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Probability of Failure on Demand (PFD)

Value that indicates the probability of a system or sub-system failing to respond to a demand.

Proof test

Test performed to reveal undetected faults in an SIS so that, if necessary, the system can be restored to its designed functionality.

Safety

Freedom from unacceptable risk.

Safety Instrumented Function (SIF)

Safety function with a specified safety integrity level, which is necessary to achieve functional safety.

Safety instrumented system (SIS)

Instrumented system used to implement one or more safety instrumented functions. An SIS is composed of any combination of sensors, logic solvers, and final elements.

Safety integrity (SI)

Average probability of a safety instrumented system satisfactorily performing the required safety instrumented functions under all the stated conditions within a stated period of time.

Safety integrity level (SIL)

Discrete level for specifying the safety integrity requirements of the safety instrumented functions to be allocated to the SIS as defined in IEC 61511 & 61508.

Safety integrity level 4 has the highest level of safety integrity; safety integrity level 0 has the lowest.

Safety lifecycle

Necessary activities involved in the implementation of safety instrumented functions occurring during the period of time that starts at the concept phase of a project and ends when all the safety instrumented functions are no longer required for use.

Safety requirements specification

Specification that contains all the requirements for the safety instrumented functions that have to be performed by the SIS in sufficient detail to design the safety instrumented system (SIS).

The term “Full requirements specification” is also used as an alternative to safety requirements specification where contrast is made with the process requirements specification that is a subset of the safety requirements specification.

Sensor

A device or combination of devices which measure the process condition (for example transmitters and transducers)

Validation

Activity of demonstrating that the safety instrumented functions and SIS under consideration after installation meet in all respects the SIS process requirements specification.

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Verification

Activity of demonstrating for each phase of the relevant safety lifecycle by analysis and/or tests, that, for specific inputs, the outputs meet in all respects the objectives and requirements set for the specific phase.

1oo3

Abbreviation for "one out of three". Usually used in connection with logic solver response to input signals, for example, solver will react if 1oo3 sensors read high pressure.

4. General Requirements

4.1. System integrity

a. The system should be of sufficient integrity in terms of the probability of failure, fault tolerance, quality of equipment and implementation and safety management to reduce what would be an unacceptable risk to a tolerable risk.

4.2. Inherently safe design

a. Prior to the design of SIS for all subsea production systems the practicality of inherently safe designs [ref. GP 24-03] should be considered.

b. This implies that all systems should start with a fully rated design which can accommodate all production environment parameters.

c. It is only if this proves to be impractical in terms of technical feasibility or disproportionate cost, that a subsea SIS may be considered.

d. The design process should document the technical and cost reasons why a fully rated system is not feasible or practical.

Thus a subsea SIS is never a preferred solution but one that is arrived at because other options are impractical.

e. If a fully rated system is selected, this GP is not applicable to the design.

f. Where subsea processing systems are applied in brown field applications, an SIS may be required to protect legacy equipment.

4.3. Applicable standards

a. The overriding requirements during the design of SIS are included in the IEC 61508 and 61511.

b. IEC 61511 has been developed primarily for the process industry and will be the reference standard that should be applied to the subsea SIS design.

c. IEC 61508 is the reference standard that applies to the equipment that should be used to implement the subsea SIS.

d. The basic reference standard within BP is IEC 61511, but BP has preferences in how to apply the standard and some additional requirements apply.

e. The preferences and additional requirements are published in the following BP documents:

GP 30–75 Guidance on Practice for SIS (SIS) – Management of the Safety Lifecycle.

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GP 30-76	Guidance on Practice for SIS (SIS) – Development of Process Requirements Specification
GP 30–80	Guidance on Practice for SIS (SIS) – Implementation of the Process Requirements Specification.
GIS 30–801	Guidance on Industry Standard for SIS (SIS) – Design and Engineering of Logic Solvers.
GP 30–81	Guidance on Practice for SIS (SIS) – Operations and Maintenance.
GP 48-03	Guidance on Practice for Layer of Protection Analysis (LOPA)

f. These GPs are directly applicable to subsea SIS design and should be applied to ensure conformity with both BP and IEC 61511 requirements.

g. The relationship between the standards above are shown in Figure 1 below .

The reasons for including preferences and additional requirements are as follows:

- *Not all methods of SIL determination published in IEC 61511-3 are able to provide the necessary assurance that risks have been reduced in line with BP criteria*
- *IEC 61511 does not include any requirements for asset, environment and reputation protection*
- *IEC 61511 does not include any requirements to reduce spurious trip rates by robust system design*
- *IEC 61511 does not consider operability or maintainability and does not include any requirements for minimising cost of operation and maintenance*

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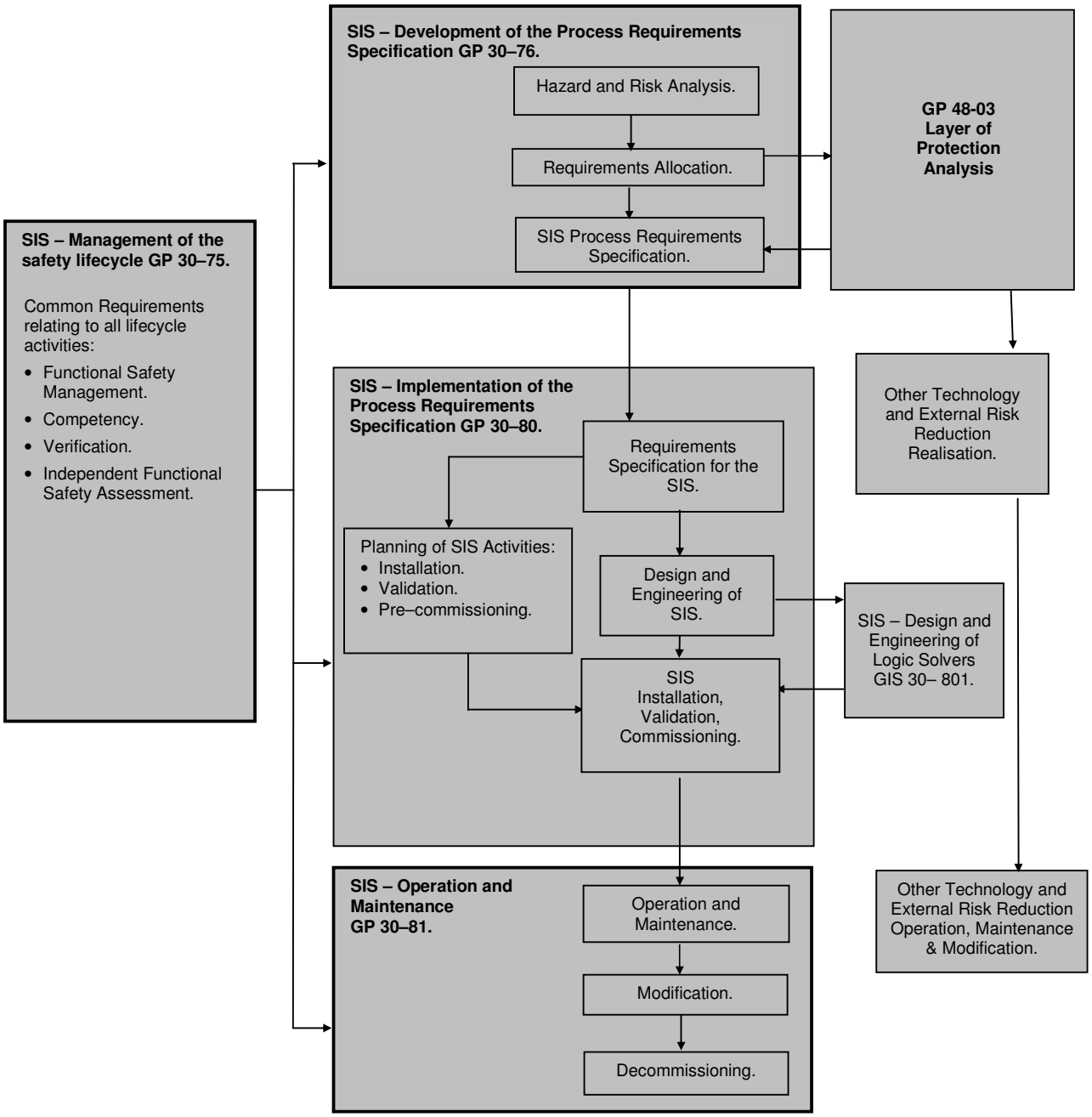

Figure 1 – Relationship between SIS ETPs quoted in 4.3 above

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5. Risk Based Design

5.1. Introduction

a. For developments that include a SIS to manage risk of safety, environmental or reputation and/or commercial loss, the risk based approach to design should be adopted.

This is for the following reasons:

- *For BP management to have confidence that corporate objectives will be achieved*
- *Many regulatory authorities demand consideration of the safety and environmental risks involved and may wish to examine documentation that demonstrates that tolerable risk has been achieved*
- *If the technology and equipment used is new or not well proven in the novel applications under consideration, the potential benefits need to be compared to the risks*

5.2. Comparison with prescriptive methods

a. The risk based approach should not be a replacement for compliance with good practice.

b. Good equipment that is well designed for the application should never be replaced by equipment on the basis of good reliability figures alone.

Not all risks can be evaluated on a numerical basis.

c. A fully rated system designed to recognised standards and codes will imply a level of tolerable risk usually arrived at through many years of industry experience.

d. Risk based standards e.g. IEC 61511 and IEC 61508 require an analysis of initial risk and then a comparison with tolerable risk.

The requirement for risk reduction to meet the tolerable risk leads to the introduction of the concept of a number of safety integrity levels.

e. Equipment required for a system that needs to meet a specific integrity level should then meet other prescriptive requirements.

f. Good design incorporates prescriptive requirements that recognises good practice, but includes the evaluation of the design using risk based techniques to demonstrate that tolerable risk targets have been achieved.

5.3. Tolerable risk

BP's goal is to drive continuous risk reduction throughout the entire range of accident risk with the ultimate goal of no accidents, no harm to people and no damage to the environment.

a. The concept of continuous risk reduction recognizes that the resources available to reduce risk are not infinite, but that we should actively seek measures to reduce risk and prioritise these measures in relation to their risk reduction effectiveness.

b. Risks to be considered should be safety, environmental damage and commercial loss

Risk targets for specified consequence severity levels are detailed in GP 48-03 on LOPA and implied in the calibration of risk graphs in GP 30-76

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5.4. Risk reduction

a. All facilities should be designed such that hazardous events do not occur during normal operation.

Hazardous events only occur in the event of a failure. The failure could be in equipment, procedures or human action.

The concept of "fail safe" was applied in the past to exclude further consideration of the failures in control and protection equipment. It is now accepted that all equipment can fail unsafe and the concept of "fail safe" is no longer sufficient justification as a design basis, if a failure can result in loss of safety, environmental damage or significant commercial loss.

Safe failures in subsea applications that adversely affect production are less tolerable than for topsides or onshore facilities where access to repair faulty equipment is readily available and at low cost.

b. Before evaluating the need for risk reduction the initial risk should be established by considering what failures can occur that would lead to hazardous events.

Suitable techniques that can be used for this include PHA and HAZOP (see GP 48-02 for Guidance on Practice for Hazard and Operability).

c. Having established hazards and potential hazard causes, it should be determined whether the hazard can be eliminated or potential causes reduced in frequency.

d. The use of fully rated facilities should be the first choice.

e. The need for risk reduction may then be determined by comparing initial risk (i.e. the risk without taking credit for SIS) with tolerable risk.

f. The risk reduction required may then be allocated to one or more SIS or other technology solutions.

g. The integrity level required from a SIS will depend on the risk reduction allocated to it. Table 2 shows the relationship between the risk reduction factor allocated to a SIS and the required safety integrity level.

Table 2 - Safety integrity level for low demand applications

Safety integrity level (SIL)	Probability of failure on demand average range (PFD avg)	Risk reduction factor (RRF) (RRF = 1/PFD)
4	$\geq 10^{-5}$ to $<10^{-4}$	>10,000 to ≤ 100,000
3	$\geq 10^{-4}$ to $<10^{-3}$	>1000 to ≤10,000
2	$\geq 10^{-3}$ to $<10^{-2}$	>100 to ≤ 1 000
1	$\geq 10^{-2}$ to $<10^{-1}$	>10 to ≤100
0	$\geq 10^{-1}$ to <1	>1 to ≤10

The above Table 2 applies to SIS operating in low demand mode i.e. where the demand rate for the safety instrumented system to take action is no more than once per year. In the majority of cases for a subsea SIS, the production control system would limit the demand on the subsea SIS to less than once per year.

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h. It should be noted that the relationship between PFD average and risk reduction factor in the above table is only valid if there are no common cause effects between protection layers and between protection layers and cause of demand.

i. However, in cases where the demand rate is high (more than once per year) or where the requirement is for continuous control for safety then Table 3 below shows the relationship between safety integrity level requirements and the tolerable frequency of failure of the safety function.

Table 3 – Safety integrity level for high demand and continuous applications

CONTINUOUS MODE OF OPERATION	
Safety Integrity Level (SIL)	**Target Frequency of Dangerous Failures to perform the safety instrumented function (per hour)**
4	$\geq 10^{-9}$ to $<10^{-8}$
3	$\geq 10^{-8}$ to $<10^{-7}$
2	$\geq 10^{-7}$ to $<10^{-6}$
1	$\geq 10^{-6}$ to $<10^{-5}$

5.5. Analysis approach

a. There are a number of methods in common use for establishing the required safety integrity level of a safety instrumented system.

Methods in common use are documented in IEC 61511-3.

b. BP has selected the Layer of Protection Analysis (LOPA) as the recommended technique for subsea SIS where:-

1. The potential loss of life is > 3, or
2. the required SIL proves to be > 2, or
3. the function is operating in high demand mode

c. A full QRA should also be undertaken to more fully understand and account for all relevant factors (ref GP 48-03, sect 5.1 (d) para. 3.)

d. A typical format for the LOPA table is shown below (from table B2 of GP 48-03).

Figure 2 – LOPA format (typical)

Likelihood values are events per year; other numerical values are probabilities of failure on demand average.													
Ref	1	2	3	4		5		6	7	8	9	10	11
					Protection layers (PLs)								
	Impact Event Description	Severity Level	Initiating Cause	Initiation Likelihood	General Process Design	BPCS	Alarms, Etc.	Additional Mitigation, Restricted Access	Additional Mitigation Dikes (Bunds), Pressure Relief	Intermedi-ate Event Likelihood	SIF PFD	Mitigated Event Likelihood	Notes

To use the LOPA approach each hazard identified is considered in turn.

The first 4 columns describe the hazard and one or more initiating causes:

Column 1: Impact Event or consequence description

Column 2: Severity level from the BP risk matrix in GP 48-03 (consequence)

Column 3: Initiating causes are listed

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Column 4: Expected frequency of occurrence for each cause

Existing (i.e. non-SIS) risk reduction measures are considered and the probability of failure of each are entered in columns 5, 6 and 7. This could include the benefit of the pipeline or riser not failing catastrophically if a "no burst" design has been adopted (see section 7.3). In the case of a low demand application, if the production control system is a cause of demand then no credit may be claimed in the BPCS (Basic Process Control System) column, see section 7.9. Credit may only be claimed for protection layers that are independent from other protection layers where credit has already been taken, and from the initiating cause event.

Note: For subsea SIS, the Basic Process Control System (BPCS) will be the Production Control System (PCS)

By multiplying the values in columns 4, 5, 6 and 7 the intermediate frequency (without any additional SIS risk reduction) associated with this cause is determined. Adding the intermediate event frequencies for each cause of the hazard will determine the likely frequency of the harmful event associated with the hazard.

Associated tolerable frequencies (for the consequence level) are entered in column 10 – see GP 48-03.

The ratio between the intermediate frequency and the tolerable frequency, where the intermediate frequency is higher than the tolerable frequency, is a measure of the required risk reduction. *From it the required probability of failure on demand and safety integrity level for the safety function allocated to the safety instrumented system is therefore determined. If the intermediate frequency is lower than the tolerable frequency then no further risk reduction is required.*

Starting with the safety consequences of the first hazard this approach is then repeated (on the same or separate LOPA sheets) to address environmental and commercial consequences. The most onerous requirement between safety, environmental and commercial becomes the required integrity specification for the safety instrumented function. This process is repeated for the second and subsequent hazards.

The final overview table is effective for risk management since it shows the relationship between hazards, causes and protection layers. A significant benefit is that it is possible to establish the main contributions to the risk. If a specific cause contributes the most to the initial risk then consideration should be given to providing several diverse means of risk reduction such as alarms or interlocks would be more cost effective than having high integrity SIS.

Full details of the approach are described in GP 48-03.

5.6. Available safety engineering resources

a. Specialist knowledge will be needed for complex applications involving high demand mode applications and where there are common cause issues between protection layers or between a protection layer and the cause of a demand.

BP internal expertise on SIS is generally good at most levels. Significant numbers of BP process and technical managers have attended awareness training and many control and instrument specialists have attended training courses on the requirements of IEC 61511 and BP Engineering Technical Practices.

A number of BP specialists are available in Aberdeen, Sunbury, Baku and Houston to facilitate LOPA assessments.

External consultants are variable and many are not aware of the limitations of the LOPA approach and the complexities introduced by the subsea environment.

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